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Master Thesis

P2P Communication in Android devices

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Abstract

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4.4 Max range of Wi-Fi Direct communication without line of sight between devices 55

Acronyms

ACK Acknowledge Packet. 24

AODV Ad hoc On-Demand Distance Vector. 10, 11, 31

AP Access Point. 8, 9, 12, 13, 17

BLE Bluetooth Low Energy. 14, 16, 26, 30

BS Base Station. 5–7

BSC Base Station Controller. 5

BSS Base Station Subsystem. 9, 11

CRT Content Routing Table. 23

CSMA/CA Carrier Sense Multiple Access with Collision Avoidance. 8, 9

CTS Clear to Send. 8

DHCP Dynamic Host Configuration Protocol. 17, 21

DSDV Destination-Sequenced Distance Vector. 31

DSSS Direct Sequence Spread Spectrum. 6

DTN Delay Tolerant Network. 27

EDGE Enhanced Data Rates for GSM. 6

EPC Evolved Packet Core. 7

ESS Extended Service Set. 9

FDD Frequency Division Duplex. 5–7

FDMA Frequency Division Multiple Access. 5, 6

FHSS Frequency Hop Spread Spectrum. 13

GM Group Member. 12, 17–19, 21–24, 26

GO Group Owner. 12, 17–19, 21–25

GPRS General Packet Radio Service. 6

GSM Global System for Mobile Communications. 5, 6

HetNet Heterogeneous Network. 7

HSPA High Speed Packet Access. 6

HWMP Hybrid Wireless Mesh Protocol. 11

IoT Internet of Things. 14, 16

IP Internet Protocol. 7, 17–24

ISM Industrial, Scientific and Medical. 13, 14

ISP Internet Service Provider. 8

LTE Long-Term Evolution. 6, 7, 22

MAC Medium Access Control. 6–9, 13, 16, 18, 19, 25, 27, 31, 34, 36–43, 45–47, 49–52

MANET Mobile Ad hoc Network. 22, 23

MAP Mesh AP. 11

MIMO Multiple Input Multiple Output. 6–8, 16

MP Mesh Point. 11

MPP Mesh Portal. 11

MS Mobile Station. 5–7, 9

MSC Mobile Switching Center. 5

NFC Near Field Communication. 15, 16

OFDM Orthogonal Frequency Division Multiplexing. 7, 8

PIT Pending Interest Table. 24

PM Proxy Member. 22

RFID Radio Frequency Identification. 15

RIP Routing Information Protocol. 37

RNS Radio Network Subsystem. 6

RTS Request to Send. 8

SC-FDMA Single Carrier Frequency Division Multiple Access. 7

SDK Software Developer Kit. 26, 27

SIM Subscriber Identity Module. 6

SSID Service Set Identifier. 12, 17

STA Station. 10, 11

TCP Transmission Control Protocol. 20, 21

TDD Time Division Duplex. 7, 15

TDMA Time Division Multiple Access. 5, 6

UDP User Datagram Protocol. 19, 20

UMTS Universal Mobile Telecommunications System. 6, 7

URL Uniform Resource Locator. 44–48, 51

UTRA UMTS Terrestrial Radio Access. 6

UTRAN UMTS Terrestrial Radio Access Network. 6

UUID Universally Unique Identifier. 33

W-CDMA Wireless Code Division Multiple Access. 6

WLAN Wireless Local Area Network. 8, 11, 13, 14

WPA Wi-Fi Protected Access. 9

WPAN Wireless Personal Area Network. 13, 14, 16

WPS Wi-Fi Protected Setup. 9

Chapter 1

Introduction

1.1 Context

Nowadays the demand for better mobile devices is higher than ever. Mobile phones are an indispensable gadget in today's society. Increasingly demanding application and connectivity requirements bring the need for devices with more capabilities, *e.g.* battery life, memory, persistent storage, Internet access speeds, *etc.* With this evolution of equipment, inevitably, comes an evolution of communication technologies.

Mobile phones, usually communicate between themselves in different ways: via mobile cellular networks, via Internet access, via Bluetooth, *etc.* New communication technologies are appearing at a fast pace and the possibilities for using them to provide new services for the users are endless.

The main communication methods use a limited number of central points, that coordinate the communication process between devices, acting as mediators in the communication channel. However, from this dependence, a question arises: if there is a limited number of central points what happens if a partial or total failure from their part occurs. This question has an answer in device to device communications.

There are many devices available, usually more than one per person, see [6], making the creation of an ad hoc network a big possibility to overcome possible failures with central points or even if one is not within reach of any central point. Despite that, this answer is not a substitute to the existing communication methods. It aims to add more range and robustness to the network and possibly reduce the workload of the infrastructured network, which has a limited capacity.

Due to the reasons just stated, ad hoc communication between devices has been lately a hot topic, with several applications being currently offered to mobile users *e.g.* FireChat and Ueppa!, see Section 2.3. This thesis offers a framework to create applications of this nature. To realise this framework a new application of this kind was implemented which allows users to access web pages using ad hoc links when they are not within range of an access point or base station.

1.2 Problem Statement

Given the context above, the main question is: where can the creation of an ad hoc network be of use to the everyday tasks people perform on their mobile devices. There are many answers to this question, thus the difficulty of choosing a relevant topic. Much of the work currently being done focus on chat applications, where messages are transmitted via an ad hoc network. Bearing this in mind, this thesis takes a further step and creates a framework to form an ad hoc network capable of transmitting packets between devices.

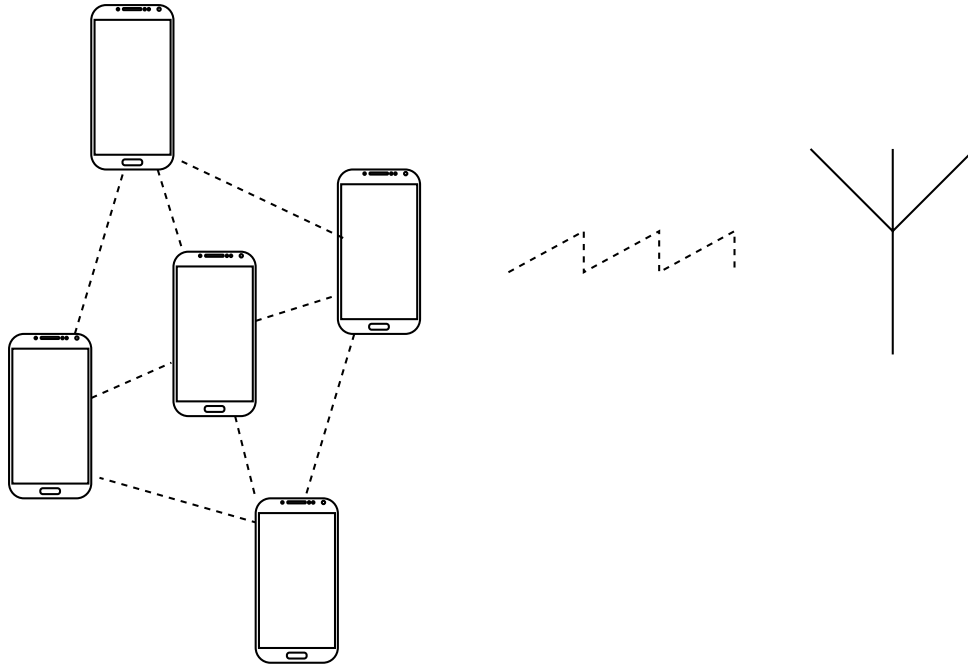


Figure 1.1: Example of a created ad hoc network

A solution is proposed to solve the inability of devices to access web pages, through a peer-to-peer application, even where there is the possibility of indirect Internet access, via communication with other devices and not directly with the infrastructure. The Android hotspot is an existing service that allows devices to share their Internet with the surrounding peers. However, this only works if a device is within immediate range of the hotspotting device, reducing the size and reach of the created network. In the solution proposed in this thesis, the devices are able to reach the Internet by sending their requests to their immediate peers, who will forward them to their neighbors until the destination is reached, travelling more than one hop¹, see the example of Figure 1.1.

It is important to note that this work does not have the purpose of replacing the existing communication infrastructure, but is, in fact, trying to complement it.

1.3 Objectives

This thesis will pursue two main objectives:

1. Developing a framework to create of a decentralized ad hoc network, where packets are transmitted between devices. Proving that, with the current unmodified Android versions and the Bluetooth technology, the creation of a network of that nature is feasible.

To materialize the framework an application that implements this framework and exchanges web pages between devices is created. The application will create a solid ad hoc network. After the creation is complete the application will provide the logic to correctly manage the web pages request throughout the network, as well as their correct delivery. This application will then be submitted to a series of tests to comprehend where it is more vulnerable and where it is more robust.

¹One hop is the distance of the communication between a device and its immediate peers. Each time the message travels between a device and its peers a hop is added to the message path.

2. The second objective will be to assess the advantages of migrating this application from Bluetooth to Wi-Fi Direct and what changes need to be made to the current Android versions to accommodate this migration. The advantages and disadvantages of Wi-Fi Direct in comparison to Bluetooth will be compared in the scope of the created framework. Conclusions will be drawn from a series of tests to compare both technologies. Also, a description of the obstacles, present in the current Android devices, preventing the development of this application using Wi-Fi Direct instead will be presented.

This thesis will not provide a market product, thus it disregards some aspects of what would be to expect from a full consumer ready application. Security is not developed in this solution, although some ideas are given on how it can be provided.

1.4 Contributions

As mentioned before the created framework has a huge amount of possibilities. The purpose of this thesis is not to limit these possibilities to the transfer of web pages. It is to provide a simple to use developer kit that can be extended easily to exchange any message format, from web pages to beacon messages.

This is an open source framework and it is hosted in a GitHub repository². In here the full application code will be presented with the necessary comments to complement the description made in Chapter 3. By using the provided mechanisms developers can made the necessary modifications to the code in order to achieve different goals, *e.g.* the creation of a peer-to-peer chat application.

Also, since the transfer of web pages is a complicated process and not much information is available on it, this application has a double usefulness, since it also demonstrates how to exchanges large files between devices.

1.5 Structure of the Thesis

The rest of this thesis is organized as follows:

- Chapter 2 will begin with a theoretical introduction of the different wireless communication technologies, analysing their features, advantages and disadvantages. This aims to provide the needed background to understand the technologies used in this thesis and the choices made along its developments. There will be an analysis on the Android's implementation of Wi-Fi Direct and some of the possibilities it may present, such as ad hoc networking and multi-hop routing. Finally, an overview of some ad hoc networking applications in Android will be given, describing their features and technologies used.
- Chapter 3 will contain the implementation of both framework and application. It will begin by a description of the steps taken to decide important parts of the framework, such as technologies and routing protocols used. The implemented network creation and communication protocols are explained, providing a better understanding of the framework. Lastly, the materialization of the framework, the peer-to-peer application to exchange web page is described, along with its features and overall packet exchanges.

²To download the code of the application clone following repository: <https://github.com/Falcato/ThesisApp.git>.

Chapter 2

State of the Art

2.1 Communication Technologies Supported by Mobile Devices

2.1.1 Mobile Networks Technologies

The first form of communication on mobile devices where the mobile cellular telecommunications provided by the Public Land Mobile Network. At first they did not have so many features as we know them now, they were limited to basic voice calls and short text messages. As devices became more sophisticated so did mobile networks, including new features, such as Internet connections and device to device communication.

Mobile networks have become common place, *i.e.*, people make millions of phone calls and text messages everyday, using the service providers' Base Stations (BSs) to enter a network, where their message/phone call is being routed to its destination. This said, it is important in the scope of this work to have some understanding on how devices communicate with each other using these mobile communication standards.

In this subsection we will briefly present the existing standards for mobile cellular networks and their evolution, passing from 2G, 3G and 4G, emphasizing this last one.

2.1.1.1 2G: GSM

Global System for Mobile Communications (GSM) is a standard, created by European Telecommunication Standards Institute, to describe second generation cellular networks. These networks differ from the first generation due to the fact that they were no longer analog, as in 1G, and became digital, allowing for voice as well as text transfer.

GSM's architecture can be seen as hierarchical, with components ranging from Mobile Stations (MSs) to Mobile Switching Centers (MSCs). MSs, the devices, have a unique number, with which a BS can identify each one of the MSs it controls. A Base Station Controller (BSC) controls multiple BSs to allocate radio channels, manage call handover between BSs and control their power levels, in order to avoid muffling the transmission of other MSs. Finally, a MSC, in charge of multiple BSs connects to a Gateway MSC where mobile registration and authentication are made.

GSM uses the air interface to transfer information, being a wireless way of communication, specifically, it uses Frequency Division Duplex (FDD), to separate the uplink and downlink frequencies, 890-915MHz and 935-960MHz, respectively. Then divides each block of frequencies into smaller channels, 125 channels of 200kHz each, using Frequency Division Multiple Access (FDMA). In each FDMA channel it's given a time slot for each MS to use, using Time Division Multiple Access (TDMA). Using this

methodology for medium access, GSM allows for a data rate of 9.6kbps per user, after encryption and error control overhead.

GSM's main technologies are voice communications, Subscriber Identity Module (SIM) authentication, encryption and accounting information, handover, enabling MSs to move and connect to a different BS maintaining the service and SMS (Short Message Service), allowing for text transfer up to 160 characters, sent to one or multiple destinations.

In order to improve GSM, General Packet Radio Service (GPRS) was introduced, also known as the 2.5G networks, adding two new elements to the previous GSM architecture, a service support node for security, mobility and access control, a gateway support node for establishing connections to external packet switched networks. Although not much improvement on data rate was made on GPRS, soon came Enhanced Data Rates for GSM (EDGE), which combined GPRS with different modulations, improving the spectral efficiency of each channel and allowing for data rates up to 384kbps.

GSM requires heavy resource planning, *i.e.*, frequency and time planning and slot assignment, meaning each user has a dedicated time and frequency and thus the number of users in a cell does not influence the cell size.

2.1.1.2 3G: UMTS

Universal Mobile Telecommunications System (UMTS) was the natural 3G evolution of the GSM/GPRS network. It used the previously created GPRS architecture and improved it using different Medium Access Control (MAC) techniques to improve even further spectral efficiency. The architecture of UMTS is divided into radio access network, UMTS Terrestrial Radio Access Network (UTRAN), in charge of managing cell-level mobility, and Radio Network Subsystem (RNS) and air interface, UMTS Terrestrial Radio Access (UTRA), similar to GPRS. Now UTRAN controls multiple RNSs, who is responsible for handover decisions. The UMTS network operates in parallel with the previously established GSM/GPRS network.

In UMTS transmission is made over two 5MHz FDD channels, using Direct Sequence Spread Spectrum (DSSS), improving both the data rate and security of transmissions. Wireless Code Division Multiple Access (W-CDMA) is now used instead of FDMA and TDMA, each user has a chipping sequence with which messages are encoded, in the destination, with the same chipping sequence the reverse process is made and the message is transmitted, allowing for similar data rates as EDGE and users to transmit simultaneously with little interference, depending on the number of users.

UMTS requires heavy power control, because the source can distinguish each user via their chipping sequences, but if one user muffles another user only one message is received in the destination, thus it is needed to control the power with which each user will transmit. This means the more users transmit simultaneously, more interference is created, assuming non ideal conditions, thus having to reduce cell size to compensate for this interference, leading to more complex cell planning.

In order to enhance the data rates of UMTS, High Speed Packet Access (HSPA) was introduced, which is an evolution of W-CDMA, 3.5G networks. This standard improved uplink and downlink speeds, by adding higher-order modulation, *e.g.*, 16QAM or 64QAM, and a more efficient retransmission mechanism in the downlink channel and by allowing parallel transmissions of multiple users, also known as Multiple Input Multiple Output (MIMO), reaching rates up to 168Mbps and 22Mbps, respectively.

2.1.1.3 4G: LTE/LTE-A

Long-Term Evolution (LTE), came to meet the specified requirements in International Mobile Telecommunications-Advanced, issued by ITU-R. But since it did not meet all the requirements to be considered a 4G network, it was considered a 3.9G network. It introduced an exclusively IP-based packet-switching core network,

denominated Evolved Packet Core (EPC), and it targets the increase of quality of service, spectrum efficiency and reduced cost.

EPC introduced new elements to the existing network, a Packet Data Network Gateway, serving as the termination of EPC towards Internet, providing Internet Protocol (IP) services, address allocation, packet inspection and policy enforcement, a Mobility Management Entity, responsible for location tracking, paging, roaming and handover, and a Policy Charging Rules Function to manage the quality of service provided.

LTE uses multiple frequency bands from 700MHz to 2600MHz, with a flexible bandwidth ranging from 1.4MHz to 20MHz, using both FDD, Time Division Duplex (TDD) and a combination of these two methods. This combined with Orthogonal Frequency Division Multiplexing (OFDM) and MIMO, for MAC, allows LTE to reach data rates of 326Mbps for downlink. In uplink a Single Carrier Frequency Division Multiple Access (SC-FDMA) is used allowing for data rates up to 86Mbps. These data rates are considerably higher than the ones reached by UMTS.

In order to further improve data rates on LTE, LTE-Advanced was introduced. This new network meets the requirements to be considered a 4G network, thus it is where 4G networks were actually introduced. Reaching up to 3Gbps for downlink and 1.5Gbps for uplink, Release 10, LTE-Advanced immensely improves data rates by using a much wider channel frequency and higher-order MIMO, up to 100MHz, also improving on spectral efficiency.

A new type of networks is also introduced, the Heterogeneous Networks (HetNets), created by deploying a low-power BS at cell edges to enhance network performance. Three types of cells are created with this network: micro or pico cells, where a relay node is used to extend the service to other devices. Femto cells, for indoor coverage at home, offices or malls, where a Home eNodeB serves as relay node for devices inside the femto cell.

Considered for 4G LTE-Advanced was the concept of D2D communications, creating direct links between devices within a small area. This technology would enable the linking of devices by using the cellular spectrum, allowing for data to be transferred from one to the other over short distances, but using a direct connection. This form of device to device has a lot of applications, *e.g.*, in disaster scenarios, where the access to the infrastructure is denied, or when the infrastructure is overloaded in *e.g.*, large public events.

4G LTE-Advanced D2D was a feature in Release 12 and brought some benefits, such as reliable and persistent communication, meaning it persists if the LTE network is disrupted, data rates, when the distance to an BS is considerable and interference reduction, by not having to communicate directly with the BS overloading the network. There are of course some issues to be addressed with this communication, such as the authorization and authentication of MSs and the fact that inter-operator communication may not be approved by the different operators, limiting the possible links.

2.1.2 Wi-Fi (IEEE 802.11)

A Wireless Local Area Network (WLAN) is a wireless network that can connect multiple devices to each other within a limited range. WLANs have become very popular in the day to day life of people. Most households have a WLAN deployed so that devices inside and around the premises can have Internet access. The popularity of WLANs is mainly due to the fact that devices do not need to be physically connected to the Access Point (AP) to access the Internet, which removes the costs of cables and the associated infrastructures.

IEEE 802.11 is the *de facto* standard for WLANs and it is commonly known as Wi-Fi. IEEE 802.11 is composed by MAC layer and Physical layer specifications for WLAN implementations, various versions have been released, but the most common are IEEE 802.11a/b/g/n/ac, mainly because they were adopted by mobile and computer manufacturers as the standard to be used in radio communication, *i.e.* wireless.

Unfortunately, the connection speeds are not as high as in wired networks, since the environment plays a big role, *i.e.* if there are obstacles between the AP and devices. Also, the number of devices in the network will affect the data speeds, since the protocol specified for the IEEE 802.11 standard is Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA). Although these are disadvantages over wired technologies, there has been done a lot of improvement on the data rates, during the development of wireless networks, reaching up to 6.93Gbps, using MIMO, high-order OFDM and enhanced MAC techniques, see [7] for more information on this topic.

In CSMA/CA the devices check the medium for clearance, *i.e.* if there is no other device transmitting at that time. Nodes attempt to avoid collisions by transmitting the full data only when the medium is clear. Hidden node is still a problem with this MAC method, meaning a node can be transmitting but its transmission is not detected by other devices, creating collisions.

In order to overcome the hidden node problem, Request to Send (RTS)/Clear to Send (CTS) can be used to reserve the access to the shared medium. A control packet RTS is sent by the transmitter, to which the receiver will answer with a CTS. If the channel is clear the packet will be sent immediately, *i.e.* if a CTS was received, else the device will wait a random period of time, named backoff time, before checking if the medium is clear again. When the backoff timer reaches zero, the device will perform the check, if the medium is clear the device will send the packet, otherwise the backoff time is set again. Due to the exponential factor of this backoff time the connections' speeds are limited when multiple users use exhaustively the network channel, whereas in wired connections, like switched Ethernet, traffic management is, typically, done through traffic flow prioritization.

Another main consequence of establishing a WLAN is the security of the communication. In wired networks there is a physical component to security, such as controlled access to the building. In WLANs networks this type of security is not relevant as, for instance, one can enter the network outside the building. Thus security protocols must be implemented to successfully prevent attacks on the communication between devices, such as WPA2 or IEEE 802.11i, see [8] for more information on security protocols.

A WLAN can have three different main modes of operation, infrastructure, ad hoc mode and Wi-Fi P2P. Besides these three main modes, IEEE 802.11s will also be briefly explained due to its characteristics and similarities with this work. In the next subsections these modes will be explained, and provided of pros and cons.

2.1.2.1 Infrastructure

Infrastructure is the most common method, usually deployed and made accessible by a local Internet Service Provider (ISP) or by a Local Area Network. The structure of the network is as follows, there is a wireless AP that manages the various devices on the network and provides the Internet access, this AP

can be either wired, *e.g.* fiber, or wireless connected to network backbone. The AP is responsible for the creation and maintenance of the network, it generates an SSID with which the network will be identified, as well as a security level, *e.g.* Wi-Fi Protected Access (WPA) or Wi-Fi Protected Setup (WPS).

MSs can then connect to the network via wireless or wired connections. In the wired connections no authentication is required as there is a physical connection and usually higher data throughput is achieved. In wireless connections there is the need of first identifying the network to which the MS wishes to connect and then to proceed according to the security level used by the AP. The access to the network is managed by the AP, the wired connections are, usually, granted priority over the network, whereas wireless connections compete for the usage of the air interface, typically, via a predefined MAC protocol, being the most used CSMA/CA.

An example of the infrastructure mode network layout can be seen in Figure 2.1.

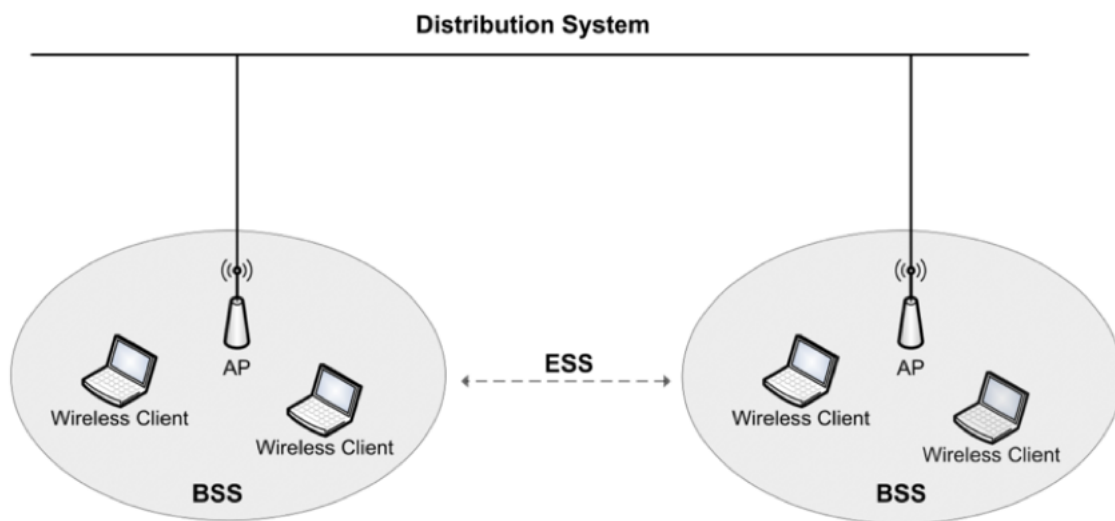


Figure 2.1: Infrastructure network layout (source: www.cse.wustl.edu)

Where each Base Station Subsystem (BSS) is a network and Extended Service Set (ESS) is a set of BSSs that form a single sub network.

The infrastructure mode is ideal if the network as a more permanent character, since the APs are, usually, developed to provide higher-power wireless radios and antennas so that the area covered by the APs is wider. Despite being the most widely deployed method there are some disadvantages associated with this method, for instance, two MSs will not be able to communicate directly even if they reside in the same network, and all their traffic is routed by the AP, which brings another problem: in case of AP failure due to, *e.g.* power failure, software failure, *etc.*, all the network will be compromised and to establish an Internet connection the MSs will have to either connect to another AP or to create the connection by themselves, which brings us to the next subsection.

2.1.2.2 Ad hoc Networks

In the ad hoc mode there is no need for a centralized AP, meaning all the devices can connect to each other if within range. An ad hoc network is slightly different from a Wi-Fi Direct network (WIFI P2P) that will be described in the next section. In ad hoc mode the network is meshed, and all the devices within it are peers, which brings some benefits, *e.g.* the direct communication between devices, without depending on a centralized point connected to the distribution system.

In ad hoc networks with a mesh topology there can be peer-to-peer exchange of traffic. This helps with the problem of having a centralized point of failure, such as the one present in infrastructure mode. Much like *torrents* files can be transferred by smaller parts and by different providers, by using this method to transfer files, packets, *etc.*, within the network higher data rates can be achieved, since multiple parts of the same file/packet can be sent simultaneously.

An example of the ad hoc mode network with a mesh topology can be seen in Figure 2.2.

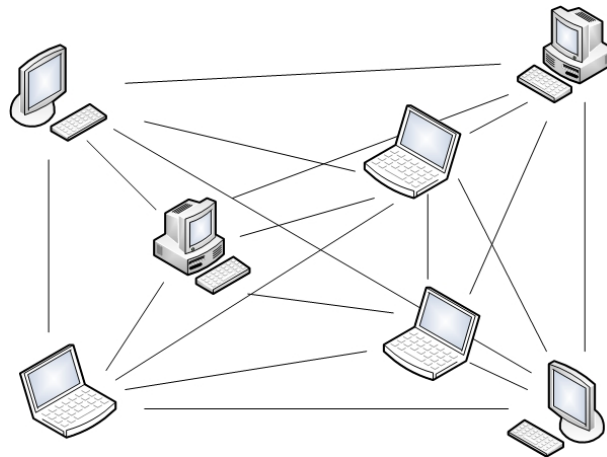


Figure 2.2: Ad hoc network layout (source: monet.postech.ac.kr)

As can be seen in Figure 2.2, one device can have multiple links connecting him to other devices in the network. Although this is a big plus if compared with infrastructure mode, it must be noted that, as said before, a device can connect to other devices if in range, otherwise they will not be able to establish a link and thus communicate. This limitation is due to the lack of a routing protocol in this network mode, so nodes cannot serve as relay for communication between two Stations (STAs), and although it is possible to implement a layer 3 (Network Layer) routing protocol with this mode, such as Ad hoc On-Demand Distance Vector (AODV), it is not intrinsic to this mode. In the next subsection, IEEE 802.11s will be introduced and we will see that it covers this limitation of this ad hoc mode.

Although there are advantages such as not having a centralized point of failure, peer-to-peer file/packet transfer described above, there is an easier setup of the network and the problem described in the infrastructure mode of not existing a direct connection between two STAs is now mitigated as every STA in the network is a peer, there are some disadvantages associated with this network mode, such as the network being more dynamic which brings a lot of changes in the network topology, the interference inherent to all the devices transmitting at the same time to different peers and there is always the scalability problem as more devices in the network mean more connections, which grow exponentially, whereas in the infrastructure mode the connections grow only linearly, so ad hoc networks don't scale well. Also, due to the lack of a routing protocol, the range of the the network will be significantly reduced, as devices do not know which route to forward the packets, in order to reach a certain destination.

Furthermore, the network will not be able to reach the Internet, since devices will communicate between themselves and not with the infrastructure, making the packet exchange limited to the local/cached information stored in the devices, unless if the infrastructure and ad hoc networks are connected through a common device. Finally, the mobility of the devices can make the maintenance of stability of the network a difficult task as links may have to be created and destroyed regularly.

2.1.2.3 IEEE 802.11s (Meshed Network)

IEEE 802.11s is a standard introduced in 2011 which aimed to provide both broadcast and unicast delivery of information. The main difference between the previously described ad hoc mode is that IEEE 802.11s supports multi-hop and implements a layer 2 routing protocol named Hybrid Wireless Mesh Protocol (HWMP).

In this standard, four main types of devices exist: Mesh Points (MPs) who establishes peer links with other MPs, Mesh APs (MAPs) that is a characteristic of MPs which provides BSS services to support communication with STAs, STAs which are devices outside the meshed WLAN and connect to the network via MAP, finally, Mesh Portal (MPP) that is the point at which devices enter and exit the network.

MPs discover potential neighbors based on beacon and probe messages, containing the WLAN Mesh Capability Element, a summary of active protocols and other channel information, and the Mesh ID, that identifies the mesh. The devices are considered to be members of the network upon the establishment of a secure peer link with neighbors within the network. In Figure 2.3, taken from [1], it is possible to visualize an example of the network:

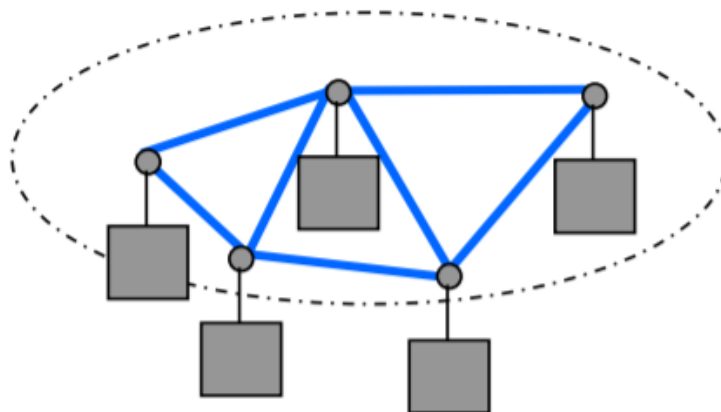


Figure 2.3: IEEE 802.11s network layout (source: [1])

Depending on the number of radio interfaces the devices have, IEEE 802.11s allows for multi-group formation, where each radio interface of each device is assigned to a different group, called Unified Channel Graph.

The routing protocol used by IEEE 802.11s, HWMP, is based on a combination of Radio Metric AODV and tree-based routing, which provides great flexibility in changing environments, great efficiency in fixed mesh deployments, and possible extensibility to metrics other than simple number of hops, such as quality of service, load balancing and power-aware. With this features, HWMP extinguished many of the ad hoc mode flaws, such as lack of routing protocol and thus inability to perform multi-hop transfer of packets and network range.

Although IEEE 802.11s comes with some benefits, pure ad hoc mode still predominates as the peer-to-peer mode, due to its simplicity. There are still some products that make use of the IEEE 802.11s, such as Linux operating system, FreeBSD operating system and Google WiFi routers.

2.1.2.4 Wi-Fi Direct

Wi-Fi Direct is a Wi-Fi standard created by Wi-Fi Alliance. The previously called Wi-Fi P2P, now Wi-Fi Direct, is an innovative way of mobile communication without the dependence of a physical AP. It can be used for different purposes, such as file transfer, Internet browsing, device communication, *etc.*. Wi-Fi Direct assumes an ad hoc topology, meaning the devices are not dependent on one another, but form a network where all devices share information, hence called peer-to-peer. In Figure 2.4, it is possible to see the difference between traditional infrastructured Wi-Fi (to the right) and Wi-Fi Direct (to the left).



Figure 2.4: Wi-Fi Direct (left) and traditional Wi-Fi (right) network layouts (source: info.tvsideview.sony.net)

Wi-Fi Direct is not dependent on an infrastructure, meaning even without access to a Wi-Fi network it is possible for devices to connect with each other, this because the Wi-Fi Direct enables devices to emit a signal to other devices in the vicinity announcing the possibility of making a connection. Users in the vicinity of the sending device receive an invitation to join a network (Wi-Fi Direct group).

The process of group creation and administration is the most important topic to this work, regarding this technology. Devices can either join existing groups or create new groups, where they will be the administrators, *a.k.a.* Group Owners (GOs) of that particular network. This type of creation forces the Wi-Fi Direct to shape its topology as a star, as is evidenced in Figure 2.4, where there is a central soft AP. It is important to make clear the distinction between a soft and a physical AP: the physical AP usually refers to a physical router, that administrates a network with wired and/or wireless devices, whereas the soft AP can be set up with a Wi-Fi adapter, present in many devices, such as mobile phones, computers, *etc.*

After the creation of a group, the GO announces to all nearby devices its group, via the Service Discovery protocol, that sends a beacon packet with an Service Set Identifier (SSID), that will be the identifier of the network. Then, the receiving devices can connect to the desired network, by sending information about the device and what type of services it supports. Along with the unique identifier of that device, when received by the GO, the devices become Group Members (GMs) of that network, much like slaves in Bluetooth, see 2.1.3.

In traditional Wi-Fi Direct, the connections are one-to-one or one-to-many, limiting the topology to a star topology, the purpose of this work is to migrate from that star topology to a more dense meshed topology where many-to-many connections are established, and the transfer of data is made faster and without as many relay nodes as in star topology.

The speeds of Wi-Fi Direct are similar to the ones in other Wi-Fi operating modes, reaching up to 250 Mbps. This is the main advantage of Wi-Fi Direct to its direct competitors, such as Bluetooth. As in other wireless technologies, the speed is affected by the environment where the network is inserted, the physical characteristics of the devices and the Wi-Fi physical layer they support, *e.g.*, 802.11a, g or n.

2.1.3 Bluetooth

A Wireless Personal Area Network (WPAN) is type of network where devices are connected wirelessly to each other, based on the standard IEEE 802.15. This definition seems to be quite similar to the one of WLAN, but there is a considerable number of differences between the two. The term personal area network derives from the use that is to be given to such networks, in other words, WPANs are to be deployed in order to connect multiple devices of one's personal area, such as home, office, *etc.*.

Bluetooth is one of the main technologies to implement a WPAN, described above. It uses the 2.4GHz Industrial, Scientific and Medical (ISM) band, it was invented by phone company Ericsson, and is used to connect devices in a short range network.

Devices connect to each other forming *piconets*, which is the term assigned to designate an ad hoc network formed by devices using Bluetooth. Each *piconet* has a master, the device that controls the network, similarly to an AP without providing access to the infrastructured network. Associated to each master there can be up to seven slaves, which are devices that take part in the same *piconet*. Multiple *piconets* can connect between themselves and form a *scatternet*, as seen in Figure 2.5:

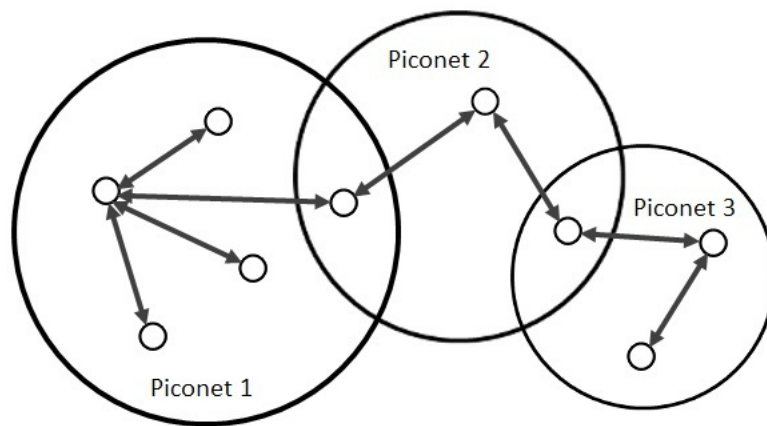


Figure 2.5: Scatternet Layout (adapted from: www.summitdata.com)

Each master is associated with a certain number of slaves, that can participate in more than one piconet, as seen above. These slaves are responsible for coordinating both *piconets*, so that no interference exists.

Bluetooth uses slow Frequency Hop Spread Spectrum (FHSS) to control the frequency of transmission of each slave, this is done by creating a hopping sequence partially based on the master device's MAC address, and then distributing the sequence to each slave on the *piconet*. Devices connect to the *piconet* by pairing with the master, forming a secure link, the master then controls the access to the medium by deciding which slave will transmit at a certain moment in time. In the *scatternet* case, the data to be transmitted from *piconet* to *piconet* is relayed by the node participating in both networks. The pairing of both *piconets* is similar to the pairing of a master and a new member of the network.

Although several advantages of Bluetooth are clear, such as low power wireless protocol, low transmission headers, ease of set up, multi group information transfer, this protocol still has a lot of downsides. The main current problems with Bluetooth consist in the low range of connections, due to the weak signal power being a feature of the technology, the limited number of users that can form a *piconet*, due to the narrow band used by Bluetooth and, finally, the low data rates of the protocol, which are heavily surpassed by the Wi-Fi standard.

WPAN uses, typically, technologies that allow communication between devices within a certain specific range, usually around 10 meters, making this type of network much smaller than the ones created by WLAN. The most common technology is Bluetooth, although there are several other technologies that are beginning to raise awareness, due to the crescent interest taken in Internet of Things (IoT), such as ZigBee. The used radio band is the 2.4 GHz ISM band, due to its general availability worldwide and its lower cost.

Bluetooth Low Energy (BLE) is the power-version of Bluetooth developed for IoT. The natural power-efficiency of Bluetooth combined with lower energy consumption provides the key factors for devices running for long periods of time without recharging. BLE's key features include: standard wireless protocol, allowing for interoperability across platforms, low idle power consumption and data encryption for security of communications, among others.

BLE achieves data rates similar to classic Bluetooth over the same distance, although the application throughputs are much smaller: 0.27Mbps compared to 0.7-2.1Mbps for classic Bluetooth. The spectrum range of BLE is the same as in classic Bluetooth, but the channels are two times wider than in Classic, consequently, there is half the number of channels. The main difference between the two lies in the power consumption and peak current consumption, 0.01-0.5W and less than 15mA for BLE, 1W and less than 30mA for classic Bluetooth. The number of slaves in BLE is implementation dependent as opposed to the fixed seven in classic Bluetooth.

BLE is appropriate for networks that rely on the longevity of the battery of the devices, application throughputs are smaller but the information to be sent is, usually, also much less than in classic Bluetooth. One of the biggest limitation of BLE is the inability to transmit voice, whereas classic Bluetooth is able. Despite this and other disadvantages of BLE there are many areas that can benefit from technologies such as this one, *e.g.* healthcare applications, logistic sensors, sports, among others, so it is not a technology that should be overlooked.

2.1.4 NFC (Near Field Communication)

Near Field Communication (NFC) is a short-range high frequency wireless communication technology that allows data transfer between devices over small distances, first introduced by three manufacturers, Sony, Nokia and Philips. Communications maintain interoperability between other different communication methods, such as Bluetooth.

NFC can be used to connect mobile applications with the physical world, *e.g.* home appliances, connect devices through physical proximity, forming a peer-to-peer network, and card emulation, creating a connection to a common infrastructure and allowing some actions on the infrastructure, such as making payments.

Evolved from Radio Frequency Identification (RFID) technology, an NFC chip operates as one part of a wireless link. Once it is activated by another chip, small amounts of data can be exchanged between the pair if within a few centimeters from each other. One of the advantages, compared to other wireless communication technologies, is that NFC does not require a setup to pair two devices, thus reducing the time and packets exchanged in the transaction, allowing for times up to 1 ms. Also, NFC chips run on low amounts of power, making this technology much more power-efficient than other technologies.

The short range of the NFC technology is a disadvantage due to its spacial limitation, but in terms of security, this spacial requirement provides a higher degree of security than Bluetooth. For instance, making NFC relatively secure to use in crowded areas, where other wireless technologies could be impossible to use to transfer sensitive data, such as credit card data.

NFC operates at 13.56MHz using Amplitude Shift Keying as the modulation scheme and TDD for simultaneous receive and transfer of data, achieving data rates up to 424kbps, and although these rates are not impressive, for the amount of data that is sought to exchange using this technology and the lack of necessity for communication setup, NFC provides relatively fast transfer times.

2.1.5 Conclusion

Mobile network technologies have been improving at a fast pace, since the demand for higher speeds is constant. With the evolution of modulation methods to higher-orders and MAC protocols improving spectrum efficiency and number of users in the network without interference, the demand for higher speeds has been successfully answered. 5G networks should focus further on resource optimization and a massively distributed MIMO system.

Wi-Fi technology has many different standards, some being the natural evolution of the others, some serving different purposes, such as IEEE 802.11s. The Wi-Fi infrastructure mode has been constantly updated with better MAC and modulation techniques, allowing for higher data rates and more users on the network. Ad hoc networks have also been evolving being the best candidate to offload some of the traffic in the infrastructure mode, also to achieve smaller, independent networks. Wi-Fi Direct has appeared as a possible method to implement ad hoc networks. Its support is still limited in devices, only allowing for some of the features it can provide. Progresses must be made in order to utilize this technology to its full capabilities.

Bluetooth has had a similar development to the IEEE 802.11 standard, evolving to faster data rates from version to version. Used for smaller networks than Wi-Fi, Bluetooth is widely used to deploy WPANs, now with the concurrence of Wi-Fi Direct, although they can both be used simultaneously. BLE was also a big development in low energy networks, allowing for fast data transfer with low power consumption. Each Bluetooth technology has its utility, and the future focus should be in expanding the number of allowed users and range of the networks.

Finally, NFC provides technology for yet another type of network. This time with a range even smaller than WPANs. It has a lot of applications but it's widely known for its easy and secure usability in transactions. It is being researched by industry giants like Amazon and AliBaba, but there is still much room for improvement, in security, network range, data rates, *etc.*

Overall we can say that most technologies have met huge improvements in short periods of time, and the tendency is to continue that way. Data rates will continue to grow as higher-level modulation techniques are discovered and new MAC protocols are proposed. More emphasis has been given to smaller device to device networks in later years, has a way to take some load from the infrastructure, or even to for networks relevant to day to day tasks (IoT).

2.2 Wi-Fi Direct in Android

For the scope of this work we are specifically interested in the way Wi-Fi Direct is implemented in Android devices. There are small differences depending on the operating systems in which Wi-Fi Direct is being implemented, thus it is not possible to universally describe Wi-Fi Direct with more detail than the one used in Subsection 2.1.2.4.

In the next section the details intrinsic to the Android operating system will be introduced and explained, followed by an in-depth description of various works on how to improve and expand the functionalities of this implementation.

2.2.1 Wi-Fi Direct Star Formation

As previously mentioned in Subsection 2.1.2.4, a peer-to-peer network is implemented in Wi-Fi Direct, by using a protocol for discovery and connection of the GO with the GMs. The GO functions as a typical Wi-Fi AP, managing the different communications of the GMs.

GOs are not predefined. It is during the group creation that the actual GO is chosen, according to the specified parameters of the protocol, *e.g.* battery percentage. This feature is relevant to manage the vitality of the network as a mesh of groups, since the GOs can be chosen dynamically extending the life of the network.

After the process of the group creation, the GO periodically sends a beacon to advertise the group, enabling other devices to discover and join the group. This advertisement is made in two different ways, either via Wi-Fi Direct, or via typical Wi-Fi. In the first way, devices discover the network via the Wi-Fi Direct discovery protocol, and join using the described set of actions. In the second way, the GO announces the SSID of the network and other devices, also known as legacy clients, connect via infrastructure mode Wi-Fi, using the SSID and password, if set, to identify the GO's network. This leaves us with two different types of clients: legacy and normal. This differentiation will be the key to overcome the lack of multi-group interaction.

In Android devices, IP addresses are predefined according to the function the device performs within the network. The GOs are automatically assigned the following IP address: 192.168.49.1/24, using Dynamic Host Configuration Protocol (DHCP). Whenever a P2P or legacy client connects to the group, DHCP is run again and the clients take an IP address ranging from 192.168.49.2/24 to 192.168.49.254/24, chosen randomly to minimize the chance of conflicts. The GOs are always assigned the same IP addresses, unless they participate in another group as a GM taking the same IP as a regular client - see [2] for a more detailed explanation on this topic.

This technology is still not implemented to the best of its capacity in Android devices. The lack of a routing protocol that can establish multi-group communication, establishing a meshed network is an essential tool to achieve ad-hoc networks. The current state of this technology in Android devices is a single group network with one-to-many links established from the GO to the GMs, which limits both the range and scalability of the network. Wi-Fi Alliance states that it is possible to overcome these limitations using stock devices, by creating software to allow for multi-group formation, although it is not standardized in Android's current version 7.0 "Nougat".

In the next section, a collection of developed work will be presented where the different authors propose different methodologies to overcome the lack of this feature in Android devices.

2.2.2 Ad hoc Networking

C. Casetti *et al.* propose in [2] a process to successfully form a meshed network, by allowing multiple groups to communicate. This proposition is based on stock Android, not requiring any "root" to be made to the devices, meaning all the actions will be performed in application layer, not involving any changes in IP addresses or MAC interfaces.

The authors state that multi-group formation can be implemented by taking advantage of both virtual network interfaces of a device, *i.e.*, the Wi-Fi or legacy interface and the Wi-Fi P2P interface, using each one to act as bridge in each group.

This said, upon experimentation, the following scenarios are not feasible in stock Android, due to the inability of creating a custom virtual network:

- a device is the GO of one group and GM in another,
- a devices is the GO of two or more groups,
- a devices is a GM in two or more groups (non-legacy).

Due to these limitations, the authors propose that a GO be a legacy client in a different group, seen in Figure 2.6:

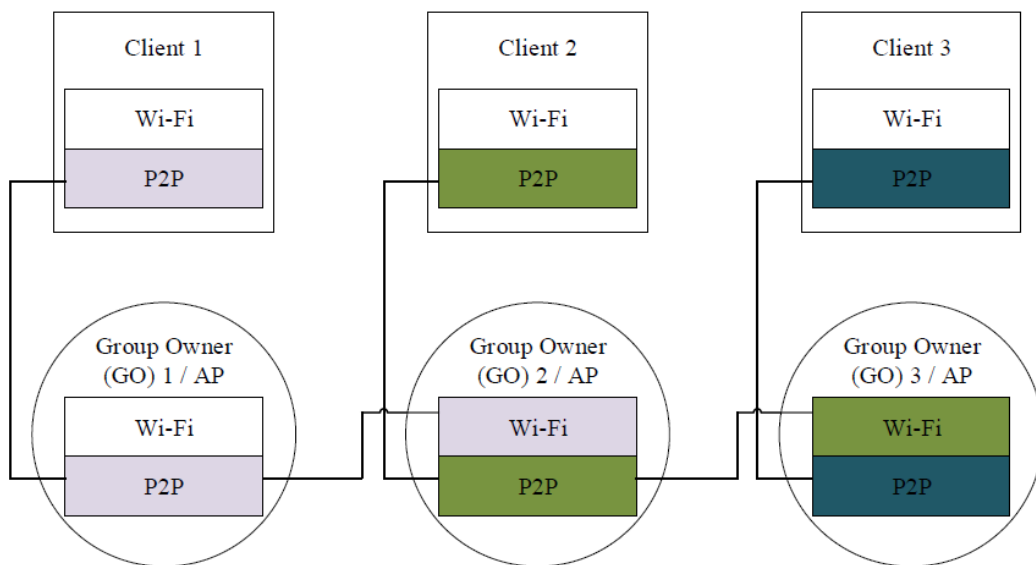


Figure 2.6: Multi-group physical topology with six devices (source: [2])

So, for each GO two network interfaces are enabled, one is the conventional Wi-Fi and the other used for Wi-Fi Direct connection. The IP addresses are assigned according to the previous description.

Two cases are distinguished by the authors: the GO is not connected to any other group as a legacy client, which is the default topology of the network. In this case all connections are feasible, as Wi-Fi Direct has been implemented in order to provide full connectivity among all devices of a single group.

In the second case, the GO is connected to another group as a legacy client as depicted in Figure 2.6 Groups 2 and 3, limiting data transfer to only a subset of D2D data. These limitation are due to two reasons, first the IP conflict of both GOs, who share the same address, 192.168.49.1, making the communication between two adjacent GOs impossible. Secondly, when a GO wants to send a unicast

packet to any client, the packet is sent through the GO's Wi-Fi interface, due to Android's implementation of routing table entries in the GO.

So in this case, client-to-GO communication is allowed since client routing tables list only one interface and there are no conflicts, in GO-to-client direction, bidirectional unicast communication is not allowed. Broadcast communication on the other hand is possible, since it is always sent through the GO's P2P interface. Although when they reach the GO acting as a legacy client they are dropped due to the IP address conflict mentioned above. Finally, client-to-client communication is bidirectional and sent through the client's P2P interface.

It is known from the first case that full connectivity among devices in a single group is allowed, even if one of the GMs is a legacy client and GO of another group. Based on this, the authors introduce the term relay node, which is used to describe this legacy client. The relay node is used to connect two groups. This node is chosen at random, upon the sending of a message from the GO to one of its clients chosen at random among those who do not act as GO in another group. It is important to note that the authors state that this message must be broadcasted to avoid sending it through the Wi-Fi interface, the problem described above in the second case. These clients provide the communication backbone and provide connectivity to all other clients in the group, except from the ones acting as GOs in another group.

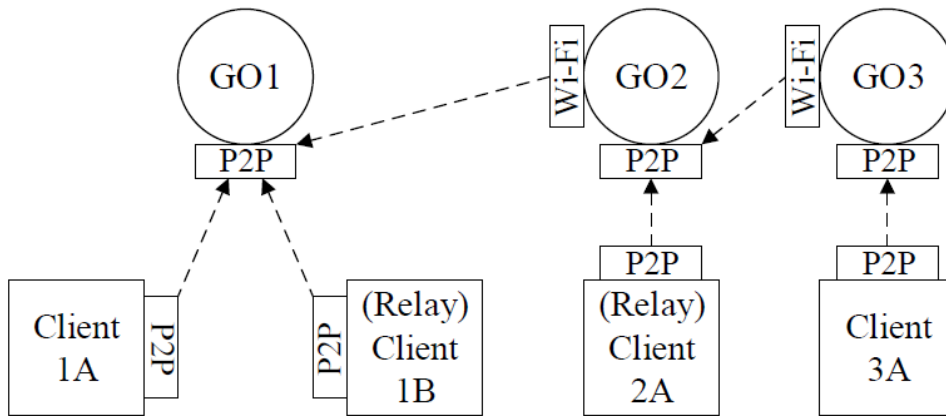


Figure 2.7: Example network topology with 3 Wi-Fi Direct groups. (source: [2])

Take Figure 2.7, where only Wi-Fi Direct connections are represented, for instance. The procedure for Client 1A to send a packet to Client 3A is as follows: Client 1A encapsulates the data in the payload of a unicast User Datagram Protocol (UDP) packet and sends it to the relay Client 1B. The packet will be forwarded by GO1 to Client 1B, at the MAC layer.

The packet is processed at the application layer and the payload is duplicated into a new UDP packet. Sent directly to GO2's standard Wi-Fi interface IP address. At the MAC layer, the packet is sent to GO1, which sends the packet to GO2, via Wi-Fi direct.

The same process is repeated by GO2, but the packet is sent as a broadcast IP packet through GO2's Wi-Fi Direct interface, to relay Client 2A. This client replicates the process of relay Client 1B, sending it to the IP address of GO3's Wi-Fi interface.

Finally, GO3 processes the received packet and sends it to its destination with the correct payload, broadcasting it, similarly to the procedure of GO2.

This mechanism is used following the second case, where the GO is connected to another group as a legacy client. With this mechanism the packet is successfully sent from group to group until its

destination is reached, using a mix of unicast and broadcast communication.

C. Funai *et al.* propose a similar approach in [3]. Their approach is to test two distinct possibilities for multi-group formation, as seen in Figures 2.8 and 2.9, where "LC" stands for legacy client and refers to clients that use the classic Wi-Fi interface, instead of the P2P interface to connect to a group.

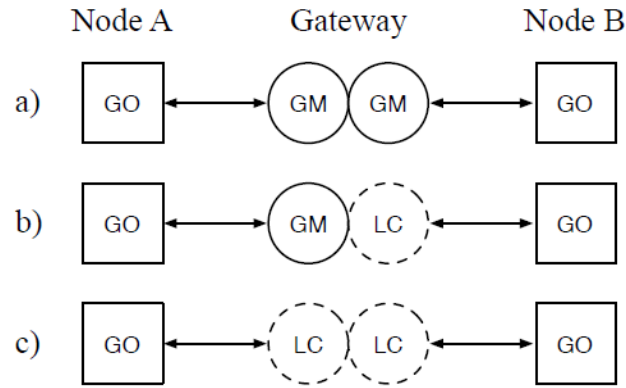


Figure 2.8: Multi-group communication scenarios where the gateway node acts as a client in two groups (source: [3])

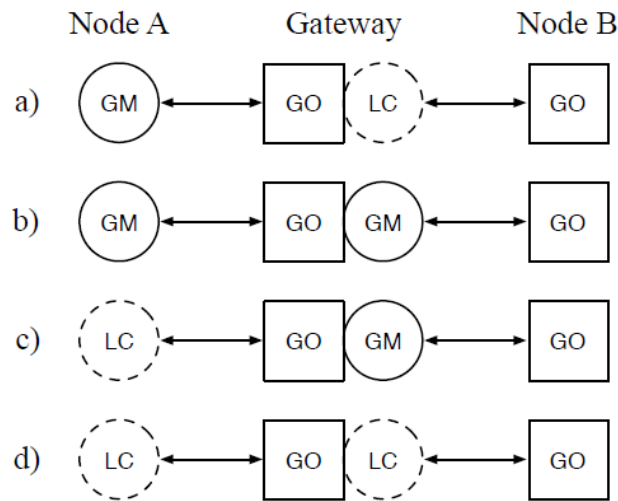


Figure 2.9: Multi-group communication scenarios where the gateway node acts as the GO in one group and as a client in the other (source: [3])

The term gateway node is introduced, referring to the device that connects multiple groups. First by iteratively switching between the different P2P groups, relaying data between them. Secondly by using UDP-based broadcast and a UDP/Transmission Control Protocol (TCP) hybrid solution to achieve multi-group communication. And finally by modifying the source code of the Android operating system.

The authors describe the limitations of stock Android, one of which the multi-group communication must be handled at the application layer and not at the network layer. Actions such as setting IP addresses and managing routing tables cannot be performed without reprogramming the operating system of the device. Another limitation, already referred in [2], is the inability to create virtual network interfaces or multiple virtual MAC entities.

These limitations result in the failure of direct implementation of the test scenarios shown in the figures above. Despite this, the authors state that it is possible to use Wi-Fi Direct functionalities simultaneously with an infrastructure wireless network, reaching the conclusion that the operating system is creating a virtual network interface. But the same interface cannot be connected simultaneously to multiple groups. Thus, scenarios *a)* and *c)* from Figure 2.8 and scenarios *b)* and *c)* from Figure 2.9 are not feasible using simple application layer procedures.

Although it is possible to use both interfaces concurrently and the connection between the groups is successfully established, the experiments from the authors suggest that it is not possible to create a unicast communication to and from the gateway node. For scenario *b)* of Figure 2.8 the gateway node was able to receive data from both groups but was not able to send. For scenario *a)* and *d)* of Figure 2.9 the gateway node was able to communicate with node A but there was no communication with node B. The authors believe this is due to the fact that the DHCP protocol assigns the same IP address to multiple GOs, creating a routing problem, also referred to by C. Casetti *et al.* in [2].

Three solutions to this problem are presented: the first is time sharing, which will allow the implementation of any scenario in the figures above. In this solution, the gateway node is alternatively connecting between groups, *i.e.* disconnecting from the current group, scanning for active devices and request to connect to the new group. In the scenarios of Figure 2.8 the gateway node acts as client in both groups, thus neither group has to be destroyed for this switch to occur. Alternatively, in the scenarios of Figure 2.9 one of the groups has to be destroyed, since the gateway node acts as owner for one group and client for the other. The main difference between the different scenarios within each figure is the protocols used to connect and disconnect to a group, *i.e.* Wi-Fi Direct, classic Wi-Fi or a hybrid combination of the two.

A different solution proposed by the authors would allow simultaneous connections between groups. This can only be achieved by using a hybrid combination of the protocol, as already discussed, so only some scenarios will be tested. The authors tested the different topologies with different network sockets, *e.g.* stream, datagram and multicast sockets. These tests showed that when combining a LC/GM, or *vice-versa*, with a multicast socket, the gateway node is able to communicate with both groups simultaneously. Although the multicast socket only encapsulates one-to-many unicast communication, underutilizing the bandwidth of both protocols.

From the authors' experiments, the gateway node is able to receive and send data over the standard Wi-Fi link, while being connected to both groups with a unicast socket. But no data can be routed with the unicast socket over the P2P link. The reason for this is that Android prioritizes standard Wi-Fi links over P2P links. So the *Hybrid* protocol is proposed, where the multicast socket acts as a control channel to change the configuration of the gateway node. The gateway node receives a control message from a GM, it then verifies which type of link it established with the group. In case of a standard Wi-Fi link, the node starts the reception of the data and disconnects from the same group after the reception is finished, creating a TCP connection with the other group to send the data. In the second case, the node is not allowed to receive data, so a notification message is dispatched and the node disconnects from both groups re-connecting with the correct configuration, *i.e.* inverting the link types.

Finally, the authors modified the source code of Android 4.4.2, altering the current implementation of Wi-Fi Direct to assign a unique IP address to each GO, mitigating the routing problem. This allows for a gateway node that uses both interfaces, and acts as GO in one group and as a legacy client in the other.

A. Shahin *et al.* propose an Efficient Multi-group formation and Communication (EMC) protocol for Wi-Fi Direct, in [4]. This protocol allows multi-group formation as the solutions presented before, only this time the protocol has some significant improvements. EMC exploits the battery conditions of the devices in the network to select the GOs of each group and enables the dynamic formation of Wi-Fi

Direct groups. With these features EMC is a very efficient protocol if battery is an essential resource, *e.g.* during an emergency period.

The authors utilized Wi-Fi Direct's service discovery feature to allow devices wishing to form a group to share information on their battery status. The algorithm will then choose the device with a richer energy reserve and elect it as the GO. The rest of the devices can then connect to the created group as GM. Some of these GMs are referred as Proxy Members (PMs) and are the GMs that link a group to another, similar to the definition of bridge and gateway nodes introduced by the other authors. PMs use their standard Wi-Fi interface to join another group, as a legacy client, forming a network topology similar to the one in Figure 2.10.

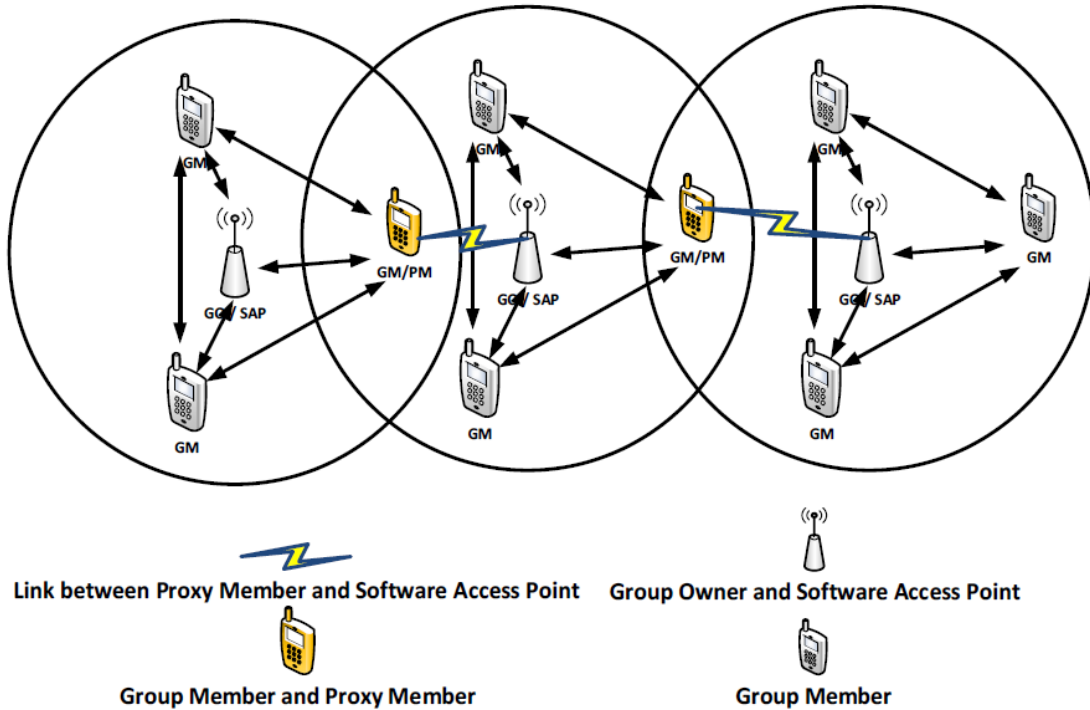


Figure 2.10: Example of a network topology after running EMC (source: [4])

After the group is created and PM selected, the GO waits for a period of time before tearing down the group and restarting the EMC protocol. This is done to ensure that the battery drain of the GO is minimal and that groups can be established with all the devices for the maximum period of time. Upon restart, the new GO is elected and the process is repeated.

In order to overcome the limitations of stock Android already discussed, the authors decided to modify Android's source code. By doing this, multi-group bidirectional unicast communication is allowed. Also, the issue of IP addresses assignment is mitigated by giving GOs different addresses.

Finally, in order to validate the protocol the authors created a chat application, which runs autonomously without any user interaction, apart from the messages to be sent. Manual override buttons are also present in the application for users to manually control the group creation and teardown.

K. Liu *et al.* propose a new implementation of Mobile Ad hoc Network (MANET) using Wi-Fi Direct in stock Android, in [5]. It is the authors' belief that MANETs using this technology can be used in LTE offloading systems. This implementation has the following properties:

- All devices must have the same setup, *i.e.* same functionalities.

- The devices must be ready to be discovered, connected and to transmit
- The MANET is dynamic so devices must be able to join different groups in the network
- All devices are able to leave or join the network, making the MANET not depend on any device

This solution follows a different approach than the previously presented. According to the authors, in order to achieve all of the properties listed above, all devices must become GOs when there is no data transmissions, creating a topology similar as the one in Figure 2.11.

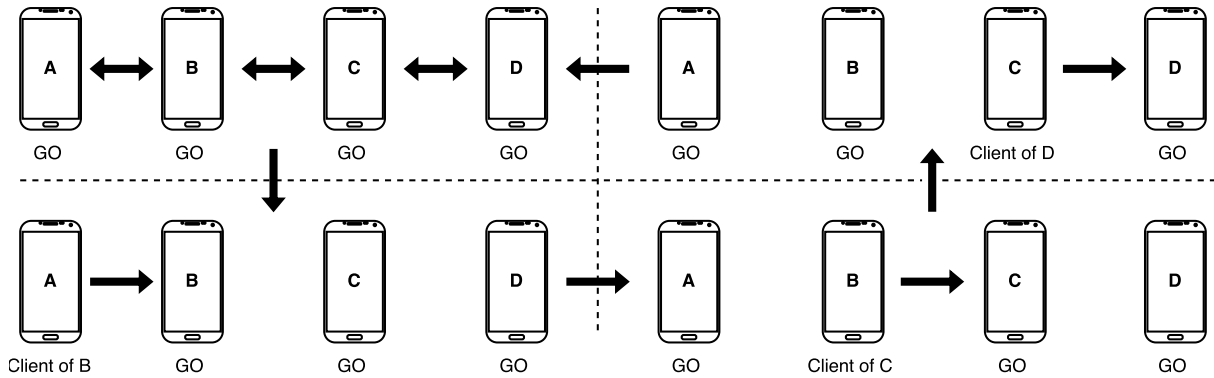


Figure 2.11: Wi-Fi Direct MANET topology (adapted from: [5])

The transmission cycle is as follows: the device with data to transmit must first remove its GO status and connect to the destination as GM, via the Wi-Fi Direct interface. Once the connection is established, the devices may communicate between them. After the transmission, the device acting as a GM disconnects from the group and becomes a GO again. This cycle is repeated whenever there is data to transmit.

This MANET topology is implemented in stock Android devices, as previously mentioned, and presents a distinct solution from the other works, since the devices in the network are constantly changing roles and groups inside the MANET. One disadvantage of this solution is that the status change of the devices are triggered by human interaction with the application, making the network somewhat dependent on human interaction.

2.2.3 Multi-Hop Routing

In the previous section some methods proposed by different authors were presented, in order to create a multi-group networks using Wi-Fi Direct. In this section the focus will be the routing algorithms implemented over some of these methods.

In [2], C. Casetti *et al.* propose a content-centric routing algorithm on top of the network topology proposed. Meaning each node knows what is the next hop to which it has to send the request for a specific content - see [9] for a detailed explanation on content-centric networks.

The authors introduce two data structures responsible for storing the information for content routing: Content Routing Tables (CRTs), providing the next hops to reach a certain content. These tables function similarly to standard IP routing tables. They store the MD5 hash of the IP address of the next hop.

There are three possible scenarios for filling the CRT:

- The simplest one where the content item is available within the group of the content requester, where the next hops of the all GMs is the IP address of the content provider.

- The second scenario is when the content is available in a different group, reachable through the group's relay node. This means the GO of the second group is connected as a legacy client to the first group and, according to the authors' scheme, all the GMs of the first group will have as next hop the group's relay node, except for the GO acting as a client. The next hop for the relay client is the IP address of the GO of the second group. Finally, the next hop of the latter is the IP address of the P2P interface of the content provider.
- The other scenario is when the content is available in a second group, reachable through the GO of the first group, which acts as a legacy client in the second group. Following the authors' scheme the next hop for all members of the first group is the IP address of the P2P interface of the GO acting as a legacy client. The GO of the first group will have as next hop the IP address of the second group's relay node. The relay client will then follow the steps from the first scenario.

The other data structure are the Pending Interest Tables (PITs), where the information about the destination of the content item is stored, they are the next hops from the reverse path of the content requests. When forwarding a content request, the nodes store the IP address of the node interface from where the request was received. With this mechanism, a "memory" of the content request path is created and utilized to then forward the content item to its requester. Upon receiving the content, the intermediate nodes forward the packet and remove the corresponding entry from the PIT. When multiple PIT entries requested the same content, the sending node replicates the packet and sends it to all the requesting devices, deleting all the corresponding entries. A content received by an intermediate node without any correspondent entry in the PIT is discarded.

The content registration, advertisement and request is done in two phases: the initial phase when a client advertises that new content is available, sending a message to the GO, which returns an Acknowledge Packet (ACK) as confirmation. The GO will then advertise within the group the availability of the new content, by sending a broadcast message to all GMs and waits confirmation from the relay node. This broadcast message is discarded at the IP layer by the legacy clients that are GOs of other groups. Thus, in order to create a multi-group advertisement, the relay client will send an advertisement to these clients and waits for the ACK.

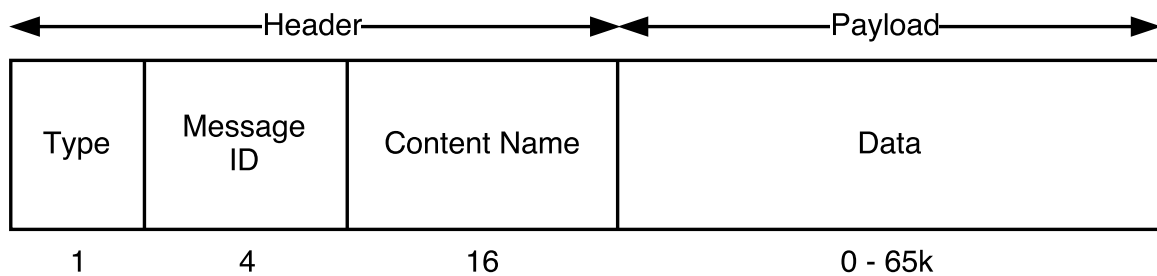


Figure 2.12: Application-layer message for content registration, advertisement, request and delivery. (adapted from: [2])

The message format can be seen in Figure 2.12, where "Type" refers to the purpose of the message, *i.e.*, Content registration, Content advertisement, Content data, Content request, Relay election or notification of GO role in another group and corresponding ACKs. "Message identifier" is used to identify what message is an ACK referring to. Content name is the MD5 hash of the content name. "Data" is the payload and can carry control or content data.

K. Liu *et. al* also provide a multi-hop routing implementation in [5]. The authors create a routing table

composed by two sub-tables, one containing all peers that are directly discovered by the node and the other composed by peers that are accessible via other peers, *i.e.*, multi-hop peers.

The first sub-table is created with a simple broadcast of the peer discovery signal and it will receive the responses from the devices in the vicinity, since in the authors' topology all devices are GOs if no data is being transmitted. The response messages should contain the MAC address of the destination devices, the gateway to reach the devices, in this case the node itself, since all nodes are neighbors and the number of hops to reach them, in this case zero.

After the first sub-table is complete all the nodes in the network have knowledge on who are their immediate peers. The nodes will then exchange routing table information between themselves to get a knowledge of all the multi-hop peers that may exist in the network. The second sub-table is filled proactively when nodes receive routing messages. The message-processing scheme is as follows: the device receives a message and checks its destination. If the destination MAC is not the device's MAC the device will look at its routing table and verify if an entry exists with that destination and where should the message be sent to, incrementing the number of hops, otherwise there is no route to the destination. If the destination MAC is the device's MAC, it will check the message type and infer if it is a routing message. If so, the device's routing table will be updated with the MAC address of the source of the message, the MAC address from where the node received the message, *i.e.*, the gateway, and the number of hops necessary to reach the source.

A			B			C			D		
ADDR	GTW	HOPS	ADDR	GTW	HOPS	ADDR	GTW	HOPS	ADDR	GTW	HOPS
B	A	0	A	B	0	A	B	1	A	C	2
C	B	1	C	B	0	B	C	0	B	C	1
D	B	2	D	C	1	D	C	0	C	D	0

Figure 2.13: Wi-Fi P2P MANET routing table. (source: [5])

In Figure 2.13 it is possible to see a complete table for four different nodes. Each node is now capable of sending a packet to its destination, without having to use a broadcast mechanism.

Two different routing mechanisms have been introduced in this section. Each mechanism is supported by a specific network scheme. This is the main problem of routing in Wi-Fi Direct, since the routing algorithm is developed at the application layer thus being always dependent on implementation, making most of the algorithms not compatible among themselves. This problem also brings some limitations in the number of users that will integrate a specific network with a specific routing scheme.

2.3 Ad hoc Networking Applications in Android

In this section some Android applications that make use of ad hoc networking will be presented, as well as the toolkits on which their development was based, if applicable. It is important in the scope of this work to know what are the offers on today's market on the ad hoc networking, to understand what has been done and what remains to be done and improved. These applications specifically make use of Wi-Fi Direct technology to establish communications or discover peers. It is worth mention that many other applications exist that create ad hoc networks but we are interested in the ones that use this technology in particular, since it will be the base to this work.

2.3.1 FireChat

FireChat is a cross-platform application that allows users to live chat with each other without access to the cellular or infrastructured network. It uses Bluetooth, Wi-Fi Direct or Apple Multipeer Connectivity to provide peer communication between devices.

FireChat is useful when there is a large concentration of users creating traffic that can, possibly, create some congestion in the infrastructured network. By using FireChat users are able to communicate between themselves with minimum delay, offloading the network and being independent on any service provider.

Users can create or join groups, *a.k.a.* chat rooms, to communicate with other users in the same group. Messages can be sent to multiple or single destinations, also messages can be either private or public: in the first case only the selected receiver/receivers will be able to see the message. In the second case the message is broadcasted to all GMs that form the chat room.

When a user sends a private message to another device, a private group is automatically created. However, senders might want to reach devices outside the groups where they are inserted, in that case the message is routed across the group as a private message to a GM that is connected to the infrastructure and can send the message to the destination, that will receive it upon establishing Internet connection.

FireChat also allows for other features, such as blocking the communication with specific users, sending of photos, following other users' FireChat activity, *etc.*

This application is built with MeshKit, a Software Developer Kit (SDK) module with methods allowing for P2P mesh connectivity within devices using this module. It is built over Bluetooth, BLE, Wi-Fi Direct, ANT and other wireless protocols.

It works on three different mechanisms: cloud to mesh where devices connected to the Internet receive data from this link and share it with the other devices within its group, using one of the technologies mentioned above. The packets hop from device to device until it reaches the destination. This mechanism uses broadcast to diffuse the packets through the network.

The second mechanism is mesh to cloud where devices connected to the Internet forward data from devices without Internet connection but with a P2P connection established with the gateway devices, *i.e.* the ones connected to the Internet.

Finally, the peer-to-peer mechanism, where the Internet is not accessed and devices transmit data between themselves using only the P2P link. Data is routed within the groups to reach its destination. Multicast or unicast transmissions can be used.

2.3.2 Uepaa!

Uepaa! is one of the fastest growing P2P software companies, alongside with OpenGarden, responsible for FireChat. Uepaa! created Uepaa! Safety App, an application that aims to provide a security service for users who spend time outdoors and where cellular or Internet connection might not be available, such as mountaineers.

The app allows users to connect directly to the companies emergency call center even if no mobile network coverage is available in the area. This is achieved by forwarding the rescue message to users in the area using Uepaa!'s application. Similarly to FireChat's peer-to-cloud mechanism, in Uepaa! Safety App the message is routed through devices in the area until a device has a connection with either a mobile network or the Internet, and the rescue message, with the user's location is then sent to Uepaa!'s call center where the user can get assistance.

Uepaa! also developed the p2pkit a cross-platform SDK that allows for P2P transmission of beacons, with configurable information. P2pKit also focuses on the battery consumption, since it can be used in battery sensitive applications such as Uepaa! Safety App. It provides P2P communication with all the associated processes, such as discovery and formation of groups. Range estimation on who are the closest peers and how close are they is also included in p2pkit modules, which can be useful to efficiently manage the battery of the device by sending only the beacons to the closest peers.

P2pkit is the base for different applications. Nearby devices using p2pkit are notified when a proximity event takes place and, although the principle is the same, applications are tailored to respond differently to certain types of events, *e.g.* Uepaa! Safety App responds to the event of receiving a beacon by checking the device's Internet or mobile signal and tries to forward the message to the call center. Other applications might trigger other responses, such as notifications to the current user, not forwarding the data but storing it and displaying it in the device.

2.3.3 Murmur

Murmur is an open-source, anonymous messaging application. Users can communicate with one another without Internet or mobile connection, similarly to the applications described above. However, Murmur uses Wi-Fi Direct and Bluetooth technologies to establish communications between the devices, creating a Delay Tolerant Network (DTN) in which the P2P transmission of messages occurs.

Much like every other P2P network, the more users Murmur has, the faster transmission of data is. Messages are broadcasted over the network and if no device is in the vicinities of the sender, the message is queued for posterior transmission, thus the delay tolerant network designation. Murmur allows users to post messages to the network, a system to upvote, store, share and search for posts.

The discovery and connection between devices is done using both Wi-Fi Direct and Bluetooth: each user advertises it is running Murmur via the Wi-Fi Direct interface with a specific name, "MUR-MUR:Bluetooth MAC", constantly searching for peers using a similar device name, *i.e.*, starting by "MURMUR". If a discovery is made, the application filters the Bluetooth MAC address from the device's name and creates a Bluetooth connection, exchanging the message. The actual exchange starts with a handshake where each device sends its contact list and the amount of shared contacts between the two is calculated. Secondly, the number of expected messages to be exchanged is sent and, upon agreement, each device transmits until that number is reached. Finally, when the exchange is complete, the received messages are saved to a local database and the devices set a backoff time before establishing other connections, avoiding redundant exchanges and unnecessary battery consumption.

Chapter 3

Prototype Peer-to-Peer Web Access over Bluetooth

In this chapter the developed peer-to-peer communication prototype will be analysed. This explanation will address the decisions of the technology and protocols to use as well as the architecture and workflow of the application.

It will begin with a brief summary of the steps taken to reach the developed application's features, functionalities and architecture. Next, it will present the obstacles that led to this solution as well as the fundamental drivers to decide upon this development and architecture to solve the problems previously stated. After the overall application's objectives and high-level architecture is described, a section on the lower-level architecture and components of the application will be presented, also containing flowcharts and diagrams on its normal operation. A summary on the limitations and future work of this application will be given, as well as some possible solutions to its current limitations, to be further explored in future work. Finally, a conclusion on the difficulties and drawbacks of the development process and overall project appreciation will be given, along with some final thoughts on the work process and methods used.

3.1 Design Choices

This section will provide the explanation and justification of the choices made for the application type, ad hoc communication technology and ad hoc routing protocol.

In Section 2.2, developed work on Android applications using Wi-Fi Direct as a mean of communication was introduced. Having the guidelines of these works in mind, the development of this application started. The main structure would always be:

- The application will have a routing algorithm that controls the destinations of the packets in each hop.
- A communication technology, *e.g.* Bluetooth or Wi-Fi Direct, handler, for both discovering nearby devices and to establish communication sockets with peers.
- A set of functions capable of analysing incoming messages and deciding which is the next step to perform, in order to complete the requests/advertises.
- Finally, a user interface where the incoming messages can be seen and analysed (for debug purposes), also providing a text area for the user to enter the requested data.

3.1.1 Application Type

The choice of the target application was mainly based on the innovation criterium. For this purpose, an investigation was made on already existing peer-to-peer applications, see Section 2.3. Most of the existing applications are designed to support text messaging with much of the developed work focusing on recreating popular applications, such as Messenger and WhatsApp, using a peer-to-peer network to route the messages to their destinations. Beacons and geolocation messages are also not completely innovative, since applications such as Uepaa!, see Subsection 2.3.2, already implement peer-to-peer applications where these types of messages are exchanged. Given this reasoning it was considered that the most innovative application type would be web browsing, supporting a multi-hop hot spot in an ad hoc network.

3.1.2 Ad Hoc Communication Technology

The choice of ad hoc network technology was another important step. The first and most obvious choice would be to use Wi-Fi Direct in both advertising and communication between devices, since this technology offers the best features to transfer files around 1Kbyte, in both range and data rate of transmission. However, during the development it proved to be impossible to continue with this approach, as Wi-Fi Direct's current Android implementation does not allow for devices to transfer files without active user participation.

Given this drawback a shift to Bluetooth was made, and a hybrid version of the application was created, where the advertisement would be done via Wi-Fi Direct and the actual transfer of the web pages would be made via Bluetooth. This method also proved to be infeasible, due to security issues, since the devices would have to display their Bluetooth MAC addresses in their Bluetooth name, making them much more vulnerable to possible attacks.

The advertisement was also a topic of debate. Two possibilities were presented: to use simple Bluetooth connections to advertise to each peer or to use BLE beacons as an advertisement method. The first method is slower, since the advertising device needs to create a connection with each discovered peer, in order to transmit its advertisement. The second method would offer a better advertisement mechanism, since it is faster and consumes less resources than the traditional Bluetooth connections (see Subsection 2.1.3), but it gives every device the ability to capture the advertisement, bringing some security issues.

The beacon advertisement is a tempting mechanism to implement, given all its advantages. It comprises two components: transmission and ranging. Transmission occurs when a device wants to issue an advertisement to a certain region¹. Ranging is the act of listening to beacon transmissions in a certain region. During the implementation of these two components it was possible to verify that the current Android implementations - tested with Android versions 6.0 and 7.0 - are not able to reproduce BLE's transmission mechanism, being only able to use the ranging.

Given these facts, the application was developed using simple Bluetooth connections for both advertisement of the devices and data transfer, although this is not the best technology for communication in an ad hoc network, it is the only one that, currently, meets all the requirements for this work. In the end of this chapter, a brief discussion on the changes that need to be made to Wi-Fi Direct's implementation in Android will be presented, and why developers could benefit from these changes.

¹ A beacon region is the physical space reached by the advertisement.

3.1.3 Ad Hoc Routing Protocol

The last step would be to create/modify a routing algorithm to control the destination of each incoming message. The requirements are simple, the algorithm simply needs to save the next hop of the shortest path leading to a device with Internet connection.

AODV is a known routing scheme used in ad hoc mobile networks. It establishes paths in a reactive way, *i.e.* only when a device wants to retrieve a web page does this protocol search for a path in which to send the packet - see [10] for the full specification of this scheme. This scheme is not the most reliable, since the requesting device should know beforehand if it is capable of reaching the Internet, otherwise users will uselessly experience long periods of path requesting and advertising every time they request a web page.

Destination-Sequenced Distance Vector (DSDV) is also known for its use in ad hoc mobile networks. This protocol uses a routing table where it stores in each entry: the destination, next hop, number of hops to reach the destination and a sequence number to avoid routing loops. The devices exchange full routing tables, creating a network where every device has total knowledge of the topology. However, DSDV requires the exchange of routing tables and their regular updates, wasting bandwidth, see [11] for more information on DSDV.

Since the proposed application does not have a specific destination as a goal, *i.e.*, a device A does not want to transmit to B, it only wants to reach a node with network access with the minimum amount of hops. Hence, the sending device will have no need to know the elements of the routing path, other than the next hop node. Thus, in order to accommodate such requirements some modifications were made to DSDV. Firstly, to reduce the signalling overhead used by DSDV, the developed version will simply exchange the best next hop estimate of the current device. Secondly, instead of a periodic exchange of tables, devices will update their tables every time a new advertise message is received and they only exchange routing information when a new best path is received.

3.2 Architecture

In this section the architectures of both framework and application are presented.

In Figure 3.1 an overview of the application is shown. It can be seen that there are two main parts of the application, the main activity and the *BluetoothService*.

- The main activity is where most of the processing logic is executed, from the analysis of the received data to the management of the routing tables. It comprises four threads: the main thread seen by the user, also known as the user interface thread; the *NetworkCheck* thread, used to perform the query regarding the Internet connection status of the device; the *loadUrl* thread, created when a *WebView* object is used to show or download a web page; finally, the *waitForWebPage* Thread used to ensure the requested web page is successfully saved in the device.
- The *BluetoothService* is used to manage the Bluetooth connections between devices, it comprises three threads: the *AcceptThread*, the *ConnectThread* and the *ConnectedThread*. Each of these threads will be explained in detail in the next subsection.

Inside the main activity the different threads communicate with each other, mainly to notify the main thread of a certain occurrence that may lead to a new set of actions. However, communication is also done between the main activity and the service, usually when the former needs to access the *BluetoothService*'s current status.

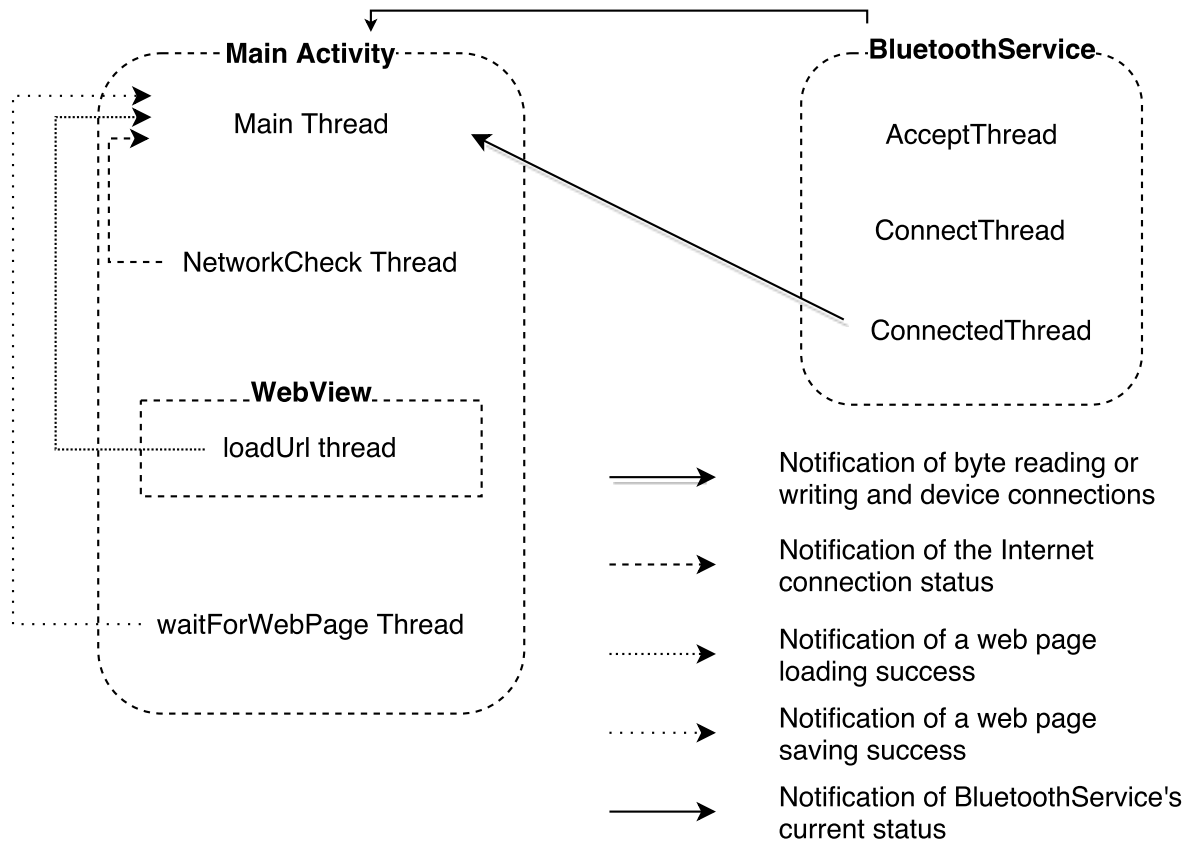


Figure 3.1: Overview of the different parts of the application and the communication between the threads running in each part

3.2.1 Bluetooth Connections

In this subsection, the Bluetooth connections between devices and their possible stages will be described and analysed.

Since the communication technology is Bluetooth, the application must have a thread² that handles the listening and acceptance of connections and the data transfer between devices. This corresponds to the *BluetoothService.java* class. It creates and listens to insecure communication sockets allowing devices to exchange data without user intervention.

The service has three different threads within it: a thread for the acceptance of incoming communications - *AcceptThread*; a thread for the initial exchange of vital information before the connection - *ConnectThread*; and a thread for the actual exchange of data between devices - *ConnectedThread*. The connection of devices goes through each of these stages, allowing the main thread to get information on the connection status of the device at a given time.

There were two different approaches to the connections of devices: either the devices stayed connected as long as possible until a new connection was requested, or the devices stayed connected for the minimal amount of time for data to be transferred. The second approach was used, since it is the one that is more energy efficient, draining a lower amount of battery from the devices.

Bluetooth communication between devices is only allowed if both devices have matching "credentials", providing a minimum amount of security to prevent against possible attacks. An application specific name and Universally Unique Identifier (UUID) represent the application, making it distinguishable from

²Thread is a sequence of instructions managed independently, usually by a scheduler from the operating system, see [12] for more documentation on threads.

any other, since the UUID of an application should not be repeated in any other.

To notify the main thread about what is being done by the *BluetoothService*, a handler is created, acting as bridge between the two parts. It can be used for various actions, such as: retrieving the status of a connection, assessing if a device is ready to receive a file, *etc.*

To substantiate the possible Bluetooth connections stages, four different textual representations are defined, one for each stage: listening, connecting, connected and not enabled. Each type of thread mentioned earlier is associated with a different connection stage. The different threads can be seen as the implementation of a stage.

In the next subsections each stage will be explained in detail, providing a better understanding on how the connections are performed.

3.2.1.1 Listening

A device is said to be in the listening stage when it has no ongoing connection but it is waiting for a new one initiated by another device. It is the "first" stage of the *BluetoothService*, since every time the service is initiated, the device is moved to this stage.

As was said previously, each connection stage is associated with a thread class. The listening stage is associated with the *AcceptThread*, which is instantiated every time the device enters this stage. The framework's connections have short durations and each time a new connection is performed, the service is restarted, entering the listening stage. Hence, it is imperative to assure there are no memory leaks or communication sockets left open. Thus, before the listening thread is instantiated, it is verified if any other Bluetooth connection threads are running, in which case they are shut down.

Once all the requirements for the instantiation of a new thread are met, a communication socket is created in which the device listens to incoming communications. To implement the listening mechanism, a loop is created whose purpose is to block the thread until a new connection is received, an error occurs or the user shuts down the application.

Whenever the device receives a new connection, it verifies the "credentials" sent in that request and compares them with the ones defined in its *BluetoothService*. If they match, the connection is accepted.

Upon successfully accepting a connection, the method assesses the status of the newly formed connection and decides upon it. If everything goes as planned, the connection should now be in the connected stage. Once this migration between stages is concluded the instance of the listening thread is destroyed and a new connected thread is created.

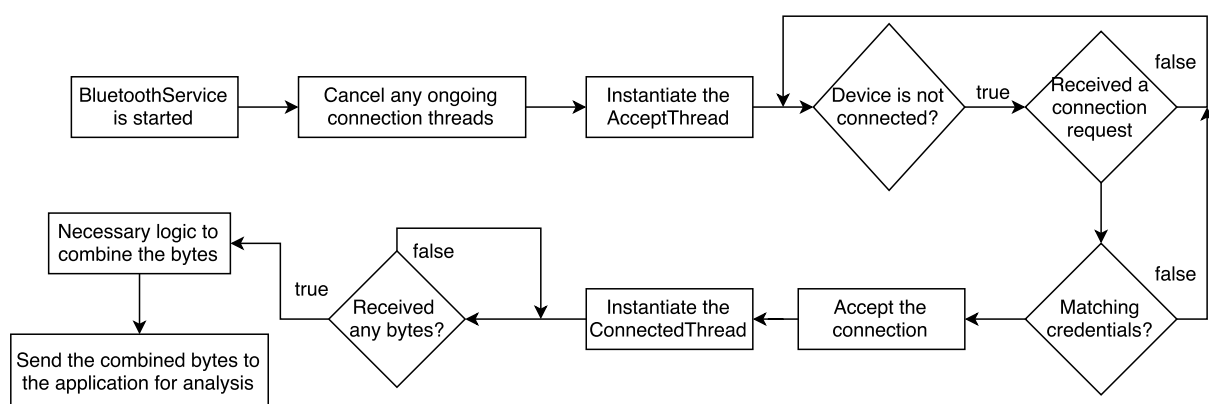


Figure 3.2: Fluxogram of a Bluetooth connection receiver's performed actions

In Figure 3.2 it is possible to see the performed actions from the point of view of a device that is waiting for incoming connections. It starts when the *BluetoothService* is initiated and finishes when the

received bytes are sent to the main thread for analysis, described in 3.2.1.3.

3.2.1.2 Connecting

Concluded the listening and accepting of connections it is necessary to understand how they are requested. For a Bluetooth connection to be performed, at least two devices must exist, one of them acting as the connection requester.

Similar to the listening thread initiation, the *ConnectThread* is only instantiated after all the previous Bluetooth connection threads running in the device are shut down. Also, to avoid delays during the connection process, the Bluetooth discovery process is shut down. Only then can the requester attempt to establish a connection with the desired device.

To identify the receiver of the connection request, the device needs to retrieve the MAC address of its counterpart, this will be explained in Subsection 3.2.2. Once this is attained, the requester can attempt to create a communication socket between both devices, using the previously defined Bluetooth "credentials" and the receiver's MAC address. If the MAC address is valid and corresponds to a device within reach, the connection is requested successfully.

In case of failure due to the rejection of the connection from the receiver, a notification is sent to the main thread, notifying the connection was not successful and the service is restarted.

However, if the sent request is accepted by the receiver, the connection state is assessed and, if no interruptions or errors occur, the connection stage is moved to the connected stage, indicating both devices are able to send and receive bytes from their counterpart.

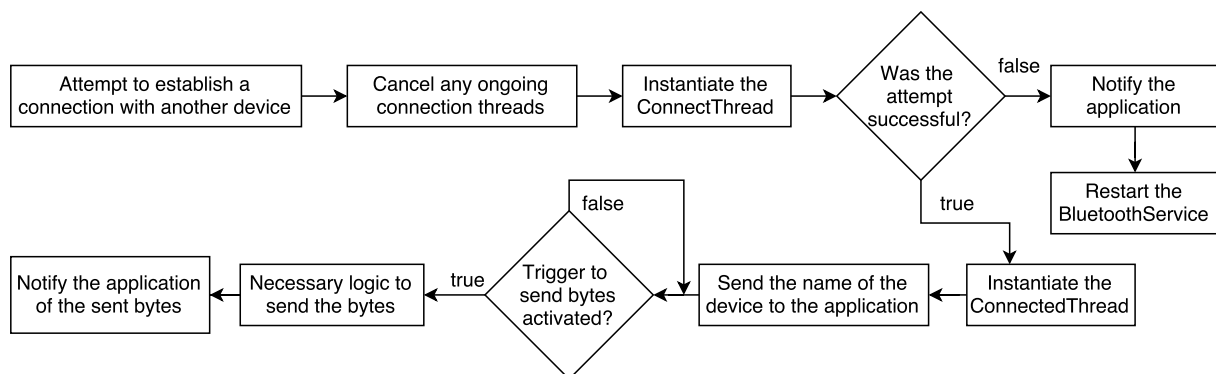


Figure 3.3: Fluxogram of a Bluetooth connection requester's performed actions

In Figure 3.3 the actions performed by a Bluetooth connection requester can be seen. Beginning by the attempt to establish a connection to the notification of the successfully sent bytes, described in the next subsection.

3.2.1.3 Connected

When the connection reaches the connected state, both the requester and the receiver devices are linked through a Bluetooth communication socket. To start the receiving and transmitting mechanisms, a *ConnectedThread* is created, after all ongoing threads are cancelled to avoid conflicts between communications or memory leaks. To notify the main thread of the connection success, the service sends the counterpart's Bluetooth identifier, *i.e.* its Bluetooth name, to the main thread.

To understand how data is transferred between the two connected devices it is necessary to explain two different mechanisms: the writing of data and the reading of data. By creating a socket linking both devices, two data streams are also created implicitly, where one provides a stream to write data into the

socket and the other provides a stream to read data from the socket - see Figure 3.4. Both writing and reading data is in the form of byte arrays that can be afterwards manipulated into the desired format.

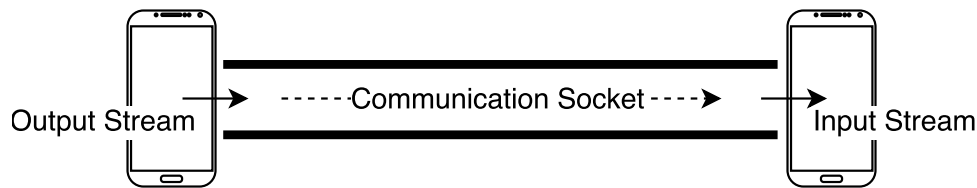


Figure 3.4: Communication channel with input and output streams

Writing bytes into the socket is done through an output stream, name given to the part of the stream that handles the writing. For any data format, the principle is the same: to convert the data into a byte array that will be sent through the stream. It is important to note that the channel has a limited size buffer shrinking the arrays' size, thus if the data to be exchanged has a large amount of bytes, it is wise to create a cycle that sends parts of that data, instead of the whole. The writing process is asynchronous, since it is only executed at a certain time following a certain trigger, *e.g.* user input. It is possible to notify the main thread about the sent bytes in case they are relevant to other processes, *e.g.* notifying that a text message was sent and prepare to receive/send an image.

The reading of data from the socket is done through an input stream. Since the output stream only writes byte arrays into the socket, the input stream will only read byte arrays. This property burdens the developer with the task of parsing the received bytes, *i.e.* identifying them and then converting them into their original data type. Also, as mentioned before, the communication socket has a limited size buffer, thus it is also the developer's responsibility to perform segmentation and reassembly of the sent data.

To send and receive different data formats within the same application, it is needed to develop a protocol to support the required multiplexing functions. Further along this chapter it will be explained how this was done in the developed application to exchange both text messages and web pages.

3.2.2 Discovery and Advertising

Now that the basic concepts on how the communication between devices are implemented are explained, it is possible to dig deeper into the intrinsics of the application itself, and what is the logic behind the routing of web pages.

The first thing in order for each device to know what the next hop of a certain request will be to fill the routing tables. This process is done by a series of neighbor discoveries³ and advertisements⁴, explained in Subsection 3.2.2.1 and 3.2.2.2, respectively. Each device will advertise its best estimate to reach the Internet. This advertisement will be received by peers and analysed.

Type	Bluetooth MAC Identifier	Estimate number of hops
------	--------------------------	-------------------------

Figure 3.5: Advertising message format

In Figure 3.5 the format of an advertisement message is shown. The type is a feature common to all messages exchanged in this application. It serves the purpose of identifying which type of message is being received. It can take four different values: *ADV*, *RQT*, *RSP* and *FAIL* for an advertisement, request, response and fail message, respectively. In this case it will take the value *ADV*. The Bluetooth

³Discovery is the act of finding nearby devices with Bluetooth on.

⁴Advertisement is the act of notifying peer devices of the cost of relaying a request to the device issuing the advertisement.

MAC identifier is always the MAC address of the Bluetooth adapter of the sender, it is then used by the receiver to populate its routing table. Finally, the estimated number of hops is the lower number of hops that separate the sender from the Internet access point plus one, the hop corresponding to the connection between sender and receiver.

Each device has two different routing tables: one that is used to store the information retrieved from the advertisement process, providing the best path for routing the requests to the Internet access point. Another used to route a response back to the original sender of the request that originated the response, as explained in the next subsection. For simplicity, the first routing table will be referred as Routing Table, while the second will be referred to as Response Table, since it handles the routing of responses.

Next hop node (MAC address)	Number of hops
Own MAC address	0 or 16
Device A's MAC address	Estimate through A
Device B's MAC address	Estimate through B
...	...
Device Z's MAC address	Estimate through Z

Table 3.1: Routing Table example and format

In Table 3.1, an example of a Routing Table is presented, where the first entry is always populated with the device's own MAC address and its hop distance estimate, which is either 0 or 16⁵, meaning the device has an Internet connection or not, respectively. Every time a device receives an advertisement message, it populates this table, either by adding a new row or updating an existing one, with the information contained in the message - see Figure 3.5. When the routing table is done being populated, each node knows its immediate peers and the best estimate through each one of those peers, giving it a full knowledge of its vicinity, *i.e.*, the sub-network created by the peers that are reached by the device using a single hop.

It is important to start by understanding how the routing tables are created and, then, how and when they are populated. Both tables follow the same principle, they are objects that relate keys to values. To a single key corresponds a single value, thus not creating duplicate entries.

In the scope of this subsection only the Routing Table will be explained - see Subsection 3.2.3 for the description of the response table. The keys of this table correspond to the MAC address of the next hop while the values correspond to the respective estimated number of hops. When querying the table for a specific MAC address it should return one and only one estimated number of hops.

There are three important things that the application needs from this table: to get the absolute minimum hop distance estimate to the Internet access point, in order to retrieve the device's best path. To get the corresponding key to the minimum hop distance estimate to the Internet access point, in order to retrieve the receiver to whom this device should send the message. Finally, to update or add a row with a new key-value pair, in order to add newly received advertisement information.

To be able to get the absolute minimum of the estimated number of hops, it is necessary to compare

⁵16 was chosen to be the representation of infinity or inability to reach a destination, since it has been represented by this number in various protocols, for instance in Routing Information Protocol (RIP), see [13]

all the existing values of the table. Since it only contains the information of its immediate peers, this process is fast and does not interfere with the rest of the application. However, if the Routing Table keeps the information from all the devices in the network, as suggested in DSDV, see Subsection 3.1.3, this could lead to significant storage consumption and could impact the performance of the application.

Having the minimum hop distance estimate to the Internet access point from the Routing Table, it is now necessary to retrieve the MAC address corresponding to the device providing this estimated number of hops. The Routing Table is searched until an entry providing the same hop distance estimate to the Internet access point is found, then the associated MAC address is retrieved. In case there are more than one entries providing the desired estimate, only the one that was found first is returned.

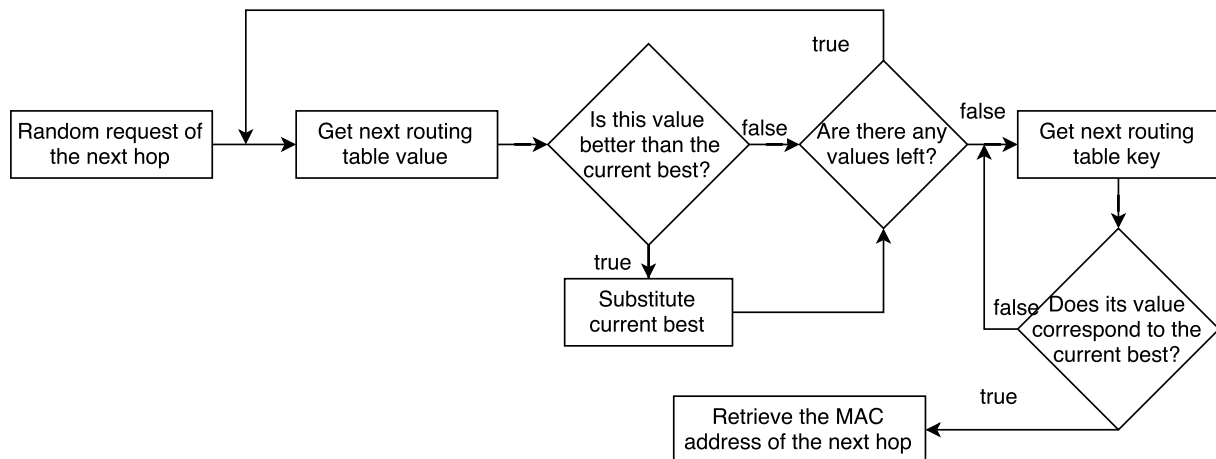


Figure 3.6: Process of retrieving the next hop from the Routing Table

In Figure 3.6 it is shown how the application proceeds to retrieve the MAC address of the next hop where a new request will be sent. It contains two main loops, one iterating through all the values in search of the lowest and one iterating through all the keys to find one that maps to that value.

Finally, the addition and update of Routing Table rows is done whenever an advertisement message is received. By separating the message in its parts, according to Figure 3.5, it is possible to retrieve both the MAC address and estimated number of hops through that peer. Having this information, it is possible to insert the retrieved key-value pair into the existing table. As mentioned before, one key maps to a single value, thus in case this key already maps to a value, the latter will be overwritten with the new one. In case the key does not exist, a new row is created mapping the key to its specific estimate. Note that, in case of a table update, the application does not compare values, *i.e.*, it does not check if the new estimate is better than the previous one, since the previous route may have been broken and thus the sender of the advertisement always advertises the most recent one.

3.2.2.1 Discovering Peers

Now that it is clear how the mechanism of modifying the Routing Table works, it is possible to discuss where and when these methods are being called. However, before that there are still some indispensable features that need mentioning:

- During the peer discovery process several peers may be found, making it necessary to create a place to store them, for further examination. To achieve this a list of Bluetooth devices is created, where each device corresponds to a found peer in the discovery process. This list is then used to retrieve information from these devices, in order to successfully establish communication sockets with them.

- To prevent the discovery process of dragging for longer than expected, using processing resources and damaging the performance of the rest of the application, it is necessary to identify if this process is finished and notify the main thread.

Before beginning the discovery process the application needs to ensure all the conditions are met. The Bluetooth status is the first to be checked, the device should have Bluetooth enabled and it should be discoverable for an unlimited amount of time. If the Bluetooth is not enabled the device cannot begin the discovery process and if the device is not discoverable its peers are not able to make their advertisement reach it.

Once the Bluetooth is set up, the initial update of the Routing Table is performed, a quick network check indicates if the device has an active Internet connection. Should the check return positive, it will add a new row to the routing with its own MAC address and 0 hops, since its estimate to reach the Internet is immediate. In case the check returns negative, meaning the device is currently unable to establish an Internet connection, the same process is performed, however instead of 0 hops, the estimate will be of 16 hops, for reasons already explained.

The device is now finished with the first step of advertisement, filling the Routing Table with its own MAC address and estimate. It is now possible to start the discovery process to advertise this same estimate to the discovered peers.

Figure 3.7 demonstrates how two devices, one without an Internet connection (left) and one with an active Internet connection (right). At this point both devices should have exactly one entry at their Routing Tables, since they have not communicated with any other device but they have established their position in the network, *i.e.*, if they have an Internet connection. Device A is unable to reach the Internet, so it adds to the Routing Table an entry with its own MAC address and an estimate of 16 hops. Device B, on the other hand, is able to reach the Internet, thus having an entry with its own MAC address and an estimate of 0 hops.

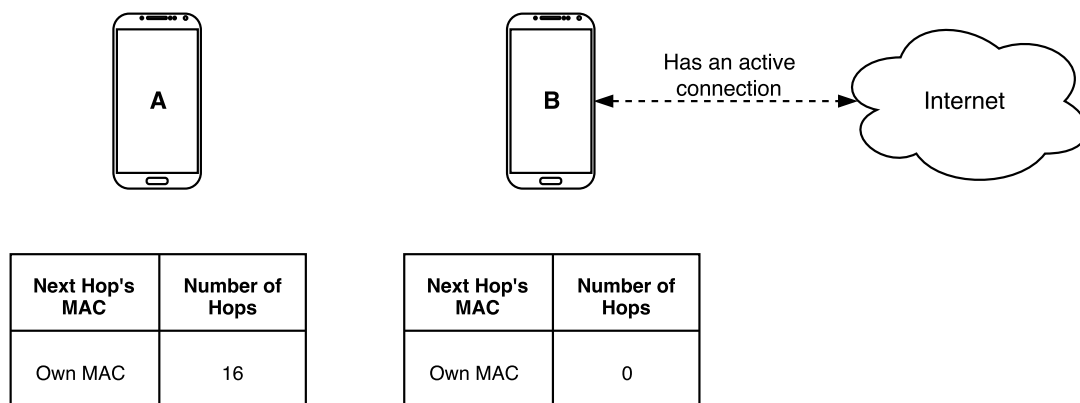


Figure 3.7: Example 1: State of the two devices after the initial step is over

A receiver responsible for the management of the Bluetooth discovery process and found peers needs to be created. The management of the discovery process is relatively simple, the receiver needs to be able to assess the discovery process status, *i.e.*, if it is starting, running or finished. The management of peer finding is more complex, the receiver needs to retrieve each peer's information and store it in the peer list previously mentioned. However, before the peer can be instantiated and added as a list item, it is needed to verify if this peer was not previously discovered, avoiding duplicates. Once the discovery is finished the receiver needs to be able to notify the rest of the application that it can proceed with the advertising process.

In Figure 3.8 it is possible to see sequence of actions the application executes to successfully perform

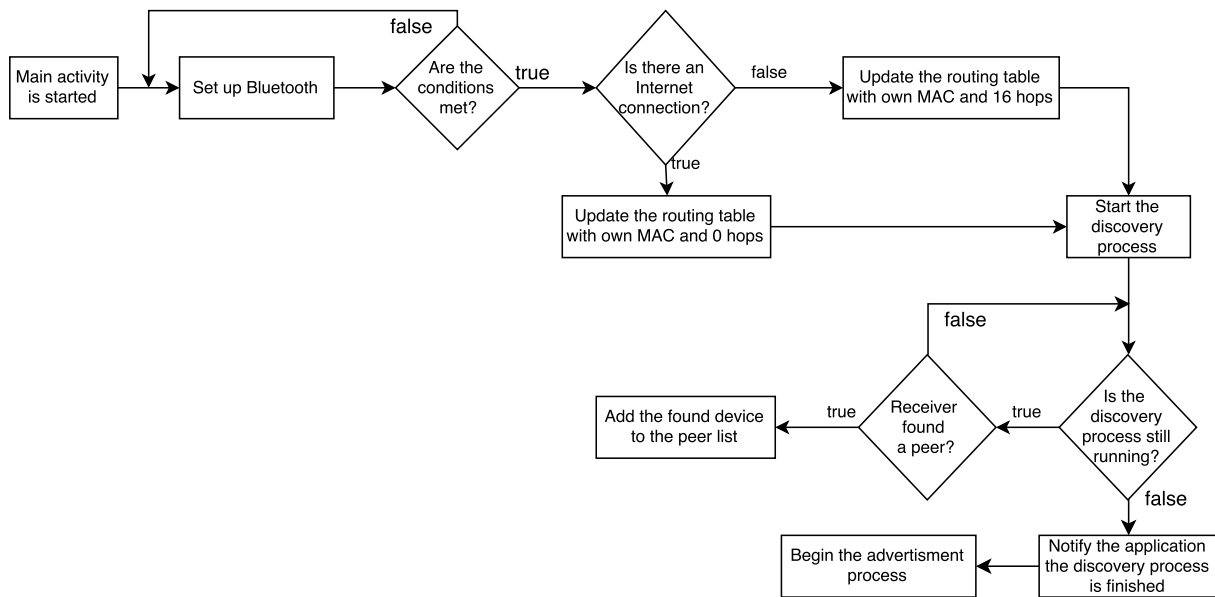


Figure 3.8: Fluxogram of the discovery process

the discovery process.

3.2.2.2 Sending an Advertising Message

The discovered peers are now stored and the device can start the advertising process. The peer list is iterated through and each item is analysed to understand if it should receive an advertisement message or not. The analysis consists of a series of checks to fit the peer into the desired category, in this case a smart phone using the application.

Since the number of Bluetooth devices is growing, it is a plausible possibility that the discovery process found a peer that does not fit into the desired category, such as a sensor or an headset. To avoid this a check is performed to assess if the peer is a smart phone. Overlooking this check can be time and resource costly as the number of attempted connections will increase.

Once the necessary checks are performed and the peer device is eligible to receive an advertisement message, the device attempts to establish a Bluetooth connection, using the mechanism described in 3.2.1. Before sending the advertisement message the application needs to ensure the connection has been successfully established and both devices are ready to write and receive bytes, through the respective streams.

If the conditions to send the message are met the device queries its Routing Table for the minimum estimated number of hops, explained in Subsection 3.2.2. To the returned value a unit is added, symbolizing the hop this message will take from sender to receiver. The advertisement is then sent, following the format seen in Figure 3.5, where the Bluetooth MAC identifier is the device's own MAC address.

Before the next iteration through the peer list, a new cycle must be performed to ensure this device does not advertise to a new peer whilst sending a message to the previous one. Thus, the device waits on confirmation that the advertisement message was successfully received by its destination before starting the process again with the next peer.

In Figure 3.9 the fluxogram of the advertising process is presented. It shows how the mechanism is executed in a visual manner. Once the process is finished the device remains active waiting for incoming connection requests.

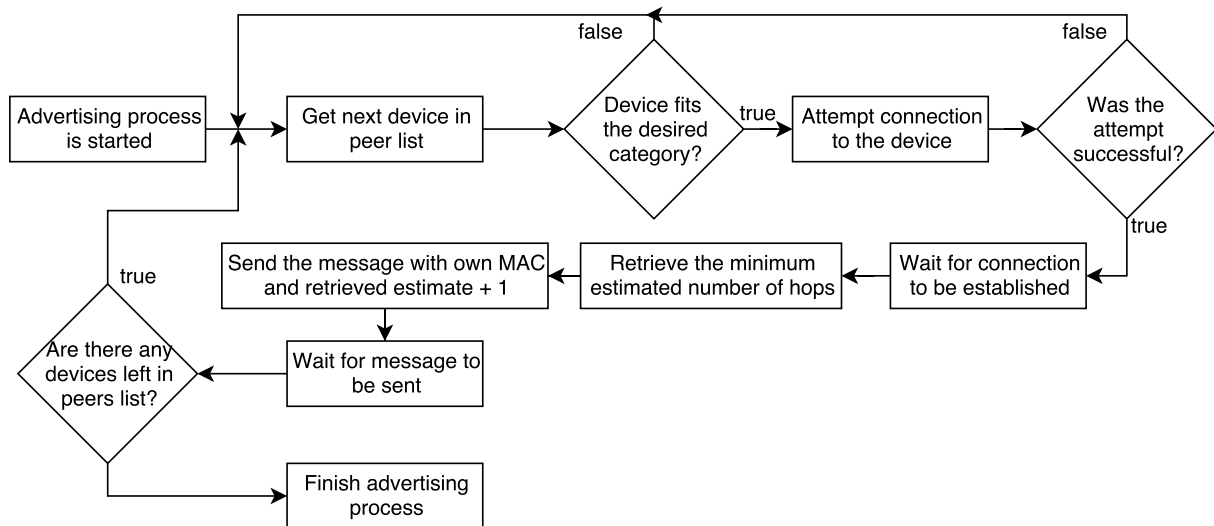


Figure 3.9: Fluxogram of the advertising process from the point of a sender

3.2.2.3 Receiving an Advertising Message

It is now covered how the transmitter of an advertisement message operates. However, to fully understand the advertising process it is necessary to analyse the receiver device and how it handles this message.

On the receiver device, the *BluetoothService* reads a certain amount of bytes from the input stream, see Figure 3.4, that need to be transmitted to the main activity. As mentioned before, a handler is used to pass the received bytes from the *BluetoothService* to the main activity. When the main activity is notified of the reception of bytes from a Bluetooth connection it analyses the context of the application, *i.e.*, what format of data is the application expecting to receive at that specific point in time. Since this subsection scope is the advertising process, only text messages are expected to be sent and received.

The connection to the advertiser is no longer required, thus the *BluetoothService* is restarted so the device can start listening to incoming connections. Simultaneously, the received bytes are converted into a text message that will be submitted to analysis, in order to identify what kind of message has the device received, from the different possibilities: advertisement, request, response or fail message.

By comparing the type present in the message, see Figure 3.5, the message is identified as an advertisement and submitted to the chain of actions specific to that message type. The first step is to extract the information contained in the message, *i.e.*, the sender's MAC address and the estimated number of hops to reach the Internet should a request be sent through that path.

Having these values, the device compares the received estimate with the best from the ones stored in the Routing Table, process described in Subsection 3.2.2. If the comparison concludes the received estimate does not top the current best, the Routing Table is updated with the received estimate and MAC address. Otherwise, it means the device has found a better path to reach the Internet, so, once the Routing Table is updated, the device takes the necessary steps to start a new advertisement process, this time advertising the new best estimate, previously described.

In Figure 3.10 a fluxogram of the actions taken by the receiver of an advertisement is shown. It reflects what was explained previously in a simplified manner, since some aspects of the mechanism are hidden as they will be discussed later.

To summarize, in Figure 3.11 the example with devices A and B from Figure 3.7 is complemented. Now device B has advertised to its peers, which include device A. Upon receiving this message, device A proceeded to store the information in its Routing Table, followed by and advertise from itself, since

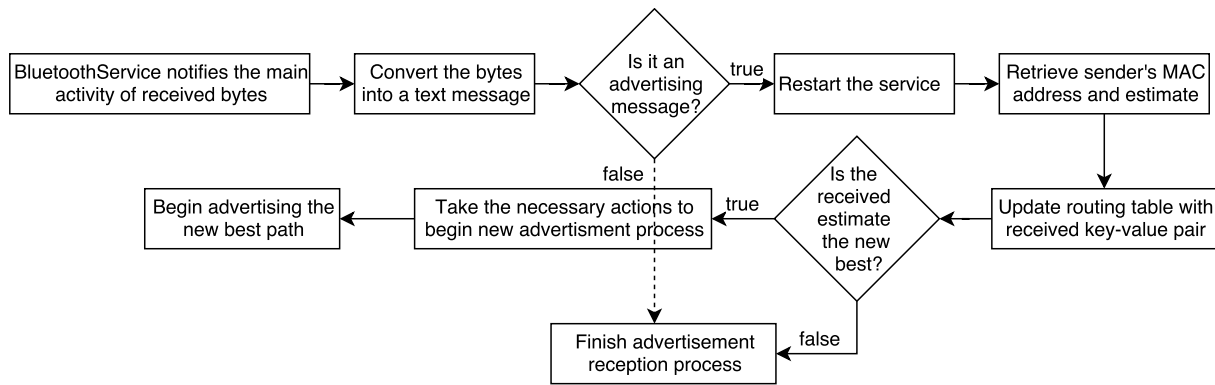


Figure 3.10: Fluxogram of the advertising process from the point of a receiver

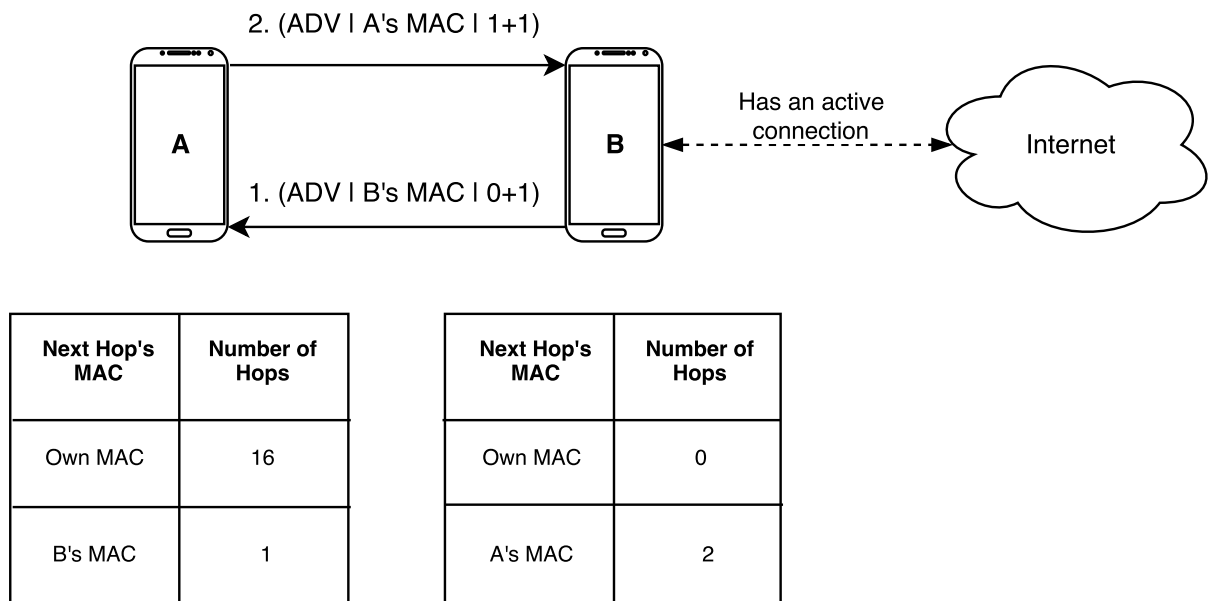


Figure 3.11: Example 1: State of the two devices after the advertising process is done

the new estimate tops the previous one. After this is concluded both devices have the shown Routing Tables, and A knows it routes to B, while B routes to itself, since A provides a poorer estimate.

If A advertises first the result would be the same, since when B is advertising A would still receive a better estimate and would advertise again. When B receives the second advertise from A it will overwrite the previous entry, maintaining the same values.

Now it should be clear how the discovery and advertising process is performed and what is the code executed at each time of the process. This is the basis of the next subsection, since without it the devices would not be able to reach the Internet unless they already had the connection.

By giving each device a full view of its vicinity it is possible to establish a network in which every device knows the best path instantly. This is done by what was described above, from discovery to advertisement. The next subsection will refer to the next step, where the devices already have their Routing Tables populated and are ready to exchange web pages.

3.2.3 Exchange of Web Pages

In this subsection the logic created and implemented to exchange the web pages will be explained in detail, also an example, similar to the previous one, Figures 3.7 and 3.11, will be shown to better

demonstrate the processes. Before describing the web page exchange process, it is necessary to explain the routing table related to the exchange of web pages, previously mentioned in Subsection 3.2.2 and referred to as Response Table.

The main purpose of the Response Table is to provide a destination for a response message. Once a device has received a request and it has an Internet connection, it should know where to send back the response. This would be easy if only this case applied, it would simply send back the response from where it received the request. But, in the case this device is a "bridge" node, *i.e.*, a node that forwarded a request, it may have received requests from different devices and it still needs to be able to differentiate each message and decide which device to send back the response to.

The Response Table has a similar structure to the Routing Table but it serves a different purpose. In Table 3.2 it is possible to see the structure of the Response Table.

Message ID	Next hop's MAC
Message ID #1	Device X's MAC
Message ID #2	Device Y's MAC
Message ID #3	Device Z's MAC
...	...
Message ID #9	Device X's MAC

Table 3.2: Response table example and format

Despite having similar structures the two tables store different information: Routing Table maps a MAC address to an estimate whereas the Response Table maps a message identifier to a MAC address. Hence, the necessity of having two distinct tables.

Two main actions must be allowed to be performed in a Response Table: it must be possible to add new rows, each referring to a specific request and it must be possible to retrieve the next hop's MAC address for a certain message identifier. Since the message identifiers are unique, there is no need to update Response Table rows as there will be no duplicates.

The second action employs a simple logic, given a message identifier the MAC address should be returned. Since to a message identifier corresponds a single MAC address there should be no problems in the response path. However, in case the requested message identifier is not found in the Response Table, the application is notified that the response can not be routed due to the lack of a next hop MAC address.

For the example three devices are used: A, B and C. Where device C has an active Internet connection, as seen in Figure 3.12. In the figure it is possible to observe the routing tables of each device after this process is completed. Device A will choose B to send a request and B will choose C, since they provide the best estimates, respectively.

3.2.3.1 Sending a Request Message

Now that the logic and implementation behind the Response Table is understood it is possible to explain the mechanism behind the exchange of web pages. This process counts with a number of

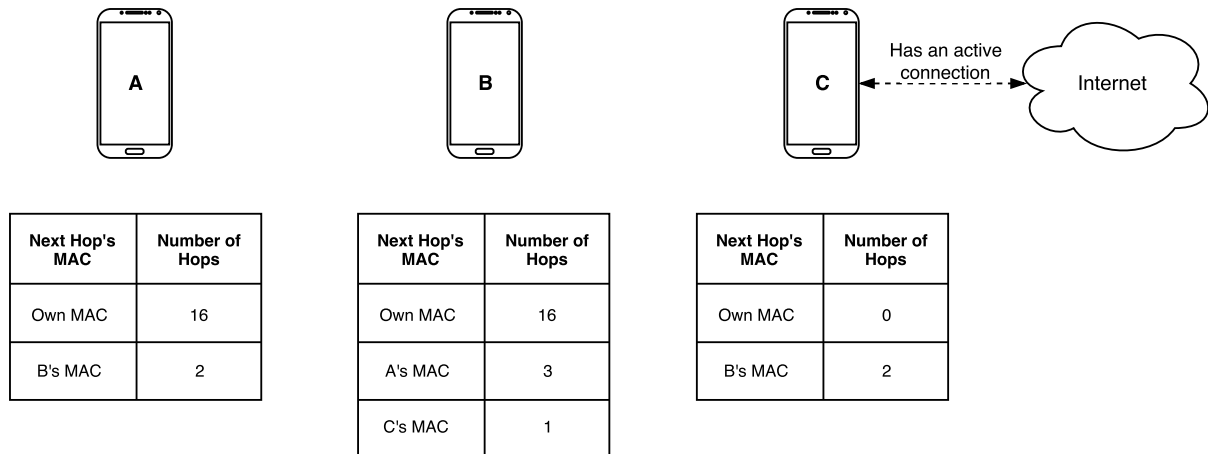


Figure 3.12: Example 2: State of the routing tables of the three devices

features that need to be mentioned before further explanation:

- A text area must be defined to enable the input of a Uniform Resource Locator (URL) from the application user. This text must be retrievable to form the web page request with the specified URL.
- A button needs to be implemented so the user may notify the application that he/she has finished inputting the desired URL. This button will act as a trigger for the application to begin the request sending.
- A mechanism to manage the actions related to web pages must be created. In this thesis the method found that best fit the requirements was the creation of a *WebView* instance.
- A handler providing the link between the *BluetoothService* and the main activity, previously mentioned in the context of the advertisement process, that can communicate the bytes received by the service to the rest of the application.
- Finally, a mechanism to identify how the received bytes should be processed, *i.e.*, what format should they be converted into. This mechanism must also provide a method to identify the received messages between the possibilities and command the application to act accordingly, *i.e.*, follow a specific set of actions for that message type.

In Figure 3.13 it can be seen the user interface of the main activity, it has five main elements: a place where the *peers* list is displayed, at the top. The received messages, this is an optional element and used for debugging as it would incur in severe security issues. A text area, as mentioned before, allowing the user to input the web page he/she desires and to capture this input to be processed. And a button to notify the activity that the process of requesting that specific web page must be initiated.

Assuming the device already established the best route to reach the Internet, *i.e.*, its routing table is populated, the journey of the web page request from the user input to the display of the response will be explained. Starting from the user input, has mentioned above a button and a text area are created, forming a user interface allowing the sending of requests based on the user input.

In Figure 3.14 a generic request message is shown. Its format does not differ much from the one presented in Figure 3.5. However two new fields are introduced: the *Message ID*, a unique identifier representing each message that will be useful to keep track of what is each message's payload and sender and the *URL to request* is the web page's URL the user is trying to access, it is considered to be the payload of the message.



Figure 3.13: User interface for the sending of request messages

Type	Message ID	Bluetooth MAC Identifier	URL to request
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Figure 3.14: Request message format

The web page request process may be initiated by two different events: when the user inputs an URL and presses the "Go!" button or when the device receives a request and its next action is to forward it to the next hop.

Beginning by the first event, the button needs to act as a trigger for the application. To achieve this the logic to begin the request process when the button is pressed must be implemented. This trigger must also be able to provide the input text by the user, containing the web page to be requested. Having the URL the request process can be initiated. Note that this process must differentiate the two possible events that lead to it, since they incur into different workflows.

Assuming the originating event is correctly identified and the process is aware that it was initiated by user interaction, the first action is to retrieve the next hop's MAC address, to whom the device shall send its request. This can be achieved by using the routing table features, see Subsection 3.2.2, that provide the best path's next hop.

If the routing table query does not return a valid MAC address the user must be notified of the request failure. However, if a valid MAC address for the next hop is returned, the device attempts to establish a connection with the next hop, following the same mechanism as in the advertising process. Should the connection attempt fail the user is also notified of the request failure, allowing him/her to restart the request process, and the *BluetoothService* restarted to keep the device listening to incoming connections.

If the connection is successfully performed, the application may proceed to the generation of the request message to be sent. The message is composed by four sections previously defined, see Figure 3.14.

- The *Type* corresponds to the message type and is already known, as the button clicking triggered

the request sending process, being populated accordingly.

- To fill the *Message ID* section a message identifier must be generated to distinguish this request between the others that may be sent throughout the network. To do this, a random number is generated between -2^{31} and 2^{31} , providing a wide range of possibilities and minimizing immensely the occurrence of duplicates.
- The *Bluetooth MAC Identifier* address is the device's own MAC address and it will allow the receiver to correctly assess the response's path.
- Finally, the *URL to request* is populated with the text retrieved from the user input, seen in Figure 3.13.

Once the request message is sent the application updates its Response Table with the generated message identifier and the MAC address of the sending device, *i.e.*, its own, as a key-value pair. With this mechanism the device is able to assess if it is the destination of a certain response or if it is a "bridge" node and needs to forward the response to the next hop. This assessment will be presented and explained in 3.2.3.2.

If the device is not deemed as the owner, there is no random identifier generation, since the value will be retrieved from the received request message. Also, the Response Table is not updated because this will be done during the receiving process, the next focus. Despite that, the connection is attempted, same as before.

However, if the connection establishment fails the user is not notified, since this request was not originated by him/her. In this case, the device queries the Response Table for the MAC address mapped by the request message identifier, corresponding to the device that sent/forwarded the request to this node. A failure notice is then sent to that device, with the intent of notifying the request originator of the inability to forward the request until it reaches the Internet.

If the connection is successfully established, the message is sent as before with the slight difference that the message identifier and the URL to be requested are retrieved from the values encapsulated in the received request message, see Figure 3.14.

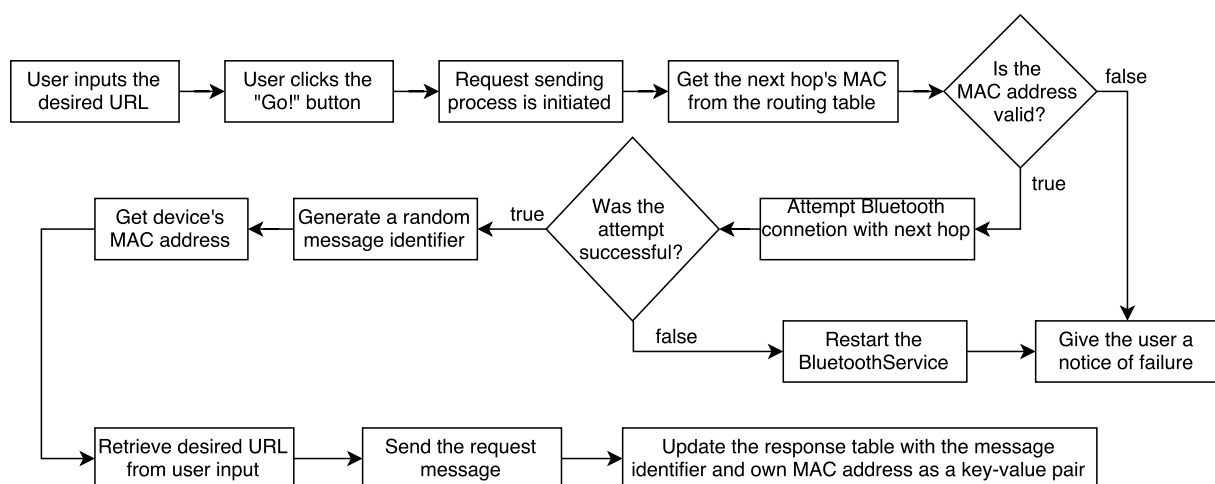


Figure 3.15: Fluxogram of the request sending process triggered by user input

In Figure 3.15 a fluxogram representing the process described above is presented. It provides a visual overview of the application workflow when user input triggers the request sending mechanism. Once the process is finished the device keeps listening to incoming connections.

3.2.3.2 Receiving a Request Message

The request receiving process is similar to the advertise receiving. The device receives a connection attempt from a peer. If the connection is successfully established the request message bytes are received by the device in *BluetoothService*.

As in the advertisement receiving process, see Figure 3.10, the received bytes are converted into a text message and the message is compared with the possible types: an advertisement, a request, a response or a failure, as mentioned before. The *BluetoothService* is also restarted.

Once the message is correctly categorized, as an advertisement, the message identifier and sender's MAC address are retrieved from the message, see Figure 3.5. In the request sending process it was mentioned that in case the device was not the owner of request, it would not update the Response Table. For devices that receive a request message but are not its owners, the table updating process is done here. Thus, the routing table is updated with the retrieved message parts.

At this point, two different workflows can be executed: one regarding the devices with Internet connection and other the devices without one. To define which approach is taken by the device a quick check of the Internet connection status is performed. If the check returns false, meaning the device has no active Internet connection, the request will be forwarded to the next hop, retrieved from the routing table, to reach a device with an Internet connection. To do this the application proceeds as described in 3.2.3.1 for a device who is not the owner of the request, where the sent URL and message identifier are the ones that were previously retrieved from the received message and the MAC address is the device's own.

However, if the Internet check returns positive it means the device is a final destination for the received request. The device will act as a communication link between the Internet and the owner of the request. It now has to retrieve the requested web page and send it backwards until it reaches the its original requester.

The methodology to save the web page had several possibilities, such as saving the web page as an image, saving only the *HTML* content or saving each element of the page individually. The first two methods are not complete, meaning the web page could lose some of its features, *e.g.* dynamic images, search fields, *etc.*. The third method would fully download the web page, however it would require additional logic to save the different elements in the same directory and to arrange them to re-create the web page with its initial format.

The solution was found by saving the web page as a web archive, it is specific to the *WebView* class, see [14]. It solves the problem of third method, since it downloads each element but compiles them in a web archive, that can be decompressed easily by *WebView*. Thus, it proved to be the better solution for this problem.

The thread *waitForWebPage*, see Figure 3.1, is used ensure the web page is successfully saved in the application's file directory. It is specially useful for the download and saving of large web pages where this process can be time consuming. If this thread is not run the device risks sending a response before having the complete web page file, failing to transmit the request web page to its destination. This process is done independently allowing the application to continue its normal functions, such as listening to incoming connections.

Once the download and saving process is completed, the device must notify the next hop of the file transfer that will occur. For this effect a response message is sent to the MAC address mapped by the received message identifier from the request. If a valid MAC address is returned, the device attempts to establish a connection and send a response message, explained in the next subsection.

In Figure 3.16 it is possible to see a fluxogram of this process. The process, as shown in the figure, ends either with sending a new response or a new request, depending on whether the device has

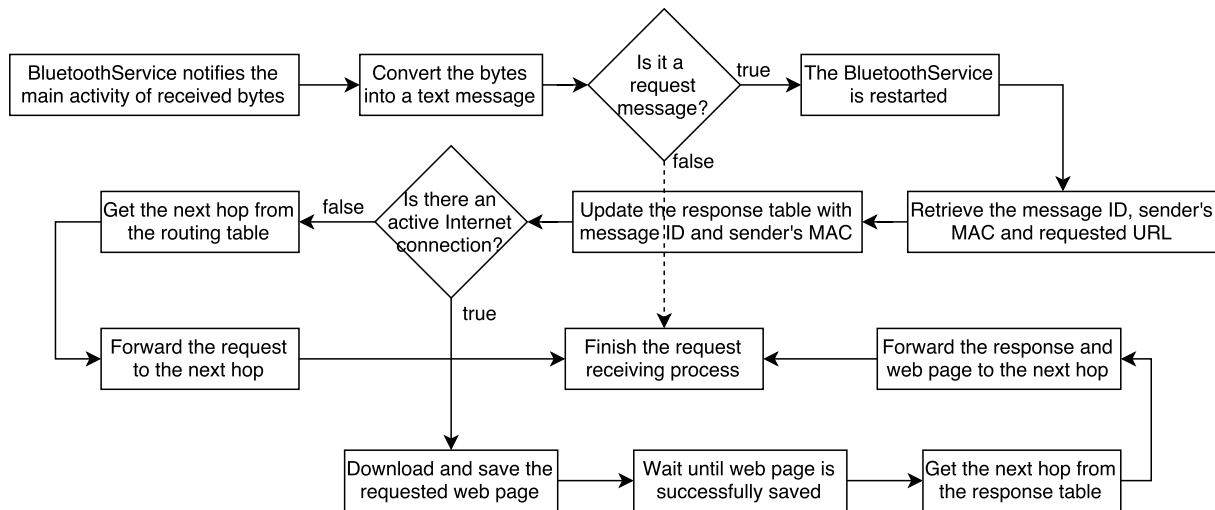


Figure 3.16: Fluxogram of the request receiving process

Internet connection or not, respectively.

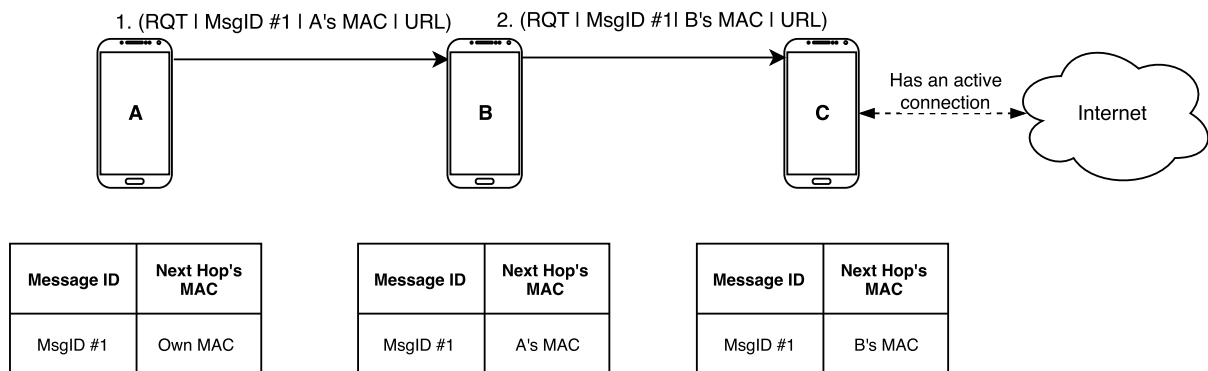


Figure 3.17: Example 2: Request sending and receiving process

Resuming the example in Figure 3.12 and supposing the user from device A wants to request a URL and inputs it correctly, the device will follow the steps explained in Subsection 3.2.3.1 and check the routing table to establish the next hop. Also its Response Table will be filled during this action, since it is the owner of the request.

Once that process is completed and the message reaches device B it will update its routing table with the newly received request. After that it checks its own routing table and assesses if it should forward the request or download the page. Since the device does not have an active connection the first option will be chosen and the request forwarded to C.

Finally, upon receiving the request, device C will update its own Response Table with the received message identifier and B's MAC address. Having an Internet connection the device will download the web page.

In Figure 3.17 it is shown the above described, as well as the three Response Tables from the devices once the requests are all sent and the web page downloaded.

3.2.3.3 Sending a Response Message and Web Page

In this subsection the process of sending a response and a web page will be covered. The response will be routed back until it reaches the owner of the request that originated this response. In the previous

section the process of receiving a request and downloading and saving the web page are explained, so it is assumed these mechanisms are understood and completed when the application enters this stage.

To send the response message to the correct destination the device queries the Response Table for the MAC address of the next hop mapped by the message identifier received in the request message. If a valid MAC address is returned a connection is attempted, as seen in the other sending processes 3.2.2.2 and 3.2.3.1.

Type	Message ID
------	------------

Figure 3.18: Format of a response message

In Figure 3.18 the format of a generic response message is shown. The *Message ID* will have a direct correspondence with the message identifier of the request that originated this response. The response message is used as a notification for the receiving to device to prepare the reception of the web page, hence its simple format.

Once the main thread is notified by the *BluetoothService* that the response message was correctly sent and received it must send the requested web page archive to the next hop. This notification is passed from the service to the main thread via the previously mentioned handler.

In this stage, the sending device does not need to attempt a new connection with the receiver, the established connection is maintained open until the web page transfer is complete. To initiate the file transfer the web archive file must be converted into a byte array, due to the Bluetooth transfer mechanism explained in 3.2.1.3. The application then retrieves the archive's file size to match the array size.

The device checks if the established connected is still open. If it is, the bytes are then written to the input stream as per usual however, in contrast to what happened with the single text messages, the file bytes can be larger than the connection stream buffer. To overcome this problem, it is necessary to implement logic to divide the large files, *i.e.*, the ones larger than the stream buffer, into smaller partitions. These partitions must be sent individually and, during the reception, they must be regrouped into the original file, as will be shown in the next subsection.

If the connection was shut down due to unexpected behaviour from one of the parts, such as a forced disconnection due to lost of range, the web archive is not sent, the web page sending process is finished and the device keeps listening to incoming connections.

In Figure 3.19 a fluxogram of the response and web page sending process is presented. It shows the mechanism from the saving of the web page to its sending. As previously described, the process is finished if no valid next hop for that message identifier is retrieved or by correctly sending the web page as expected.

3.2.3.4 Receiving a Response Message and Web Page

In the receiver side, the web page and response are received and the device must assess if it is the final destination or if it is a relay node for a different device, in which case the web page will not be displayed, but the response and web page are forwarded.

This process begins when the handler notifies the main thread a message has been received, as the other receiving processes. The message is compared with the possible types and is identified as a response message.

At this point, the device knows it will be receiving a web page archive so the connection is not shut down as it happens in the other receiving process. This mechanism allows the application to have gains in the overall time consumption of the web page exchange.

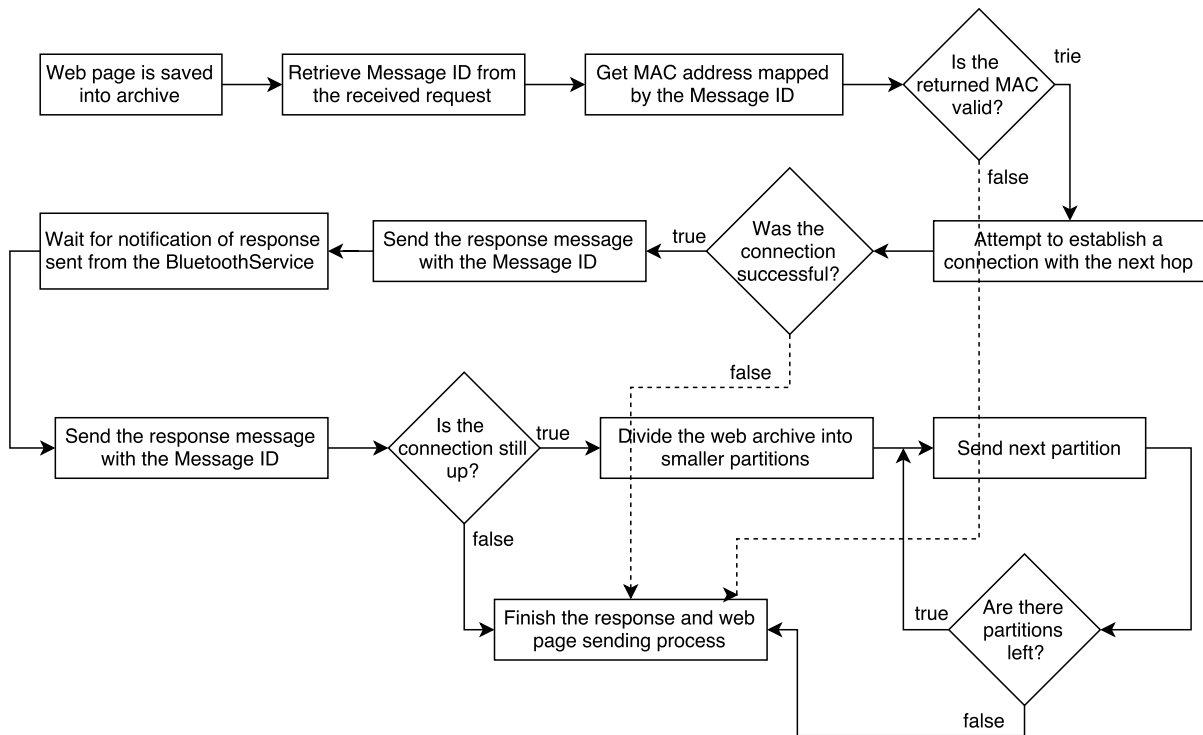


Figure 3.19: Fluxogram of the response and web page sending process

The *BluetoothService* is notified that the next received bytes will correspond to a web page archive. Since the connection is still up, new incoming connections will be blocked not allowing other device to interfere with this exchange until it is completed.

Once the message is identified and passed onto the main thread it will be analysed, *i.e.*, the message identifier will be extracted, see Figure 3.5. This is done to retrieve the next hop from the Response Table. Two options are presented: either the device is the destination of that response or it isn't and the message must be forwarded to the next hop.

The sender will then proceed with the transfer of the web page archive bytes. At this point this device is aware that it will be receiving a web archive and not a text message, using the implemented logic in *BluetoothService* for the reception of this data type. The device receives the different partitions of the web page archive and then joins them into a single byte array, that is transferred to the main thread, through the handler.

Once the main thread is notified of the received web archive the device saves it in the application's directory. The service is restarted and is now able to receive new connections, changing the receiving logic to the reception of text messages, since it is not expecting to receive more partitions for the time being.

The device now has received both the response and the web page and it has all the necessary parts to decide which of the two options to pursue. To achieve that, the Response Table is queried with the retrieved message identifier, from the response message. This query returns a MAC address and the application verifies if it is valid or not.

If the MAC address is deemed valid a new check is performed, this time with the purpose of assessing if the device is the final destination of the response. If the retrieved MAC address does not correspond to the device's, meaning this device is not the destination, it attempts to establish a connection with the next hop, identified by the retrieved MAC address. If the connection is accepted and establish the response and web page sending process is repeated, see 3.2.3.3.

On the other hand, if the device is deemed the owner of the request that originated this response, *i.e.*, its MAC address corresponds to the one retrieved from the Response Table, it means the web page archive must be unpacked and displayed to the user.

As mentioned before, the *WebView* class is used to manage the actions performed with web page and these ones are no exception. So, the *WebView* is initialized and made visible to the user. The web archive is then unpacked and displayed to the user using methods inherent to this class, see [14] to learn which ones may be useful for this purpose.

When the user receives the requested web page, he/she might want to navigate through other pages, originated from the first, for instance in a Google search, where the user requested Google's front page and the performs a search, where a subsequent page is requested. As it stands, the user would be shown a "no Internet connection" error. This lack of continuity severely affects the usability of the application thus, developing a solution to this problem is obligatory.

A solution that proved to be effective is to create a mechanism to detect web page loading errors, such as the "no Internet connection" error. Once the mechanism is triggered, meaning an error occurred, the application must retrieve the requested URL and form a new request message from it, see 3.2.3.1 for the explanation of this process. This mechanism must overwrite the usual action of simply loading the web page, when requested by the user.

With this mechanism when the requested web page is loaded and displayed to user, he/she is free to interact with the web page as in the case of a normal web browser. Once this interaction leads to a new web page being requested and displayed the solution's mechanism is triggered and a new request is formed and sent, being submitted to the web page exchange process.

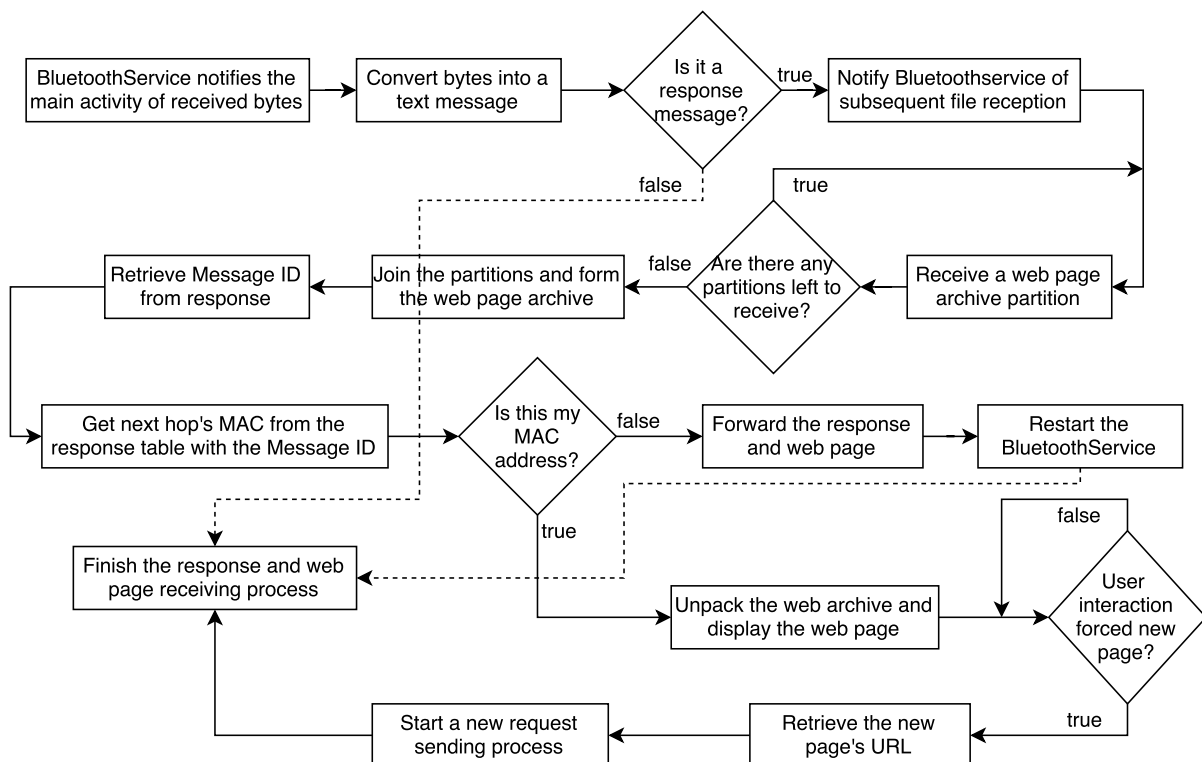


Figure 3.20: Fluxogram of the response and web page receiving process

In Figure 3.20 a simplified fluxogram of the response and web page receiving process is shown. It is possible to visualize the file receiving workflow as well as the different possibilities for the receiver of the response: forwarding the response or displaying the web page. It is also shown the mechanism behind the multi-page request. With the shown implementation the user is capable of seeing the requested web

pages and navigate through those pages without having to manually send each request.

To finalize the example from Figures 3.12 and 3.17, device C, after finishing the download of the web page, will check its Response Table and send a response message to device B, which is the next hop retrieved for that specific message identifier *MsgID #1*. The response is followed by the web page archive, previously downloaded, as described in Subsection 3.2.3.3.

Device B receives the response and the web page following the steps previously explained in Subsection 3.2.3.4 and checks its Response Table for that message identifier. Device A's MAC is returned from that query and that's the destination for B's response, so device B sends the response and web page to A.

A receives the response and web page following the same steps as B. However, when checking the next hop for that message identifier device A gets its own MAC address and concludes it is the final destination for that response, proceeding to display the web page requested by the user, as described in this subsection.

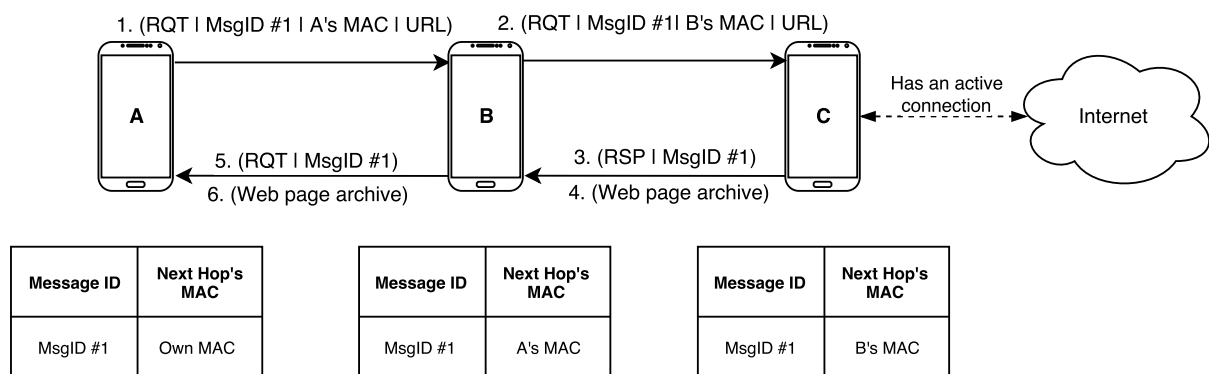


Figure 3.21: Example 2: Sending and receiving of response messages and web pages

Figure 3.21 illustrates this example and messages exchanged between the three devices, as well as the Response Tables, previously established in Figure 3.17.

Chapter 4

Tests and Results

In this chapter several experiments will be performed in order to assess the quality and features of technologies and developed application. The main goals are to obtain an empiric and realistic conclusion on which technology serves better the purpose of this thesis and to assess how the application fares when subject to different stress tests.

This chapter will be divided in two different sections: one regarding the comparison between Bluetooth and Wi-Fi Direct via different tests and other regarding the tests performed with the developed application, to better understand where it performs better and worse, proving or not if the theoretical choices made translate into actual performance gains.

4.1 Bluetooth vs. Wi-Fi Direct

This section will cover the differences, advantages and disadvantages of both Bluetooth and Wi-Fi Direct. A series of experiments will be conducted and their results analysed, providing a justification on which technology is best suited for this application and applications with a similar architecture and/or purpose.

Since the first implementation of Bluetooth in Android several releases have been developed. Different Bluetooth versions provide different Quality of Service (QoS), this may impact the performed tests as a device running a newer Bluetooth version may provide better results than a device running an older version. To avoid confusion all the tested devices will be running Bluetooth version 4.0.

The tests will range from battery consumptions to data rates analysis and most of them will be backed up by both theoretical and empirical results, although in some of them, due to the inability of getting precise measures, the results will be taken from previous developed works.

4.1.1 Ranges of communication

The ranges of communication of both technologies are of extreme importance. They can reduce or increase greatly the number of hops a packet has to pass through, in order to reach the destination. If the range of communication is too short, the number of connections made will increase, this may cause an overload of the network, and the deterioration of the communication medium. On the other hand, if the communication range is long the devices are able to jump through bigger hops, creating less traffic in the network and establishing the least possible number of connections.

Both technologies share some similarities, they are both dependent on the environment of the communication, the elements that are surrounding the devices and possible obstacles in the way. The experiments were conducted, for the obstacle experiment, in a corridor of Torre Norte in the vicinities

of Instituto Superior Técnico and, for the line of sight experiment in the outside area of the same. It is important to note that although this experiments were made with as little interference as possible, there are certain elements that are impossible to controls, such as wireless communications from other devices, metal objects, such as metal lockers and cars.

Bluetooth establishes four different classes for the devices that may use this technology, depending on the transmitting power. Mobile phones are inserted in class 2 and, for that class, the specified average range of transmission in order to have a reliable connection is 10 meters, from [16].

Wi-Fi Direct on the other hand offers, theoretically, ranges of communication up to, approximately, 200 meters, from [17], which poses for a much better solution, in terms of network off-loading and general depth.

In order to verify these claims from both technologies, two mobile devices were taken to an open space, although with some limitations as described above, and several searches were made, until the devices stopped being discovered by one another. After measuring the distance between both devices, the results were taken, and prove what was already to be expected, although with some twists.

Bluetooth was able to create a connection between devices from a distance up to 42 meters apart, see Figure 4.1 for the overall scheme of this experiment. This value is a lot more than what was expected judging by the theoretical value of 10 meters, although the health of the connection was not verified, see 4.1.4 for these tests. Using Wi-Fi Direct the devices were able to communicate from a maximum distance of 77 meters, see Figure 4.2 for the overall scheme of this experiment, which is, considerably, smaller than the theoretical value of 200 meters.

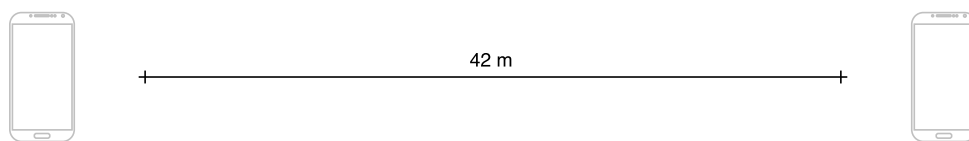


Figure 4.1: Max range of Bluetooth communication with line of sight between devices

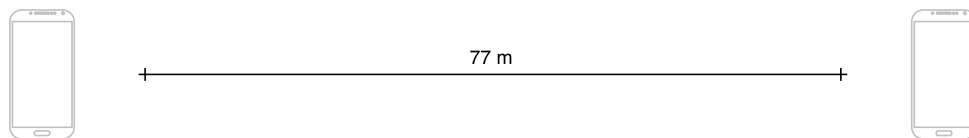


Figure 4.2: Max range of Wi-Fi Direct communication with line of sight between devices

Both tests were made with a direct line of sight between devices. For the next ones there will be obstacles in the way of communication. It is expected that this affects greatly the communication ranges. The first test was made using Bluetooth technology where a wall was blocking the line of sight between devices, see Figure 4.3. The second test was made using Wi-Fi Direct, and, in order to maintain the same environment as the previous experiment, to get reliable results, it was situated in the same place as the first, see Figure 4.4. However, due to the environment configuration, it was impossible to recreate the experiment with only one wall, so two walls are now dividing the devices. Since the walls introduce a loss in the signal power, the more walls are between devices, the bigger the losses will be.

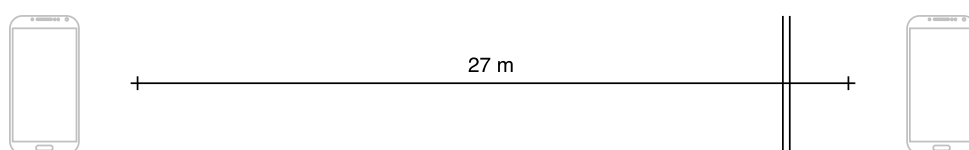


Figure 4.3: Max range of Bluetooth communication without line of sight between devices

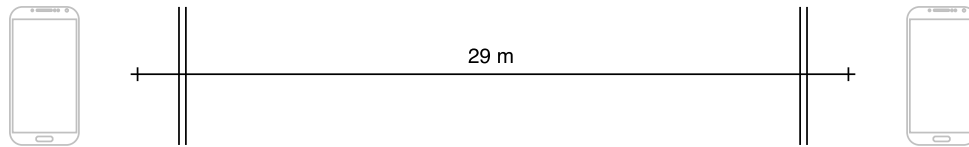


Figure 4.4: Max range of Wi-Fi Direct communication without line of sight between devices

As expected the obstacle, in this case the wall, created a significant decrease on the maximum range of communication. Bluetooth was able to communicate from a distance of 27m, closer to the theoretical 10 meters.

Wi-Fi Direct was also able to communicate from a smaller maximum distance, measuring 29 meters, with the signal passing through both walls. From a smaller distance it was verified that this technology could communicate with only wall in the way, meaning it also surpasses Bluetooth when an obstacle is in the way of communication.

After these experiments it is possible to conclude that Wi-Fi Direct is more desirable, since it provides better coverage than Bluetooth to similar areas. Also, there is no evidence that Wi-Fi Direct suffers more losses from obstacles, maintaining its desirability. This was already to expect, both from the theoretical values and from the transmission powers¹, since Bluetooth is mostly known for its lower transmit powers, if compared to technologies such as Wi-Fi.

4.1.2 Battery consumptions

4.1.3 Discovery times

The discovery times are a critical time factor for this application. The discovery process is the biggest time consumer during an application run thus, minimizing it comes with a great advantage for the overall performance of the application.

For this test three mobile devices were used: Samsung Grand Neo running Android version 4.2.2, Motorola Moto G2 running Android version 7.1 and Huawei P8 Lite running Android version 6.0, providing an heterogeneous sample space. For each device 10 discoveries were performed, providing a large sample size.

Bluetooth version 4.0 theoretically provides a discovery time of 10.24ms, as mentioned in [19] and [20], and, to confirm this hypothesis, the three devices were put to the test. Each device was forced to do multiple discoveries with a different number of discovered devices, ranging from 0 devices found to 3 devices found.

¹Transmission powers impact directly the range of transmission, since they affect the signal strength, a crucial characteristic for receivers to better capture the transmissions. A bigger transmit power, usually, creates a bigger signal strength leading to the signal being captured over bigger distances, as referred in [18], for instance.

4.1.4 File transfer data rates

4.2 Testing the developed application

4.2.1 Battery consumption during use

4.2.2 Discovery times

4.2.3 Connection times

4.2.4 File transfer data rates

Chapter 5

Conclusion

There are also some features that lack implementation, such as the request of multiple pages, video streaming and file downloads.

If this idea is pursued and further thought on its development is given it is my conviction that it can be a valuable asset to Android devices - such as is hot spot nowadays. Ho, to achieve a customer ready solution many problems must be solved, as well as new features added.

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Appendix A

Application code

A.1 InitActivity.java

```
package com.example.falcato.btrouting;

import ...

public class InitActivity extends Activity {

    private static final String TAG = "InitActivity";
    Button goButton;

    @Override
    protected void onCreate(Bundle savedInstanceState) {
        super.onCreate(savedInstanceState);
        setContentView(R.layout.activity_init);
    }

    @Override
    protected void onStart (){
        super.onStart();

        // Check if device has an Internet connection
        new NetworkCheck().execute();

        goButton = (Button) findViewById(R.id.button);
        goButton.setOnClickListener(new View.OnClickListener() {
            @Override
            public void onClick(View v) {
                Intent intent = new Intent ( InitActivity.this, BtActivity.class );
                startActivity(intent);
            }
        });
    }
}
```

```

private class NetworkCheck extends AsyncTask<Void, Void, Boolean> {

    @Override
    protected Boolean doInBackground(Void... params) {
        Log.i(TAG, "hasActiveInternetConnection()");
        try {
            HttpURLConnection urlc = (HttpURLConnection) (
                new URL("http://clients3.google.com/generate_204").openConnection());
            urlc.setRequestProperty("User-Agent", "Test");
            urlc.setRequestProperty("Connection", "close");
            urlc.setConnectTimeout(1500);
            urlc.connect();
            return (urlc.getResponseCode() == 204 && urlc.getContentLength() == 0);
        } catch (IOException e) {
            Log.e(TAG, "Error checking internet connection", e);
        }
        return false;
    }

    @Override
    protected void onPostExecute(Boolean result) {
        ((RoutingApp) getApplicationContext()).setHasNet(result);
    }
}
}

```

A.2 BtActivity.java

```

package com.example.falcato.btrouting;

import ...

public class BtActivity extends Activity {

    // Debugging
    private static final String TAG = "BluetoothActivity";
    private static final boolean D = true;

    Button goButton;
    EditText mEdit;
    WebView mWebview;

    // Message types sent from the BluetoothChatService Handler
    public static final int MESSAGE_STATE_CHANGE = 1;

```

```

public static final int MESSAGE_READ = 2;
public static final int MESSAGE_WRITE = 3;
public static final int MESSAGE_DEVICE_NAME = 4;
public static final int MESSAGE_TOAST = 5;
public static final int FILE_READ = 6;
public static final int FILE_WRITE = 7;

// Key names received from the BluetoothService Handler
public static final String DEVICE_NAME = "device_name";
public static final String TOAST = "toast";

// Intent request codes
private static final int REQUEST_ENABLE_BT = 3;

// Name of the connected device
private String mConnectedDeviceName = null;
// List of peer devices
private ArrayList<BluetoothDevice> peers = null;
// String buffer for outgoing messages
private StringBuffer mOutStringBuffer;
// Local Bluetooth adapter
private BluetoothAdapter mBluetoothAdapter = null;
// Member object for the chat services
private BluetoothService mService = null;
// Check if peer discovery is finished
private boolean discoveryFinished = false;
// Save the message ID
private int msgID = 0;

@Override
public void onCreate(Bundle savedInstanceState) {
    super.onCreate(savedInstanceState);
    if (D) Log.e(TAG, "+++ ON CREATE +++");

    // Set up the window layout
    setContentView(R.layout.activity_bt);

    // Get local Bluetooth adapter
    mBluetoothAdapter = BluetoothAdapter.getDefaultAdapter();

    // Initialize peers array
    peers = new ArrayList<>();

    // If the adapter is null, then Bluetooth is not supported
    if (mBluetoothAdapter == null) {
        Toast.makeText(this, "Bluetooth is not available", Toast.LENGTH_LONG).show();
        finish();
    }
}

```

```

        return;
    }

}

@Override
public void onStart() {
    super.onStart();
    if(D) Log.e(TAG, "++ ON START ++");

    // If BT is not on, request that it be enabled.
    if (!mBluetoothAdapter.isEnabled()) {
        Log.e(TAG, "mBluetoothAdapter not enabled");
        Intent enableIntent = new Intent(BluetoothAdapter.ACTION_REQUEST_ENABLE);
        startActivityForResult(enableIntent, REQUEST_ENABLE_BT);

    } else {
        Log.e(TAG, "mBluetoothAdapter enabled");
    }

    // Register for broadcasts when a device is discovered
    IntentFilter filter = new IntentFilter(BluetoothDevice.ACTION_FOUND);
    this.registerReceiver(mReceiver, filter);

    // Register for broadcasts when discovery has finished
    filter = new IntentFilter(BluetoothAdapter.ACTION_DISCOVERY_FINISHED);
    this.registerReceiver(mReceiver, filter);

    mWebview = (WebView) findViewById(R.id.webView);
    mWebview.getSettings().setJavaScriptEnabled(true);
    mWebview.getSettings().setAllowFileAccess(true);
    mWebview.getSettings().setDomStorageEnabled(true);
    mWebview.getSettings().setAllowContentAccess(true);
    mWebview.getSettings().setAllowFileAccessFromFileURLs(true);
    mWebview.getSettings().setJavaScriptCanOpenWindowsAutomatically(true);

    // Make this device discoverable
    ensureDiscoverable();

    // update route table and start discovery
    // If device has net
    if(((RoutingApp)getApplicationContext()).getHasNet())
        ((RoutingApp)getApplicationContext()).updateRouteTable
            ("ADV;" + getOwnMAC() + ";0");
    // Otherwise infinite number of hops
    else
        ((RoutingApp)getApplicationContext()).updateRouteTable

```

```

        ("ADV;" + getOwnMAC() + ";16");

// Remove comments
doDiscovery();
setupBluetoothService();

goButton = (Button) findViewById(R.id.buttonGo);
mEdit = (EditText)findViewById(R.id.editText);
goButton.setOnClickListener(new View.OnClickListener() {
    @Override
    public void onClick(View v) {
        // Test
        //getPage(mEdit.getText().toString());

        // Remove comments
        sendRequest(true, -1, mEdit.getText().toString());
    }
});
}

@Override
public void onDestroy() {
    super.onDestroy();
    // Stop the Bluetooth chat services
    if (mService != null) mService.stop();
    if (D) Log.e(TAG, "--- ON DESTROY ---");
    unregisterReceiver(mReceiver);
}

private String getOwnMAC () {
    if (Build.VERSION.SDK_INT > 22)
        return android.provider.Settings.Secure.getString(this.getContentResolver(),
            "bluetooth_address");
    else
        return mBluetoothAdapter.getAddress();
}

private void ensureDiscoverable() {
    if (D) Log.i(TAG, "ensure discoverable");
    if (mBluetoothAdapter.getScanMode() !=
        BluetoothAdapter.SCAN_MODE_CONNECTABLE_DISCOVERABLE) {
        Intent discoverableIntent = new Intent(BluetoothAdapter.ACTION_REQUEST_DISCOVERABLE);
        discoverableIntent.putExtra(BluetoothAdapter.EXTRA_DISCOVERABLE_DURATION, 0);
        startActivity(discoverableIntent);
    }
}
}

```

```

private void doDiscovery() {
    if (D) Log.i(TAG, "doDiscovery()");
    discoveryFinished = false;

    // If we're already discovering, stop it
    if (mBluetoothAdapter.isDiscovering()) {
        mBluetoothAdapter.cancelDiscovery();
    }

    mBluetoothAdapter.startDiscovery();
    Toast.makeText(getApplicationContext(), "Starting discovery. Please wait...",
        Toast.LENGTH_SHORT).show();
}

private void setupBluetoothService() {
    Log.i(TAG, "setupBluetoothService()");
    // Initialize the BluetoothChatService to perform bluetooth connections
    mService = new BluetoothService(this, mHandler);

    // Initialize the buffer for outgoing messages
    mOutStringBuffer = new StringBuffer("");
}

private void advertisePeers() {
    Log.i(TAG, "advertisePeers()");
    for (BluetoothDevice peer : peers){
        Log.i(TAG, "Peer class: " + peer.getBluetoothClass().getDeviceClass());
        // Check if peer is a cell phone
        if (peer.getBluetoothClass().getDeviceClass() == 524){
            //Debug
            //if(!peer.getName().contains(";HUAWEI P8 lite")) {
            // Check if peer is using app
            if (peer.getName().contains(";")) {
                Log.i(TAG, "Will advertise to: " + peer.getName());
                mService.connect(peer);

                // Wait until connection is done
                while (mService.getState() != BluetoothService.STATE_CONNECTED) {
                    if (mService.getState() == BluetoothService.STATE_LISTEN) {
                        Log.e(TAG, "Failed to connect, listening");
                        mService.start();
                        break;
                    }
                }
            }

            // Device is connected, advertise
            int nrHops = ((RoutingApp) getApplicationContext()).getMinHop() + 1;

```



```

        sendMessage("ADV;" + getOwnMAC() + ";" + nrHops);

        // Wait until connection is finished
        long initTime = System.currentTimeMillis();
        while (mService.getState() != BluetoothService.STATE_LISTEN) {
            if (System.currentTimeMillis() - initTime > 5000) {
                break;
            }
        }
    }
    //Debug
    //}
}

private void sendRequest(boolean owner, int msgID, String message) {
    Log.i(TAG, "sendRequest()");

    // Get the address of the next hop
    BluetoothDevice nextHop = mBluetoothAdapter.getRemoteDevice(
        ((RoutingApp)getApplicationContext()).getNextHop());
    // In case there is no next hop
    if (nextHop.getAddress() == null){
        Log.i(TAG, "There is no next hop");
        sendFail(msgID);
        return;
    }

    Log.i(TAG, "Will send request to: " + nextHop.getAddress());
    mService.connect(nextHop);

    // Wait until connection is done
    for (int aux = 0; mService.getState() != BluetoothService.STATE_CONNECTED; aux++){
        if (mService.getState() == BluetoothService.STATE_LISTEN){
            Log.e(TAG, "Failed to connect, listening");
            mService.start();
            // Failed to connect send fail notification
            sendFail(msgID);
            return;
        }
    }

    // If device is the one sending the request
    if (owner) {
        // Device is connected, send request
        Random rn = new Random();

```

```

        int newMsgID = rn.nextInt();
        // Message -> RQT ; Message ID ; Own MAC ; Data
        sendMessage("RQT;" + newMsgID + ";" + getOwnMAC() + ";" + message);
        // Update the response table with own MAC to know when the response is received
        ((RoutingApp)getApplicationContext()).updateRspTable(newMsgID, getOwnMAC());
        // If device is forwarding the request
    }else{
        // Message -> RQT ; Message ID ; Own MAC ; Data
        sendMessage("RQT;" + msgID + ";" + getOwnMAC() + ";" + message);
    }
}

private void sendResponse(int msgID) {
    Log.i(TAG, "sendResponse(int msgID) " + msgID);
    // Retrieve the requester's MAC
    String nextHopMAC = ((RoutingApp)getApplicationContext()).getRspHop(msgID);
    // If message ID exists in the response table
    if (nextHopMAC != null){
        // Get the address of the next hop
        BluetoothDevice nextHopDevice = mBluetoothAdapter.getRemoteDevice(nextHopMAC);
        Log.i(TAG, "Will send response to: " + nextHopDevice.getAddress());
        mService.connect(nextHopDevice);

        // Wait until connection is done
        for (int aux = 0; mService.getState() != BluetoothService.STATE_CONNECTED; aux++){
            if (mService.getState() == BluetoothService.STATE_LISTEN){
                Log.e(TAG, "Failed to connect, listening");
                mService.start();
                return;
            }
        }
        // Send the response message
        sendMessage("RSP;" + msgID);
    }else{
        Log.i(TAG, "MAC for requested Message ID not found");
    }
}

private void sendFail(int msgID) {
    Log.i(TAG, "sendFail(int msgID) " + msgID);
    // Retrieve the requester's MAC
    String nextHopMAC = ((RoutingApp)getApplicationContext()).getRspHop(msgID);
    // If message ID exists in the response table
    if (nextHopMAC != null){
        // Get the address of the next hop
        BluetoothDevice nextHopDevice = mBluetoothAdapter.getRemoteDevice(nextHopMAC);
        Log.i(TAG, "Will send fail notification to: " + nextHopDevice.getAddress());
    }
}

```

```

        mService.connect(nextHopDevice);

        // Wait until connection is done
        for (int aux = 0; mService.getState() != BluetoothService.STATE_CONNECTED; aux++){
            if (mService.getState() == BluetoothService.STATE_LISTEN){
                Log.e(TAG, "Failed to connect, listening");
                mService.start();
                return;
            }
        }
        // Send the response message
        sendMessage("FAIL;" + msgID);
    }else{
        Log.i(TAG, "MAC for requested Message ID not found");
    }
}

private void sendMessage(String message) {
    // Check that we're actually connected before trying anything
    if (mService.getState() != BluetoothService.STATE_CONNECTED) {
        Log.e(TAG, "Not connected, can't send message");
        return;
    }

    // Check that there's actually something to send
    if (message.length() > 0) {
        // Get the message bytes and tell the BluetoothChatService to write
        byte[] send = message.getBytes();
        mService.write(send);

        // Reset out string buffer to zero and clear the edit text field
        mOutStringBuffer.setLength(0);
    }
}

private void sendFile() {
    Log.i(TAG, "sendFile()");

    File file = new File(getFilesDir() + "file.mht");
    int size = (int) file.length();
    byte[] bytes = new byte[size];

    try {
        BufferedInputStream buf = new BufferedInputStream(new FileInputStream(file));
        buf.read(bytes, 0, bytes.length);
        buf.close();
    } catch (IOException e) {

```

```

        e.printStackTrace();
    }

    mService.writeFile(bytes);

    Log.i(TAG, "sent file with " + bytes.length + " bytes in: " + getFilesDir() + "file.mht");
}

private void analyzeMessage(String message) {

    // Advertising message
    if (message.contains("ADV")){
        // Check if new shortest path was found
        if (Integer.parseInt(message.split(";")[2]) <
            ((RoutingApp)getApplicationContext()).getMinHop()){
            Log.i(TAG, "New best path will advertise");
            // If so, update table, initiate discovery and advertise new path
            ((RoutingApp)getApplicationContext()).updateRouteTable(message);
            discoveryFinished = false;
            doDiscovery();
        }else{
            Log.i(TAG, "New path is not the best will not advertise");
            // Otherwise update table and continue listening
            ((RoutingApp)getApplicationContext()).updateRouteTable(message);
        }

        // Request message
    }else if (message.contains("RQT")){
        // Save the message ID
        msgID = Integer.parseInt(message.split(";")[1]);
        // Update the response table
        ((RoutingApp)getApplicationContext()).updateRspTable(
            Integer.parseInt(message.split(";")[1]), message.split(";")[2]);

        // If device is not connected to the Internet
        if (!((RoutingApp)getApplicationContext()).getHasNet()){
            // Forward the request
            sendRequest(false, Integer.parseInt(message.split(";")[1]), message.split(";")[3]);
        } // If it is connected, fetch the web page and send the response
        }else{
            getPage(message.split(";")[3], Integer.parseInt(message.split(";")[1]));
        }

        // Response message
    }else if (message.contains("RSP")){

        // Save message ID to know the file name

```

```

msgID = Integer.parseInt(message.split(";")[1]);

// If device is the destination
if (((RoutingApp)getApplicationContext()).getRspHop(Integer.parseInt(
    message.split(";")[1])).equals(getOwnMAC())){
    // Request was successfully sent and response was received
    Log.i(TAG, "Received my response.");

// Otherwise forward response to destination
}else{
    // Forward the response
    Log.i(TAG, "Not the final destination will forward response.");
}
}else if (message.contains("FAIL")){
    // Save message ID to know the file name
    msgID = Integer.parseInt(message.split(";")[1]);

// If device is the destination
if (((RoutingApp)getApplicationContext()).getRspHop(Integer.parseInt(
    message.split(";")[1])).equals(getOwnMAC())){
    // Request was successfully sent but response failed
    Toast.makeText(getApplicationContext(), "Unfortunately there was a problem along " +
        "the path. Please try again later.",
        Toast.LENGTH_SHORT).show();

// Otherwise forward response to destination
}else{
    // Forward the failed request
    Log.i(TAG, "Not the final destination will forward fail notification.");
    sendFail(msgID);
}
}
}

private void getPage(String url, final int msgID){
    Log.i(TAG, "getPage(String url, final int messageID)");
    //mWebView.setVisibility(View.VISIBLE);
    mWebView.setWebViewClient(new WebViewClient() {
        public void onPageFinished(WebView view, String url) {
            // Fix to load all pages and not send 0 bytes

            File file = new File(getFilesDir() + "file.mht");

            try {
                file.createNewFile();
            } catch (IOException e) {
                e.printStackTrace();
            }
        }
    });
}

```

```

    }

    view.saveWebArchive(getFilesDir() + "file.mht");
    //mWebView.setVisibility(View.INVISIBLE);

    waitForWebPage dloader = new waitForWebPage();
    dloader.execute();
}

});
mWebView.loadUrl("https://" + url);
}

@Override
public void onBackPressed(){
    // If a page is being displayed, let the user enter a new URL
    if (mWebView.getVisibility() == View.VISIBLE) {
        mWebView.setVisibility(View.INVISIBLE);
        // Otherwise act normally and go back
    }else{
        super.onBackPressed();
    }
}

/* --- Logic to display the file --- */

private void loadPage(){
    Log.i(TAG, "loading page...");

    mWebView.getSettings().setCacheMode( WebSettings.LOAD_CACHE_ELSE_NETWORK );
    mWebView.setVisibility(View.VISIBLE);
    // #1 try to send a re-request
    mWebView.setWebViewClient(new WebViewClient(){
        @Override
        public void onReceivedError(WebView view, WebResourceRequest request,
                                   WebResourceError error) {
            if (Build.VERSION.SDK_INT >= Build.VERSION_CODES.LOLLIPOP) {
                Log.i(TAG, "No Internet connection, sending a re-request of: " +
                    request.getUrl().toString().split("://")[1]);
                view.loadUrl("about:blank");
                sendRequest(true, -1, request.getUrl().toString().split("://")[1]);
            }
        }
    });
    mWebView.setWebChromeClient(new WebChromeClient());

    if (Build.VERSION.SDK_INT < 22) {
        loadArchive();
    }
}

```

```

    } else {
        mWebview.loadUrl("file:/// " + getFilesDir() + "file.mht");
    }

    Log.i(TAG, "Loaded page in: file:/// " + getFilesDir() + "file.mht");
}

private void loadArchive(){
    String rawData = null;
    try {
        rawData = getStringFromFile(getFilesDir() + "file.mht");
    } catch (Exception e) {
        e.printStackTrace();
    }
    mWebview.loadDataWithBaseURL(null, rawData, "application/x-webarchive-xml", "UTF-8", null);
}

public String getStringFromFile (String filePath) throws Exception {
    File fl = new File(filePath);
    FileInputStream fin = new FileInputStream(fl);
    String ret = convertStreamToString(fin);
    //Make sure you close all streams.
    fin.close();
    return ret;
}

public String convertStreamToString(InputStream is) throws Exception {
    BufferedReader reader = new BufferedReader(new InputStreamReader(is));
    StringBuilder sb = new StringBuilder();
    String line = null;
    while ((line = reader.readLine()) != null) {
        sb.append(line).append("\n");
    }
    reader.close();
    return sb.toString();
}

/* --- End of logic --- */

private final BroadcastReceiver mReceiver = new BroadcastReceiver() {
    @Override
    public void onReceive(Context context, Intent intent) {
        String action = intent.getAction();

        // When discovery finds a device
        if (BluetoothDevice.ACTION_FOUND.equals(action)) {
            Log.i(TAG, "Found a device.");

```

```

        // Get the BluetoothDevice object from the Intent
        BluetoothDevice device = intent.getParcelableExtra(BluetoothDevice.EXTRA_DEVICE);
        // If new peer not counted already add it to peer list
        if (!peers.contains(device)) {
            peers.add(device);
        }
        // When discovery is finished, change the Activity title
    } else if (BluetoothAdapter.ACTION_DISCOVERY_FINISHED.equals(action)) {
        if(!discoveryFinished) {
            TextView peerText = (TextView) findViewById(R.id.textViewPeers);
            Log.i(TAG, "Discovery finished.");
            // Stop the discovery
            mBluetoothAdapter.cancelDiscovery();
            discoveryFinished = true;
            Toast.makeText(getApplicationContext(), "Discovery finished",
                Toast.LENGTH_SHORT).show();
            Log.i(TAG, "Peers found: " + peers.toString());
            peerText.setText("Peers found: " + peers.toString());
            advertisePeers();
        }
    }
}

}

};

// The Handler that gets information back from the BluetoothChatService
private final Handler mHandler = new Handler() {
    @Override
    public void handleMessage(Message msg) {
        switch (msg.what) {
            case MESSAGE_STATE_CHANGE:
                if(D) Log.i(TAG, "MESSAGE_STATE_CHANGE: " + msg.arg1);
                switch (msg.arg1) {
                    case BluetoothService.STATE_CONNECTED:
                        Log.e(TAG, "Status: connected");
                        break;
                    case BluetoothService.STATE_CONNECTING:
                        Log.e(TAG, "Status: connecting");
                        break;
                    case BluetoothService.STATE_LISTEN:
                        Log.e(TAG, "Status: listen");
                        break;
                    case BluetoothService.STATE_NONE:
                        Log.e(TAG, "Status: none");
                        break;
                }
                break;
            case MESSAGE_WRITE:

```



```

byte[] writeBuf = (byte[]) msg.obj;
// construct a string from the buffer
String writeMessage = new String(writeBuf);
// handle sent message
Log.i(TAG, "Sent a new message: " + writeMessage);

// If a response was sent follow with the corresponding file
if (writeMessage.contains("RSP;")){
    sendFile();
}
break;
case MESSAGE_READ:
byte[] readBuf = (byte[]) msg.obj;
// construct a string from the valid bytes in the buffer
String readMessage = new String(readBuf, 0, msg.arg1);
// handle received message
TextView recvText = (TextView) findViewById(R.id.textViewReceived);
Log.i(TAG, "Received a new message: " + readMessage);
recvText.setText(recvText.getText() + "\n" + readMessage);

// Restart the Bluetooth Service
if (!readMessage.contains("RSP;")) {
    mService.start();
}else {
    mService.fileReady = true;
}
analyzeMessage(readMessage);
break;
case MESSAGE_DEVICE_NAME:
// save the connected device's name
mConnectedDeviceName = msg.getData().getString(DEVICE_NAME);
Log.i(TAG, "Connected to " + mConnectedDeviceName);
break;
case MESSAGE_TOAST:
break;

case FILE_READ:
Log.i(TAG, "Received a new file");

byte[] readFileBuf = (byte[]) msg.obj;
try {

    File file = new File(getFilesDir() + "file" + msgID + ".mht");
    if (!file.exists()) {
        file.createNewFile();
    }
}

```

```

        FileOutputStream stream = new FileOutputStream(
            getFilesDir() + "file.mht", false);
        stream.write(readFileBuf);
        stream.flush();
        stream.close();

        Log.i(TAG, "Saved the file in: " + getFilesDir() + "file.mht");
    } catch (FileNotFoundException e) {
        e.printStackTrace();
    } catch (IOException e) {
        e.printStackTrace();
    }
}

// Restart the Bluetooth Service
mService.start();
mService.fileReady = false;

// If I am the destination
if (((RoutingApp)getApplicationContext()).getRspHop(msgID).equals(getOwnMAC())) {
    // Display the page
    loadPage();
}else{
    sendResponse(msgID);
}

break;

case FILE_WRITE:
    byte[] writeFileBuf = (byte[]) msg.obj;
    try {

        File file = new File(getFilesDir() + "file.mht");
        if (!file.exists()) {
            file.createNewFile();
        }

        FileOutputStream stream = new FileOutputStream(
            getFilesDir() + "file.mht", false);
        stream.write(writeFileBuf);
        stream.flush();
        stream.close();

        Log.i(TAG, "Saved the file in: " + getFilesDir() + "file.mht");
    } catch (FileNotFoundException e) {
        e.printStackTrace();
    } catch (IOException e) {
        e.printStackTrace();
    }
}

```

```

        }
        // Display the page
        loadPage();
        break;
    }
}
};

private class waitForWebPage extends AsyncTask<Void, Void, Void>{
    File file = new File(getFilesDir() + "file.mht");
    @Override
    protected Void doInBackground(Void... params) {
        Log.i(TAG, "Downloading webpage...");
        while(!(file.length() > 0)){
        }
        return null;
    }

    @Override
    protected void onPostExecute(Void result){
        Log.i(TAG, "saved web archive in: " + getFilesDir() + "file.mht with " +
            file.length() + " bytes");
        sendResponse(msgID);
    }
}
}
}

```

A.3 RoutingApp.java

```

package com.example.falcato.btrouting;

import ...

public class RoutingApp extends Application {

    private static final String TAG = "RoutingApp";

    private boolean hasNet;
    // Table with routing hops
    public Map<String, Integer> routeTable = new HashMap<>();
    // Table with MACs corresponding to message ID's
    public Map<Integer, String> rspTable = new HashMap<>();

    public boolean getHasNet () {
        Log.i(TAG, "getHasNet()");
    }
}

```

```

        return hasNet;
    }

    public void setHasNet (boolean hasNet) {
        Log.i(TAG, "setHasNet() " + hasNet);
        this.hasNet = hasNet;
    }

    public void updateRouteTable (String msg) {
        Log.i(TAG, "updateRouteTable()");
        String dest = msg.split(";")[1];
        int hops = Integer.parseInt(msg.split(";")[2]);

        routeTable.put(dest, hops);
    }

    public int getMinHop () {
        Log.i(TAG, "getMinHop()");
        int minHop;
        try {
            minHop = Collections.min(routeTable.values());
        } catch (NoSuchElementException e){
            Log.e(TAG, e.toString());
            minHop = 16;
        }

        Log.i(TAG, "Minimal nr of hops is: " + minHop);
        return minHop;
    }

    public String getNextHop () {
        Log.i(TAG, "getNextHop()");
        int minHop = getMinHop();
        if (minHop == 16)
            return null;
        else
            return getKeyFromValue(routeTable, minHop);
    }

    private String getKeyFromValue (Map<String, Integer> hm, Integer value) {
        Log.i(TAG, "getKeyFromValue()");
        for (String key : hm.keySet()) {
            if (hm.get(key).equals(value)) {
                return key;
            }
        }
        return null;
    }

```

```

    }

    public void updateRspTable (int msgID, String MAC) {
        Log.i(TAG, "updateRspTable()");
        rspTable.put(msgID, MAC);
        Log.i(TAG, "Updated message table: " + rspTable.toString());
    }

    public String getRspHop (int msgID) {
        Log.i(TAG, "getRspHop()");
        if (rspTable.containsKey(msgID))
            return rspTable.get(msgID);
        else
            return null;
    }
}

```

A.4 BluetoothService.java

```

package com.example.falcato.btrouting;

import ...

public class BluetoothService {
    // Debugging
    private static final String TAG = "BluetoothService";
    private static final boolean D = true;

    // Name for the SDP record when creating server socket
    private static final String NAME_INSECURE = "BluetoothRouteInsecure";

    // Unique UUID for this application
    private static final UUID MY_UUID_INSECURE =
        UUID.fromString("8ce255c0-200a-11e0-ac64-0800200c9a66");

    // Member fields
    private final BluetoothAdapter mAdapter;
    private final Handler mHandler;
    private AcceptThread mInsecureAcceptThread;
    private ConnectThread mConnectThread;
    private ConnectedThread mConnectedThread;
    private int mState;
    boolean fileReady = false;

    // Constants that indicate the current connection state
    public static final int STATE_NONE = 0;          // we're doing nothing

```

```

public static final int STATE_LISTEN = 1;    // now listening for incoming connections
public static final int STATE_CONNECTING = 2; // now initiating an outgoing connection
public static final int STATE_CONNECTED = 3; // now connected to a remote device

/**
 * Constructor. Prepares a new BluetoothChat session.
 * @param context The UI Activity Context
 * @param handler A Handler to send messages back to the UI Activity
 */
public BluetoothService(Context context, Handler handler) {
    mAdapter = BluetoothAdapter.getDefaultAdapter();
    mState = STATE_NONE;
    mHandler = handler;
}

/**
 * Set the current state of the chat connection
 * @param state An integer defining the current connection state
 */
private synchronized void setState(int state) {
    if (D) Log.i(TAG, "setState() " + mState + " -> " + state);
    mState = state;

    // Give the new state to the Handler so the UI Activity can update
    mHandler.obtainMessage(BtActivity.MESSAGE_STATE_CHANGE, state, -1).sendToTarget();
}

/**
 * Return the current connection state. */
public synchronized int getState() {
    return mState;
}

/**
 * Start the chat service. Specifically start AcceptThread to begin a
 * session in listening (server) mode. Called by the Activity onResume() */
public synchronized void start() {
    if (D) Log.i(TAG, "start");

    // Cancel any thread attempting to make a connection
    if (mConnectThread != null) {mConnectThread.cancel(); mConnectThread = null;}

    // Cancel any thread currently running a connection
    if (mConnectedThread != null) {mConnectedThread.cancel(); mConnectedThread = null;}

    setState(STATE_LISTEN);
}

```

```

        // Start the thread to listen on a BluetoothServerSocket
        if (mInsecureAcceptThread == null) {
            mInsecureAcceptThread = new AcceptThread();
            mInsecureAcceptThread.start();
        }
    }

    /**
     * Start the ConnectThread to initiate a connection to a remote device.
     * @param device The BluetoothDevice to connect
     */
    public synchronized void connect(BluetoothDevice device) {
        if (D) Log.i(TAG, "connect to: " + device);

        // Cancel any thread attempting to make a connection
        if (mState == STATE_CONNECTING) {
            if (mConnectThread != null) {mConnectThread.cancel(); mConnectThread = null;}
        }

        // Cancel any thread currently running a connection
        if (mConnectedThread != null) {mConnectedThread.cancel(); mConnectedThread = null;}

        // Start the thread to connect with the given device
        mConnectThread = new ConnectThread(device);
        mConnectThread.start();
        setState(STATE_CONNECTING);
    }

    /**
     * Start the ConnectedThread to begin managing a Bluetooth connection
     * @param socket The BluetoothSocket on which the connection was made
     * @param device The BluetoothDevice that has been connected
     */
    public synchronized void connected(BluetoothSocket socket, BluetoothDevice
        device) {
        if (D) Log.i(TAG, "connected");

        // Cancel the thread that completed the connection
        if (mConnectThread != null) {mConnectThread.cancel(); mConnectThread = null;}

        // Cancel any thread currently running a connection
        if (mConnectedThread != null) {mConnectedThread.cancel(); mConnectedThread = null;}

        // Cancel the accept thread because we only want to connect to one device
        if (mInsecureAcceptThread != null) {
            mInsecureAcceptThread.cancel();

```

```

        mInsecureAcceptThread = null;
    }

    // Start the thread to manage the connection and perform transmissions
    mConnectedThread = new ConnectedThread(socket);
    mConnectedThread.start();

    // Send the name of the connected device back to the UI Activity
    Message msg = mHandler.obtainMessage(BtActivity.MESSAGE_DEVICE_NAME);
    Bundle bundle = new Bundle();
    bundle.putString(BtActivity.DEVICE_NAME, device.getName());
    msg.setData(bundle);
    mHandler.sendMessage(msg);

    setState(STATE_CONNECTED);
}

/**
 * Stop all threads
 */
public synchronized void stop() {
    if (D) Log.i(TAG, "stop");

    if (mConnectThread != null) {
        mConnectThread.cancel();
        mConnectThread = null;
    }

    if (mConnectedThread != null) {
        mConnectedThread.cancel();
        mConnectedThread = null;
    }

    if (mInsecureAcceptThread != null) {
        mInsecureAcceptThread.cancel();
        mInsecureAcceptThread = null;
    }

    setState(STATE_NONE);
}

/**
 * Write to the ConnectedThread in an unsynchronized manner
 * @param out The bytes to write
 * @see ConnectedThread#write(byte[])
 */
public void write(byte[] out) {
    // Create temporary object

```



```

        ConnectedThread r;
        // Synchronize a copy of the ConnectedThread
        synchronized (this) {
            if (mState != STATE_CONNECTED) return;
            r = mConnectedThread;
        }
        // Perform the write unsynchronized
        r.write(out);
    }

    public void writeFile(byte[] out) {
        Log.i(TAG, "writeFile(byte[] out)");
        // Create temporary object
        ConnectedThread r;
        // Synchronize a copy of the ConnectedThread
        synchronized (this) {
            if (mState != STATE_CONNECTED) return;
            r = mConnectedThread;
        }
        // Perform the write unsynchronized
        r.writeFile(out);
    }

    /**
     * Indicate that the connection attempt failed and notify the UI Activity.
     */
    private void connectionFailed() {
        Log.i(TAG, "connectionFailed()");
        // Send a failure message back to the Activity
        Message msg = mHandler.obtainMessage(BtActivity.MESSAGE_TOAST);
        Bundle bundle = new Bundle();
        bundle.putString(BtActivity.TOAST, "Unable to connect device");
        msg.setData(bundle);
        mHandler.sendMessage(msg);

        // Start the service over to restart listening mode
        BluetoothService.this.start();
    }

    /**
     * Indicate that the connection was lost and notify the UI Activity.
     */
    private void connectionLost() {
        Log.i(TAG, "connectionLost()");
        // Send a failure message back to the Activity
        Message msg = mHandler.obtainMessage(BtActivity.MESSAGE_TOAST);
        Bundle bundle = new Bundle();

```

```

        bundle.putString(BtActivity.TOAST, "Device connection was lost");
        msg.setData(bundle);
        mHandler.sendMessage(msg);

        // Start the service over to restart listening mode
        BluetoothService.this.start();
    }

    /**
     * This thread runs while listening for incoming connections. It behaves
     * like a server-side client. It runs until a connection is accepted
     * (or until cancelled).
     */
    private class AcceptThread extends Thread {
        // The local server socket
        private final BluetoothServerSocket mmServerSocket;

        public AcceptThread() {
            BluetoothServerSocket tmp = null;

            // Create a new listening server socket
            try {
                tmp = mAdapter.listenUsingInsecureRfcommWithServiceRecord(
                    NAME_INSECURE, MY_UUID_INSECURE);
            } catch (IOException e) {
                Log.e(TAG, "Listen() failed", e);
            }
            mmServerSocket = tmp;
        }

        public void run() {
            if (D) Log.i(TAG, "BEGIN mAcceptThread" + this);
            setName("AcceptThread");

            BluetoothSocket socket = null;

            // Listen to the server socket if we're not connected
            while (mState != STATE_CONNECTED) {
                try {
                    // This is a blocking call and will only return on a
                    // successful connection or an exception
                    socket = mmServerSocket.accept();
                } catch (IOException e) {
                    Log.e(TAG, "Accept() failed", e);
                    break;
                }
            }
        }
    }

```

```

        // If a connection was accepted
        if (socket != null) {
            synchronized (BluetoothService.this) {
                switch (mState) {
                    case STATE_LISTEN:
                    case STATE_CONNECTING:
                        // Situation normal. Start the connected thread.
                        connected(socket, socket.getRemoteDevice());
                        break;
                    case STATE_NONE:
                    case STATE_CONNECTED:
                        // Either not ready or already connected. Terminate new socket.
                        try {
                            socket.close();
                        } catch (IOException e) {
                            Log.e(TAG, "Could not close unwanted socket", e);
                        }
                        break;
                }
            }
        }
    }
    if (D) Log.i(TAG, "END mAcceptThread");
}

public void cancel() {
    if (D) Log.i(TAG, "Cancel " + this);
    try {
        mmServerSocket.close();
    } catch (IOException e) {
        Log.e(TAG, "Close() of server failed", e);
    }
}

}

/**
 * This thread runs while attempting to make an outgoing connection
 * with a device. It runs straight through; the connection either
 * succeeds or fails.
 */
private class ConnectThread extends Thread {
    private final BluetoothSocket mmSocket;
    private final BluetoothDevice mmDevice;

    public ConnectThread(BluetoothDevice device) {
        mmDevice = device;
    }

```

```

BluetoothSocket tmp = null;

// Get a BluetoothSocket for a connection with the
// given BluetoothDevice
try {

    tmp = device.createInsecureRfcommSocketToServiceRecord(
        MY_UUID_INSECURE);
} catch (IOException e) {
    Log.e(TAG, "Create() failed", e);
}
mmSocket = tmp;
}

public void run() {
    Log.i(TAG, "BEGIN mConnectThread");
    setName("ConnectThread");

    // Always cancel discovery because it will slow down a connection
    mAdapter.cancelDiscovery();

    // Make a connection to the BluetoothSocket
    try {
        // This is a blocking call and will only return on a
        // successful connection or an exception
        mmSocket.connect();
    } catch (IOException e) {
        // Close the socket
        try {
            mmSocket.close();
        } catch (IOException e2) {
            Log.e(TAG, "Unable to close() socket during connection failure", e2);
        }
        connectionFailed();
        return;
    }

    // Reset the ConnectThread because we're done
    synchronized (BluetoothService.this) {
        mConnectThread = null;
    }

    // Start the connected thread
    connected(mmSocket, mmDevice);
}

public void cancel() {

```

```

        try {
            mmSocket.close();
        } catch (IOException e) {
            Log.e(TAG, "Close() of connect socket failed", e);
        }
    }
}

/**
 * This thread runs during a connection with a remote device.
 * It handles all incoming and outgoing transmissions.
 */
private class ConnectedThread extends Thread {
    private final BluetoothSocket mmSocket;
    private final InputStream mmInStream;
    private final OutputStream mmOutStream;

    public ConnectedThread(BluetoothSocket socket) {
        Log.i(TAG, "Create ConnectedThread");
        mmSocket = socket;
        InputStream tmpIn = null;
        OutputStream tmpOut = null;

        // Get the BluetoothSocket input and output streams
        try {
            tmpIn = socket.getInputStream();
            tmpOut = socket.getOutputStream();

        } catch (IOException e) {
            Log.e(TAG, "temp sockets not created", e);
        }

        mmInStream = tmpIn;
        mmOutStream = tmpOut;
    }

    public void run() {
        Log.i(TAG, "BEGIN mConnectedThread");
        byte[] buffer = new byte[8192];
        ByteArrayOutputStream output = new ByteArrayOutputStream();
        int bytes;

        // Keep listening to the InputStream while connected
        //while (no notification received)
        while (true) {
            try {

```

```

        // Read from the InputStream
        bytes = mmInStream.read(buffer);

        if (!fileReady) {
            // Send the obtained bytes to the UI Activity
            Log.e(TAG, "nr of bytes: " + bytes);
            mHandler.obtainMessage(BtActivity.MESSAGE_READ, bytes, -1, buffer)
                .sendToTarget();
        } else {
            // Join the chunks of the file until we get the full file
            Log.e(TAG, "Joining file chunks of " + bytes + "bytes");
            output.write(buffer, 0, bytes);

            // If we received the full file
            if (bytes < 990) {
                byte[] out = output.toByteArray();
                output.flush();
                output.close();
                Log.e(TAG, "nr of bytes file: " + out.length);
                mHandler.obtainMessage(BtActivity.FILE_READ, out.length, -1, out)
                    .sendToTarget();
            }
        }

    } catch (IOException e) {
        Log.e(TAG, "disconnected", e);
        connectionLost();
        break;
    }
}

/**
 * Write to the connected OutputStream.
 * @param buffer The bytes to write
 */
public void write(byte[] buffer) {
    Log.i(TAG, "write(byte[] buffer)");
    try {
        mmOutputStream.write(buffer);
        mmOutputStream.flush();
        // Share the sent message back to the UI Activity
        mHandler.obtainMessage(BtActivity.MESSAGE_WRITE, -1, -1, buffer)
            .sendToTarget();
    } catch (IOException e) {
        Log.e(TAG, "Exception during write", e);
    }
}

```

```

    }

    public void writeFile(byte[] buffer) {
        Log.i(TAG, "writeFile(byte[] buffer)");
        try {
            // Send the file in chunks of 990 bytes
            Double nrSends = Math.ceil((double) buffer.length / (double) 990);
            Log.i(TAG, "will send " + Math.round(nrSends) + " chunks");
            for (int currSend = 0; currSend < Math.round(nrSends); currSend++){
                if ((currSend + 1) * 990 > buffer.length) {
                    Log.i(TAG, "sending final chunk from " + (currSend * 990) + " to " +
                        (currSend * 990 + (buffer.length - (currSend * 990))));
                    mmOutputStream.write(buffer, currSend * 990, (buffer.length -
                        (currSend * 990)));
                    mmOutputStream.flush();
                    Log.i(TAG, "sent final chunk");
                }else {
                    Log.i(TAG, "sending chunk from " + (currSend * 990) + " to " +
                        ((currSend * 990) + 990));
                    mmOutputStream.write(buffer, currSend * 990, 990);
                    mmOutputStream.flush();
                    Log.i(TAG, "sent chunk");
                }
            }

            // Debug purposes
            /*mHandler.obtainMessage(BtActivity.FILE_WRITE, buffer.length, -1, buffer)
                .sendToTarget();*/

        } catch (IOException e) {
            Log.e(TAG, "Exception during write file", e);
        }
    }

    public void cancel() {
        try {
            mmSocket.close();
        } catch (IOException e) {
            Log.e(TAG, "Close() of connect socket failed", e);
        }
    }
}
}
}

```