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Extending Wi-Fi Direct Single-Group Network to Multi-Group Network Based on Android Smartphone

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Abstract

Nowadays, a very widespread of smartphones, especially Android smartphones, is observed. This is due to presence of many companies that produce Android based phones and provide them to consumers at reasonable prices with good specifications. The actual benefit of smartphones lies in creating communication between people through the exchange of messages, photos, videos, or other types of files. Usually, this communication is through the existence of an access point through which smartphones can connect to the Internet. However, the availability of the Internet is not guaranteed in all places and at all times, such as in crowded places, remote areas, natural disasters, or interruption of the Internet connection for any reason. To create a communication between devices, it is resorted to creating an ad hoc network using Device-to-Device technology. Wi-Fi Direct technology offers a suitable platform for creating an ad hoc network, as it supports the speed and range of standard Wi-Fi. In this paper, a mechanism is proposed to build an infrastructure-less ad hoc network, through developing the Wi-Fi direct protocol for Android smartphones. This network provides users ability to have a reliable communication, using the reliable Transmission Control Protocol only, and can continuously expand. Therefore it would be very beneficial in the absence of other infrastructure communication media such as cellular or Wi-Fi internet access.

Keywords: Wi-Fi Direct, Android smartphones, Device-to-Device technology, ad hoc network, reliable communication.

توسيع شبكة المباشرة واي فاي للمجموعة الواحدة لشبكة المجموعات المتعددة القائمة على الهاتف الذكي اندرويد

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الخلاصة

في الوقت الحاضر، نلاحظ إنتشار الهواتف الذكية على نطاق واسع، وخاصة الهواتف الذكية التي تعمل بنظام اندرويد. ويرجع ذلك إلى وجود العديد من الشركات التي تنتج هواتف أندرويد وتوفرها للمستهلك بأسعار معقولة و مواصفات جيدة. تكمن الفائدة الفعلية للهواتف الذكية في خلق التواصل بين الناس من خلال تبادل الرسائل، الصور، الفيديوهات أو أي نوع من الملفات. وعادة ما يكون هذا التواصل من خلال وجود نقطة

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وصول يمكن من خلالها للهواتف الذكية الاتصال بالإنترنت. غير أن توافر الإنترنت غير مضمون في جميع الأماكن وفي جميع الأوقات، كما هو الحال في الأماكن المزدحمة، المناطق النائية، عند حصول الكوارث الطبيعية، أو انقطاع الاتصال بالإنترنت لأي سبب من الأسباب. ولإنشاء اتصال بين الهواتف الذكية ، يتم اللجوء إلى إنشاء شبكة مخصصة باستخدام تكنولوجيا جهاز إلى جهاز. توفر تكنولوجيا مباشرة واي فاي منصة مناسبة لإنشاء شبكة مخصصة ، حيث أنها تدعم سرعة ونطاق الواي فاي القياسية. وفي هذه الورقة، تُقترح آلية لإنشاء شبكة مخصصة من الهواتف الذكية التي تعمل بنظام اندرويد باستخدام تكنولوجيا مباشرة واي فاي يكون لديها اتصالات موثوقة مع القدرة على التوسع المستمر.

1. Introduction

The Wi-Fi network is created in infrastructure mode or ad hoc mode. In infrastructure mode, there is a need for a specific device that takes a specific role, like an access point (AP), to enable establishment of network. In ad hoc mode, devices cooperate to organize themselves to create a network[1]. Therefore, it is possible to create an ad hoc network anywhere and at any time only from available smartphones without need for any specific device to take a specific role[2]. Android phones make up 71% of smartphone market worldwide according to Sept 2021 statistics [3]. Android phones after version 4.0, which was released in 2011[4], support the Wi-Fi Direct technology. This means that, most if not all, Android phones currently support this technology. This Device-to-Device(D2D) technology offers good features such as a maximum speed of 250 Mbps and a maximum range of 200 meters[5][6], which makes it a candidate for creating an ad hoc network. Compared to Bluetooth, Wi-Fi Direct is much better in terms of speed and range, as Bluetooth offers speeds up to 3 Mbps[7] and a range of up to 10 meters[8]. The Wi-Fi ad hoc mode is not supported by all smartphones unless rooting the smartphone, which is not easy for all users.

Many studies have emerged an interest in establishing ad hoc network using Wi-Fi Direct technology [8-10], but some of them did not mention how to build the network and how to distribute roles between smartphones[11]. Furthermore, the adoption of broadcasting in transmission of data within the network [10][9], is unreliable data transmission. In this paper, a new mechanism is proposed to form an ad hoc network of android smartphones using Wi-Fi Direct technology. The communication through this network is reliable depending on the Transmission Control Protocol (TCP) exclusively.
This paper is structured as follows. An overview of Wi-Fi Direct technology is provided in Section 2, while Section 3 shows Wi-Fi Direct limitations and multi-group challenges in Wi-Fi Direct technology. In Section 4, a discussion of related works is presented. The proposed network topology mechanism is described in Section 5. Properties of the proposed network are provided in Section 6. While Section 7 shows experiments and results. Finally, conclusions and future work are presented in Section 8.

2. Wi-Fi Direct

Wi-Fi Direct is a Device-to-Device(D2D) wireless communication technology developed by Wi-Fi Alliance [11]. The Network Interface Controller (NIC) of the smartphone, which supports this technology, is logically separated into two interfaces[9]. The Wi-Fi interface is used in traditional Wi-Fi connection and the Peer-to-Peer (P2P) interface is used in Wi-Fi Direct connection. Smartphones communicate and transfer data between them within a P2P group. In the group, one of the smartphones is the Group Owner (GO) and acts as Access Point (AP), and the rest of the smartphones, who connect to the GO, are clients. The smartphone, that is chosen to be GO, activates the Dynamic Host Configuration Protocol (DHCP) server and starts giving itself the IP address (192.168.49.1) and providing its clients with addresses (192.168.49.x), where x is a number between 2 and 254[12]. The GO announces itself by sending a beacon periodically so that the smartphones in its Wi-Fi range discover it and join its group. Client who connects to the GO through the P2P interface is called a P2P client while client who connects to the GO, as an AP via Service Set Identifier (SSID) and password, through the Wi-Fi interface is called a legacy client, as shown in Figure 1. Each smartphone (whether it is a GO, P2P client, or legacy client) in the group can communicate with the rest smartphones in the same group. The data between clients is forwarded through the GO in the Media Access Control (MAC) layer. The smartphone discovers the smartphones (peers) in its Wi-Fi range by running the Device Discovery procedure. In the Device Discovery procedure, smartphones exchange some information (e.g. the smartphone name and MAC address of the P2P interface)[10].

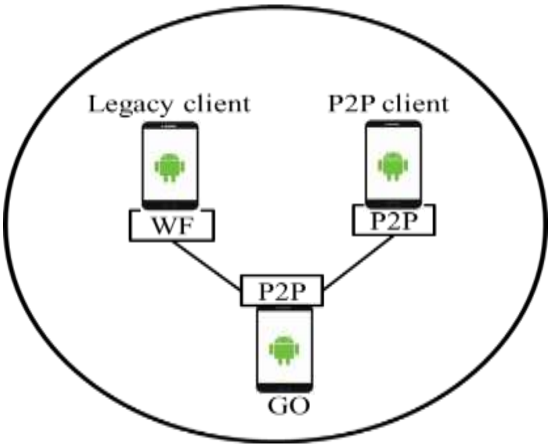


Figure 1: P2P group

The role of each smartphone, whether it is a GO or client, in the group is not predetermined but depends on the method used to form the group. There are three methods of group formation, which are Standard, Persistent, and Autonomous[9]. In the Standard method, the smartphone selects one of the peers to connect with, then the GO Negotiation phase begins to agree on which smartphone should become the GO. The GO is chosen by exchanging intent value (between 1 and 15) between the two smartphones that want to connect. The smartphone with the highest intent value becomes the GO. The Standard method is considered the slowest among other group formation methods[13]. In the Persistent method, if the group is destroyed, the smartphones can reconfigure it another time for another session. When the group is re-formed, each smartphone takes its previous role, whether it was a GO or a client without the need for a GO Negotiations phase. The client can invite the GO to reconfigure the group or vice versa by performing the P2P Invitation procedure. The Persistent method is faster than the Standard method. In the Autonomous method, the developer can select a smartphone to become a GO without going through the GO Negotiations phase. This method of group formation is the fastest compared to other methods, as the time of group formation in this method can take one-third of the time taken in the Standard method and half the time taken in the Persistent method[14].

3. Wi-Fi Direct Multi-Group Challenges

There are two limitations in Wi-Fi Direct technology that restrict the groups to connect and create an ad hoc network. The limitations are [15]:

1- The smartphone cannot be a P2P client of more than one group at the same time.

2- The GO of a group cannot be a P2P client of another group at the same time.

To achieve a multi-group network, the two interfaces (the Wi-Fi and the P2P interface) of the smartphone can be used at the same time. However, the issue is not completely resolved because there are two problems. The first problem is the IP address conflict when a GO connects to another GO as a legacy client because all GOs get the same IP address (192.168.49.1/24)[16], as shown in Figure 2 (a). For example, when GO2 tries to send a packet to GO1, this packet will be sent to itself (local loop) because the destination address is the same as its IP address. When GO2 receives a packet from GO1, GO2 will ignore that packet because the source IP address is the same as its IP address (considers that as a local loop). The second problem is the interface priority when the P2P interface and Wi-Fi interface are connected at the same time. The priority will be either for the P2P interface[17][18] or the Wi-Fi interface[16]. When the priority is for the Wi-Fi interface, the smartphone can establish and receive a Transmission Control Protocol (TCP) connection on its Wi-Fi interface, while the P2P interface TCP connection passes through the Wi-Fi interface as well. Therefore, it is not possible to establish a TCP connection on the P2P interface, but only receive, as shown in Figure 2 (b). On the other hand, when the priority is for the P2P interface, it is possible to establish and receive a TCP connection on the P2P interface, but on the Wi-Fi interface only receive a TCP connection, as shown in Figure 2 (c).

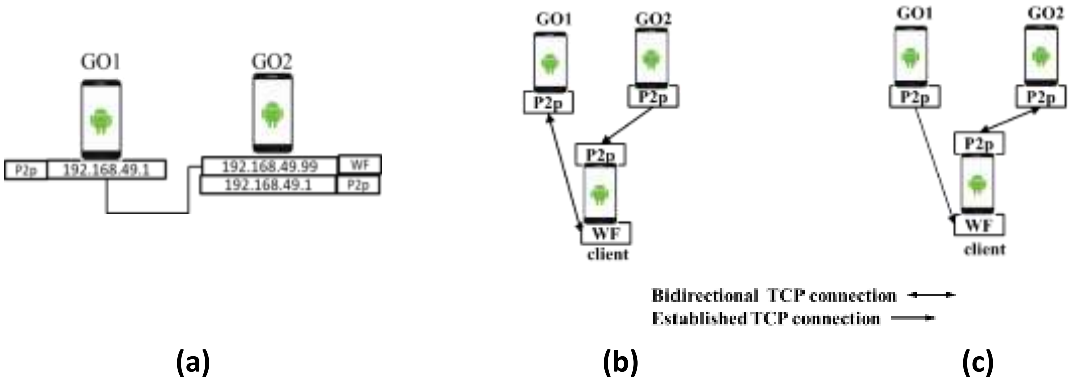


Figure 2: Multi-Group problems (a) IP address conflict (b) Wi-Fi interface priority (c) P2P interface priority

4. Related Work

Wi-Fi Direct technology has attracted the attention of researchers due to its advantages that make it qualified to create an ad hoc network. This technology was invented to create a single-hop connection, so trying to make it work on a multi-hop network is a challenge since many obstacles are faced.

Furutani et al. [2] introduced an information diffusion approach for multihop communication, working on virtual cell concept where a group of smartphones connects to form a virtual cell. Smartphones locations are relied on using GPS to continuously form and dismantle cells in order to diffuse the information through groups. The device's dependence on GPS to determine which cell it should belong to is ineffective, because the GPS signal is not accurate[19].

Sunil et al. [7] achieved a multi-hop network by disconnecting a P2P client from its group and then connecting to another group, within its range, to deliver a message. After delivering the message, the P2P client disconnects from the current group and then reconnects with its previous group. Liu et al. [8] proposed a method to form a multi-hop network by making all smartphones take the role of GO. The transfer of data is archived by connecting the smartphone, that wants to transfer data to the next hop, which is already GO, as a P2P client.

Di Felice et al. [14] rely on a P2P client called Group Relay (GR) to achieve multi-hop communication by switching GR between groups to transmit a safety message. Intuitively, there is more than one message sent over the network at one time. So the disconnections and reconnections in [2], [7], [8], and [14] cause a delay in the network due to the time taken by Wi-Fi Direct connection procedure. The delay is regarded as a deficiency, as the number of messages and the number of groups to pass through increase. In this paper, the deficiency is overcomed by keeping the groups of the network connected all the time, so there is no disconnection and reconnection.

References [9], [11], [10], [16], and [17] follow the same principle in achieving inter-group communication by making the GO connects as a legacy client with another GO. This type of connection causes the IP conflict problem due to the connection of GO to GO. Therefore, they are depending on a P2P client, called Relay Node, to relay data between GOs. Hence, in each group, there will be a permanent Relay Node to transfer data between GOs. In this paper, the IP conflict is overcomed by disjoining a GO to another GO. Also, in these references, the connected GOs are in the Wi-Fi range of each other which causes interference between these groups. This interference leads to reducing the throughput which in turn is decreased as the number of GOs, in the Wi-Fi range of each other, increases. In this paper, there is no direct connection between any two GOs, but instead, GO connects to another GO through the two interfaces (P2P interface and Wi-Fi interface) of a client. User Datagram Protocol (UDP), was used by references [10], [9], and [16] in part of the data transfer. While in this paper the data is transmitted exclusively through a reliable TCP connection. References [11], and [17] did not mention how to set up the network and define the role of each smartphone, whether it is a client or a GO. In addition, they did not mention how the SSID and Password were communicated to clients who wish to connect as a legacy. In this paper, a mechanism to form the network topology overrides the latter mentioned issues.

In [20], the authors propose techniques for building a communications backbone using Wi-Fi Direct and Wi-Fi interfaces, to support multi-hop communication in Wi-Fi Direct networks and implemented using MATLAB and simulation programs. However, due to the IP conflict of two connected GOs, the authors did not mention how the data are reliably transferred between the members (GOs) of the communications backbone.

Shahin and Younis. [21] proposed a protocol called Efficient Multi-group formation and Communication (EMC) to support multi-group communication by modifying Android source code to make each group get a different subnet. GO is chosen based on the smartphone’s battery level. This reference needs rooting permission to make changes on Android System. Any changes made below the application layer require rooting the smartphone which is not easy for users and also may affect the performance of the smartphone. While this paper does not make any modifications below the application layer so that there is no need to root the smartphone.

5. Methodology

In this paper, a mechanism is proposed that utilizes Wi-Fi Direct technology to extend Wi-Fi Direct single group network to a multi-group network based on Android smartphones. Such a multi-group network is infrastructure-less (no AP or base station) and enables smartphones to share data based on reliable data communication. Also, the proposed mechanism transcends the Wi-Fi Direct multi-group limitations and challenges, so that groups can communicate with each other to enlarge the Wi-Fi Direct communication distance, which is limited by Wi-Fi transmission range in a single group. This section consists of three parts;

the first is to form the network, the second is to prepare the network for reliable communication, and the third is to construct the routing table.

5.1 Network Topology Formation Mechanism

This mechanism plays the main role in forming the network so that no GO is connected with another GO. Thereby, the problem of IP address conflict of connecting GO to GO can be solved. Therefore, before establishing any physical connection, the smartphone role is determined, before joining the network, based on the number of smartphones that are in its Wi-Fi range and its battery charge. There are three stages for network formation; first stage is: **Discover the Neighbors**, second stage is **Announcing the Neighbors**, and third stage is **Electing GOs and Their Members**. It is found necessary to define the following terms that are used repeatedly in the rest of this section.

Connection Procedure: initially the smartphone connects to a GO through the P2P interface, and establishes a TCP connection with the GO then the GO immediately sends the SSID and Password to the smartphone. Having received the SSID and Password, the smartphone changes its connection to GO from P2P to Wi-Fi interface and becomes a legacy client. Then the smartphone continuously performs the Device Discovery procedure to be discoverable while it is in the network.

Link Client: A client has a prior connection with a GO through its Wi-Fi interface, then the client connects, through its P2P interface, to another GO who sends it a P2P invitation.

5.1.1 Discover the Neighbors

Initially, when each smartphone joins the network, it changes its name by concatenating its battery charge with its identification number (ID), where each smartphone generates a randomly three-digit ID. For example, if the smartphone (D1) generates its ID (111) with full charge (battery charge 100%), hence when it is trying to join the network its name field becomes "111#100", and then it starts the Device Discovery procedure provided by Wi-Fi Direct to detect the smartphones that are within its Wi-Fi range. If a GO is detected, it connects to that GO, if not then the Device Discovery procedure remains active for 6 seconds. From the practical work, it is found that 6 seconds is enough for the smartphone to discover more than one smartphone. At the end of this stage, each smartphone will have a list of its peers and information about these peers, which are their names and MAC addresses as mentioned in section 2.

Figure 3 shows the flowchart of the **Discover the Neighbors** stage.

Figure 3: Discover the Neighbors

5.1.2 Announcing the Neighbors

At this stage, each smartphone changes its name again by concatenating the IDs of its Peers with its name and then performs the Device Discovery procedure again as a means of announcing the list of peers discovered in the first stage to the rest of its neighbors. Table 1 shows an example of how the smartphone name is changed during the first and second stages for three smartphones that discovered each other, as shown in Figure 4, the circle around the smartphone represents its Wi-Fi range. At the end of this stage, each smartphone knows its neighbors' peers through their name fields.

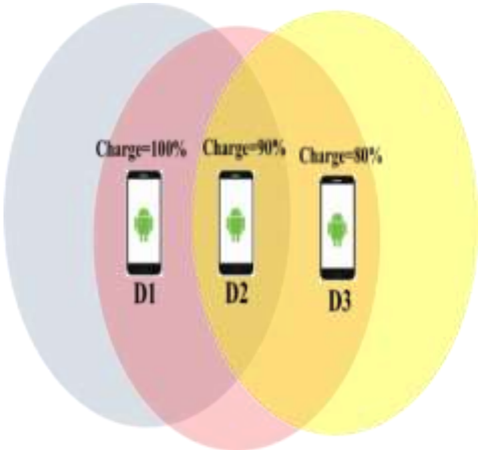


Figure 4: Three smartphones, each smartphone in the Wi-Fi range of each other smartphone/s

Table 1: Example of the first two stages for smartphones in Figure 4

Smartphone	ID	Battery charge	Name after the first stage	Name after the second stage
D1	111	100%	111#100	111#100/222
D2	222	90%	222#90	222#90/111/333
D3	333	80%	333#80	333#80/222

Figure 5 shows the flowchart of the **Announcing the Neighbors** stage.

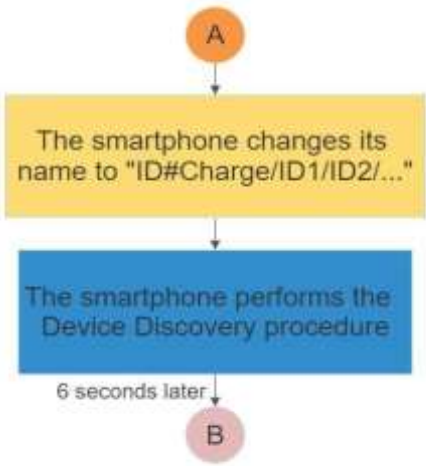
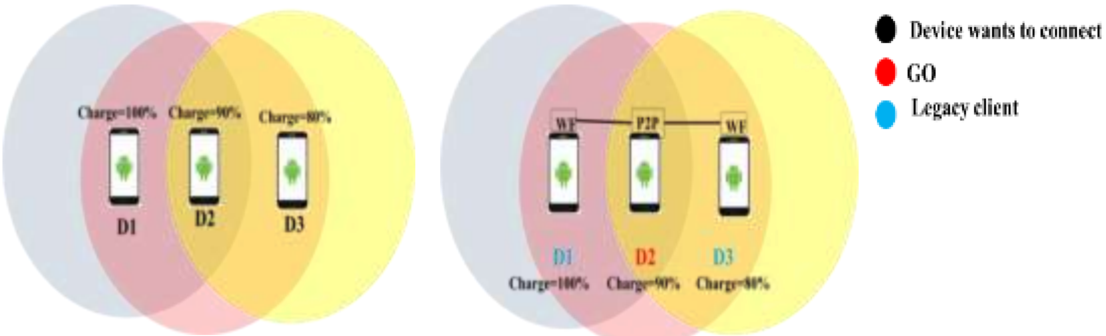


Figure 5: Announcing the Neighbors

5.1.3 Electing GOs and Their Members

As shown in Figure 6, at this stage, the role of the smartphone is determined based on the battery charge and the number of peers according to the following criteria:

Case 1: A smartphone that covers more peers declares itself as GO, and smartphones in its Wi-Fi range perform the **Connection Procedure** to connect as its legacy clients. As shown in Figure 6 (a), D2 covers both D1 and D3, while D1 and D3 cover just D2. Therefore, D2 becomes GO, while D1 and D3 connect as legacy clients to D2, as shown in Figure 6 (b).



(a) **(b)**

Figure 6: Smartphone that covers more peers becomes GO (a) D1, D2, and D3 want to connect (b) D2 becomes GO, D1 and D3 connect to D2 as legacy clients

Note: the smartphone becomes GO based on the Autonomous method of group formation, which is the fastest. The same applies to all other GOs which will be mentioned later.

Case 2: when all smartphones cover each other, the smartphone with a higher battery charge becomes GO. Other smartphones perform the Device Discovery procedure to discover the GO and then perform the **Connection Procedure**. As shown in Figure 7 (a) the smartphones, D1, D2, and D3, cover all others. The smartphone D1 becomes GO because it has a higher battery charge and its neighbors, D2 and D3, become its legacy clients, as shown in Figure 7 (b).

(a) **(b)**

Figure 7: Smartphone with a high battery charge becomes GO (a) D1, D2, and D3 want to connect (b) D1 becomes GO, D2 and D3 connect to D1 as legacy clients

Case 3: A smartphone that detects GO in its Wi-Fi range, connects to that GO as a legacy client by performing the **Connection Procedure**. As shown in Figure 8 (a), smartphone D4 detects GO, which is D1, in its Wi-Fi range. Therefore, D4 connects to D1 as a legacy client as shown in Figure 8 (b).

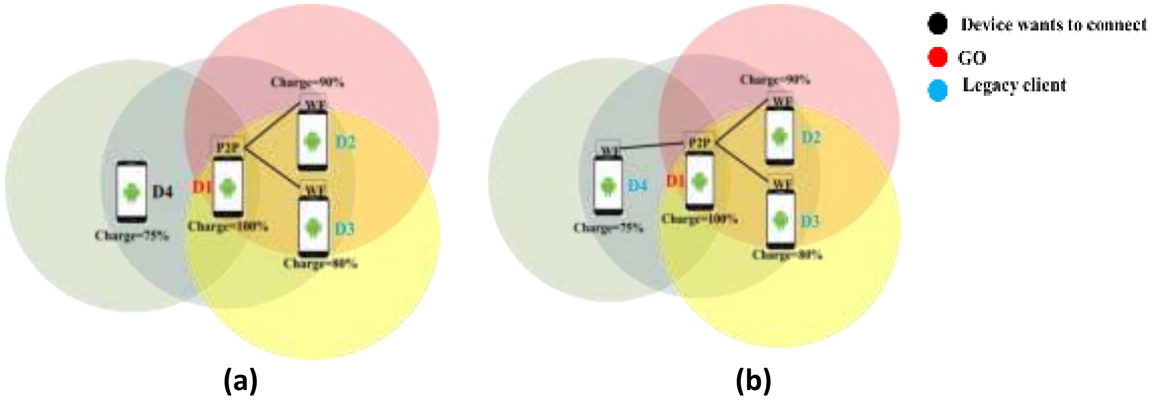


Figure 8: Smartphone connects to an existing GO (a) D4 wants to connect the network (b) D4 connects to D1 as a legacy client

Case 4: A smartphone that has no GO in its Wi-Fi range, but there is a legacy client, declares itself as GO and sends a P2P invitation to that legacy client. As a consequence, the legacy client becomes **Link Client**. As shown in Figure 9 (a), there is no GO in the Wi-Fi range of smartphone D4 but a legacy client, which is D3. As a result, D4 becomes GO while D3 becomes **Link Client**, as shown in Figure 9 (b).

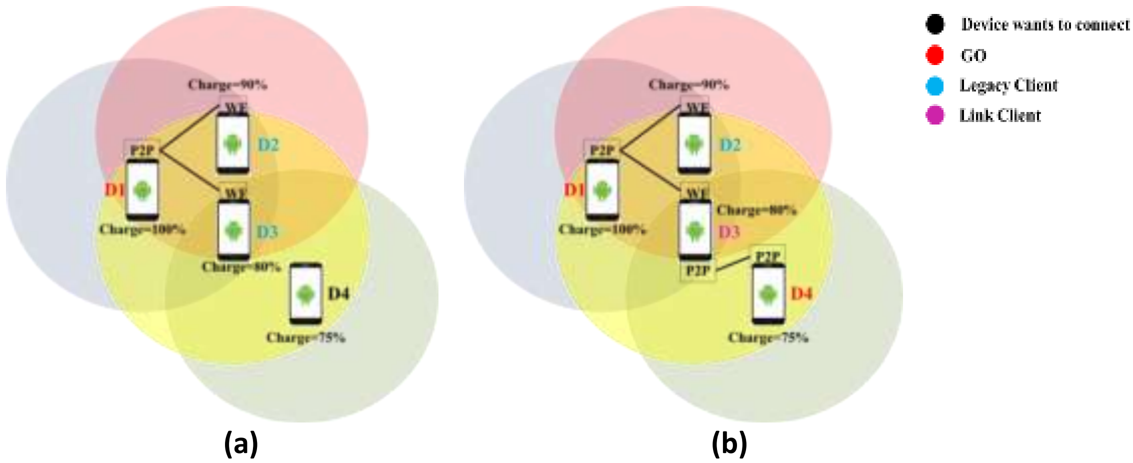
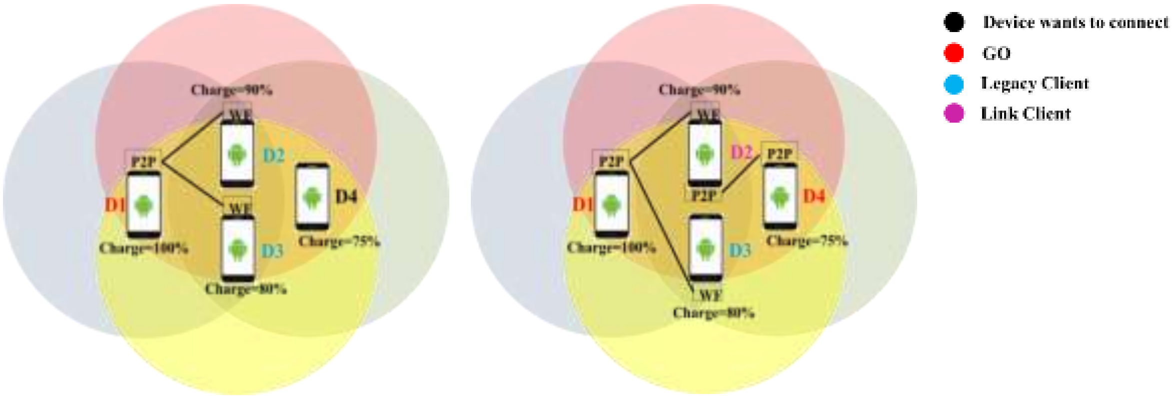


Figure 9: Smartphone joins through a legacy client (a) D4 wants to connect (b) D4 becomes GO, and D3 becomes **Link Clint**

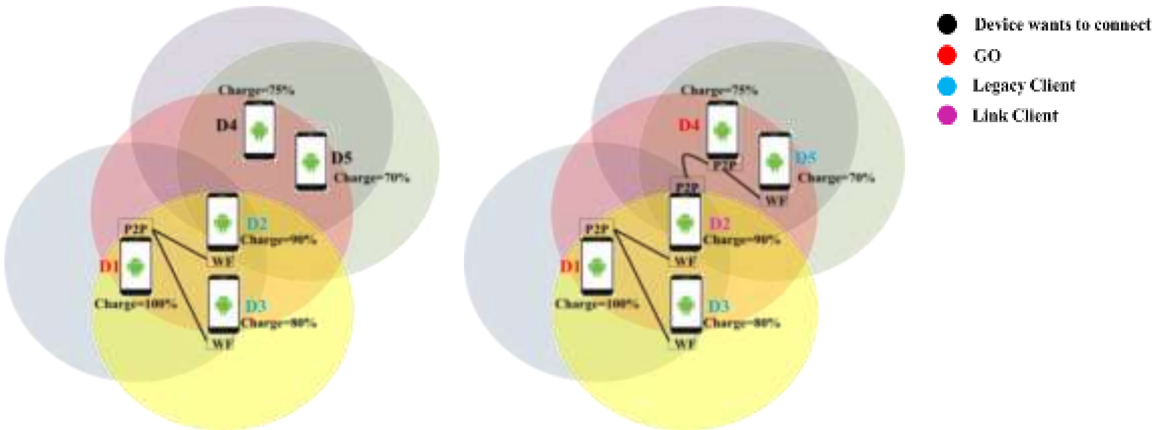
Case 5: A smartphone that has no GO in its Wi-Fi range, while there is more than one legacy client, declares itself as GO and sends a P2P invitation to the legacy client, which has a higher battery charge, to become a **Link Client**. As shown in Figure 10 (a), there is no GO in the Wi-Fi range of smartphone D4 but D2 and D3, which are legacy clients. Hence, as shown in Figure 10 (b), D4 becomes GO and D2, which is of higher battery charge than D3, becomes **Link Client.**



(a) **(b)**

Figure 10: Smartphone joins through a legacy client of higher battery charge (a) D4 wants to join (b) D4 becomes GO and D2 becomes **Link Client**

Case 6: Smartphones cover each other and there is no GO in their Wi-Fi range but a legacy client. The smartphone with a higher battery charge becomes GO and sends that legacy client a P2P invitation to be **Link Client**. While the other smartphones connect as legacy clients with that GO by performing the **Connection Procedure**. Figure 11 (a) shows that more than one smartphone, D4, and D5, cover each other and also cover a legacy client, which is D2. D4, which is of higher battery charge than D5, becomes GO. While D2 becomes **Link Client**, and D5 connects as legacy client to D4, as shown in Figure 11 (b).



(a) **(b)**

Figure 11: Smartphone with a high battery charge becomes GO and joins through a legacy client (a) D4 and D5 want to join (b) D4 becomes GO, D2 becomes **Link Client** and D5 connects to D4 as a legacy client

Case 7: Smartphones that cover each other and there is no GO in their Wi-Fi range but only legacy clients. The smartphone of higher battery charge becomes GO and sends to the legacy client of higher battery charge a P2P invitation to be **Link Client**. While other smartphones connect as legacy clients with that GO by performing the **Connection Procedure**. As shown in Figure 12 (a), more than one smartphone, D4 and D5, cover each other and also cover more than one legacy client, which are D2 and D3. D4, which is of higher battery charge than D5, becomes GO. While D2, which is of higher battery charge than D3, becomes **Link Client**, and D5 connects as legacy client to D4, as shown in Figure 12 (b).

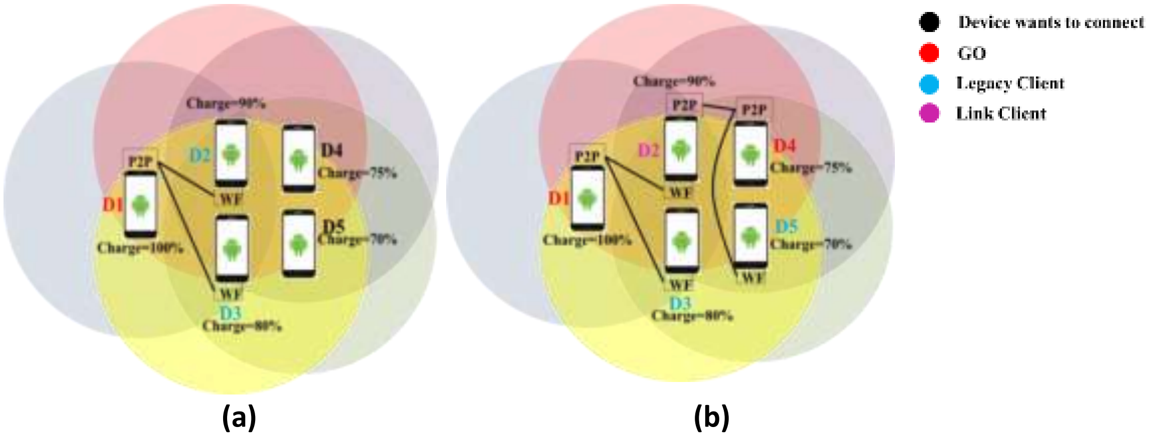


Figure 12: Smartphone with a high battery charge becomes GO and joins through a legacy client of higher battery charge (a) D4 and D5 want to join (b) D4 becomes GO, D2 becomes **Link Client** and D5 connects to D4 as a legacy client

Figure 13 shows the flowchart of the **Electing GOs and Their Members** stage.

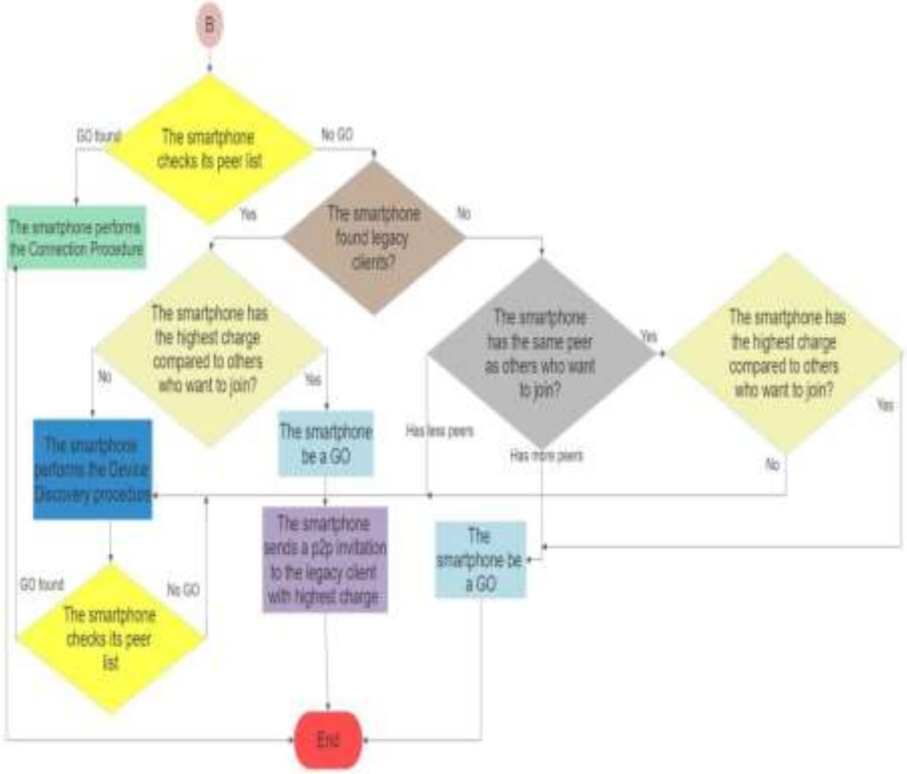


Figure 13: Electing GOs and Their Members

5.2 Preparing Network for Reliable Communication

Before building the routing table and starting message transfer, this part is responsible for overcoming the Wi-Fi interface priority problem, mentioned in section 3, and setting up the network for reliable data transfer:

1. In fact, to send and receive data between two smartphones within a group they must be aware of their IP addresses. Like any two smartphones in a network, the sender needs to know the IP address of the receiver to establish a TCP or UDP connection to send its message to that receiver. The IP address of GO is known to all smartphones, which is 192.168.49.1, so its clients can send data to it. Even though the GO is the one that gives its clients IP addresses,

the Android system does not provide a method for the developer to obtain the clients' IP addresses[11]. Therefore, clients must deliver their IP addresses to the GO. But the existence of the **Link Client**, which has two interfaces, yields the interface priority problem. To solve this issue, each legacy client delivers its name in a unicast packet to its GO through a TCP connection, while each **Link Client** multicasts its name in a multicast packet, as shown in Figure 14 (a). The GO then extracts the smartphone name from the content of the packet, and the IP address (which is the IP address of the packet), and maintains a list of IP addresses and smartphone names of its group's clients. In multicast, the smartphone can specify the interface (P2P or Wi-Fi interface) from which it is sending or receiving regardless of its Android version [11][17][18]. So the **Link Client**, whether it has priority for the P2P interface or the Wi-Fi interface, can communicate the IP address of each interface to its associated GO from that interface using multicast. The reliability of the multicast messages has been added in the application layer, which means the sender (**Link Client**) waits for an acknowledgment to make sure the multicast message is not lost.

2. The GO then provides group information (IP addresses and smartphone names, as well as the keyword "LC" with the information of the smartphone that is **Link Client** to be known for other clients) to its clients in unicast by establishing a TCP connection with each client including the **Link Client**, as shown in Figure 14 (b) the one side pointed black arrow. For example, the GO D2 established a TCP connection with its group **Link Client** D3. As a result, each legacy client will obtain its group's information, while each **Link Client** will obtain the information of its two groups. After that, each legacy client establishes a TCP connection with its group **Link Client**. As shown in Figure 14 (b) the one side pointed black arrow, for example, legacy client D1 established a TCP connection with its group **Link Client** D3.

3. The interface priority problem of the **Link Client** is overcome by keeping the TCP connections, established in step 2 above by the GO and legacy clients with the **Link Clients,** open through the lifetime of the network operation. Hence, each **Link Client** communicates with GO or legacy clients of either one of its side groups through reusing the aforementioned established TCP connections[11][17][18], illustrated in Figure 14 (b) by the one side pointed red arrow. **Link Clients** that exist in the same group communicate with each other through their common GO as a next-hop. Actually, many practical tests were conducted in this aspect. It is found that the previously established TCP connection, for example, GO D4 and the P2P interface of **Link Client** D3 shown in Figure 14 (b), is kept alive can be reused to transfer data from the D3 P2P interface to D4. The same process is applied when data transfer is between the rest smartphones GO D2 and D3 Wi-Fi interface.

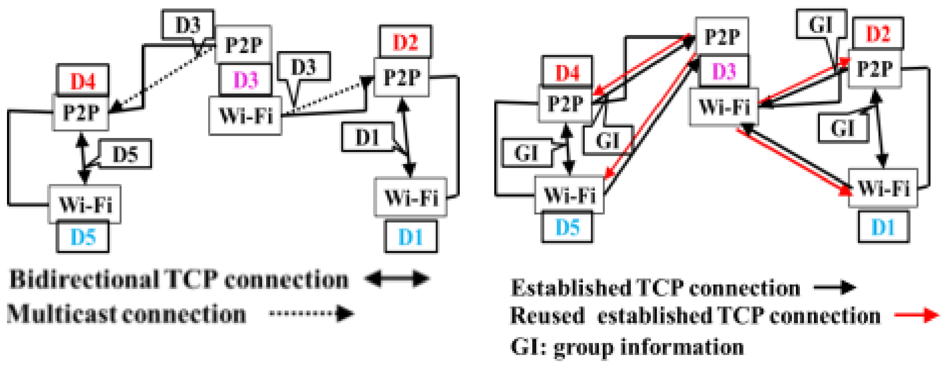


Figure 14: Preparing the network for reliable communication (a) clients send their names (b) GO distributes group information

5.3 Routing Table Construction

Each smartphone must be able to communicate with the rest of the network smartphones, whether they are in the same group or another group, so a routing table is built inside each smartphone.

1. Each GO starts building its routing table with its clients' information (The IP addresses and smartphone names), from the first step of the "preparing network for reliable communication" process, as shown in Figure 15 (a).
2. From the second step in the process of "preparing network for reliable communication", each legacy client obtained its group information. While the **Link Client** obtained the group information of its P2P connection and the group information of its legacy connection, as shown in Figure 15 (b).
3. The routing information is exchanged between groups through **Link Clients**. The **Link Clients** send the smartphone names list that received from the GO to the other GO and legacy clients on the other side using the TCP connection that was previously established, as shown in Figure 15 (c). GO and legacy clients update their routing table by adding the smartphones existing in other groups.
4. When there is more than one **Link Client** in one group, the GO of that group is responsible to redirect the smartphones names list, received from one of its **Link Clients,** to its other **Link Clients** because there is no TCP connection between two **Link Clients** in the group to which they belong.
5. Routing information continues to be exchanged between groups through **Link Clients**.

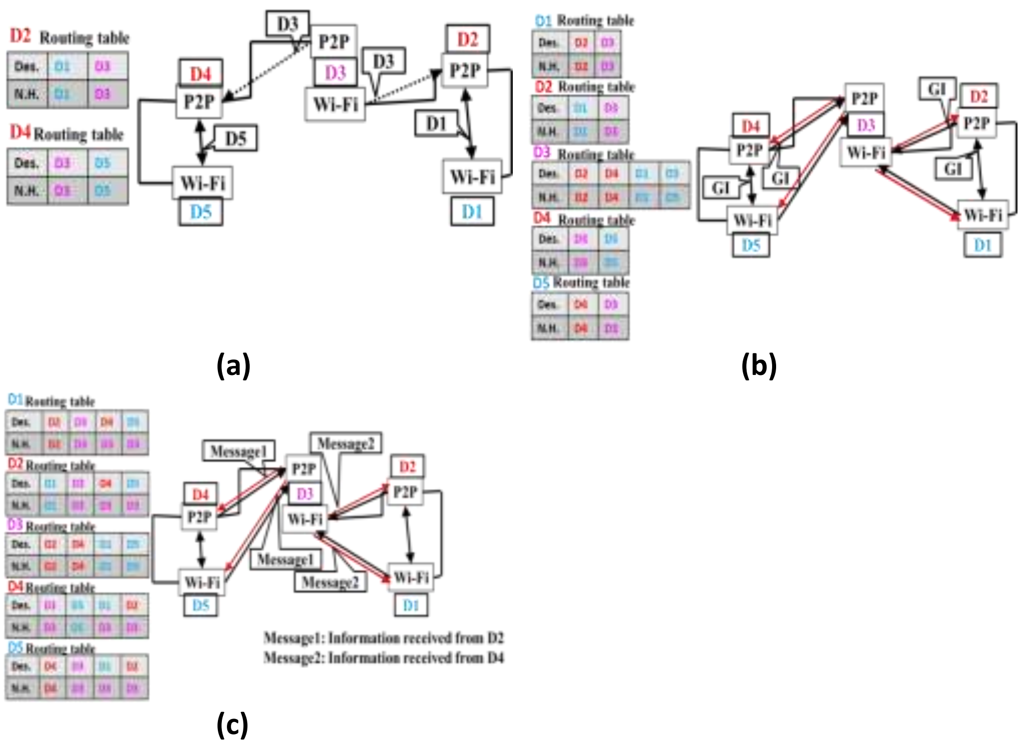


Figure 15: Routing table construction process (a) clients send their names (b) GO distributes group information (c) **Link Client** sends the smartphone names list to its other group

Figure 16 shows the message format which contains smartphones names that are used to send messages. The message is sent by following the routing table. For example, by following the routing table in Figure 15 (c) when smartphone D1 wants to send a message to D2 or D3, the message is sent directly by establishing a TCP connection using the IP address of D2 or D3 because they are in the same group. While for sending a message to D4 or D5, that message is first sent to D3, and then D3 redirects that message to D4 or D5 using the previously established TCP connection by D4 and D5.

Destination smartphone name	Source smartphone name	Payload

Figure 16: Message format

6. Proposed Network Properties

This work focused on achieving the following properties:

- Eliminate the problem of IP address conflict, mentioned in section 3, by applying the “network topology formation mechanism”, provided in section 3, which prevents a GO from connecting another GO directly.
- Addressing the interface priority problem mentioned in section 3, which causes a misdirection transfer of the TCP connection. This problem is solved by applying the “preparing network for reliable communication” provided in section 4, which sets up the network to depend only on unicast transmission.
- The GOs are distributed in a way that no GO, in the network, is placed within the range of any other GO. Hence, combining smartphones in the same range into one group, minimizing the number of the network groups. Consequently, the number of hops in the network is decreased, which in turn increases the network throughput. For example, GOs, D1, and D4 in Figures 7-10 are not in the Wi-Fi range of each other.
- Due to the above-mentioned distribution of the GOs in the network, interference between groups, that affects the performance of the network, is reduced (more interference means greater delay due to packet loss[11] [22]).
- The proposed network formation is conducted in such a way that there are always GO smartphones at the edge of the network, especially when a large number of smartphones join the network. This formation mechanism is flexible and facilitates expanding the network for the new smartphone to quickly join the network. As in the case of GO, D4, in Figures 7 and 8 where D4 is situated at the edge of the network and that facilitates expanding the network from its edges smoothly. So that the new arrival smartphones can join the network easily from the edges.
- There are no previous settings to be done or a need to root the Android smartphone.

7. Experiments and Results

This work was developed based on Android studio 4.1.1 using Java programming language. The smartphones that were used in the implementation were HTC One with Android version 4.4.2, Samsung Galaxy Note 3 with Android version 5.0, Samsung Galaxy S4 with Android version 5.0.1, LG G2 with Android version 5.0.2, Xperia Z1 (Sony) with Android version 5.1.1. All the smartphones that were used support Wi-Fi Direct; all of them have an Android version above 4.0. The experiment test was performed in the aspects of measuring:- 1- time of Device Discovery procedure 2- throughput of GO to a client data transfer 3- throughput of a client to GO data transfer 4- throughput of a client to client data transfer 5- the effect of distance on delay 6- throughput of inter-group data transfer. Only the reliable data transfer protocol TCP was relied upon to transmit data. In the intra-group, files of images and videos of different sizes (2 MB, 10 MB, 30 MB, 60 MB, and 90 MB) were sent at a distance up to 1 meter, to determine what might affect the throughput (average throughput). While in the inter-group, a file of size 30 MB was used in the data transfer test. As shown in Figure 14, a network consisting of two groups was formed based on the network topology formation mechanism mentioned in section 4. The first group consists of GO, Sony, and two clients, HTC and S4. The second group consists of GO Note 3 and two clients HTC and S4. In the beginning, the application was running on the first three smartphones, which are HTC, Sony, and S4, and they were all in the same range. At the end of the third stage of the network topology formation mechanism, Sony became the GO because it was with a higher battery charge than HTC and S4. After that, HTC and S4 connected to Sony according to the implementation of the **Connection Procedure**. After the formation of the first group, Note 3 was placed in the domain of S4, which is a legacy client, so Note 3 announced itself as a GO and sent a P2P invitation to S4 (S4 became a **Link Client**). Then G2 joined the network by connecting to the GO, Note 3, by performing the **Connection Procedure**.

Note: the measured throughput presented in subsections 7.2 to 7.6 is based on the network topology of Figure 17.

Figure 17: Two-group network

7.1 Time of Device Discovery procedure

Table 2 shows the results of the time express in which second each smartphone discovers one to four smartphones in the Device Discovery procedure. These results were measured after activating the Device Discovery procedure in the four smartphones in advance to be detected by the intended smartphone, which cannot be the case in reality since there must be a possibility that the discovery procedure will run asynchronously in practical cases. So enough time, 6 seconds, is devoted to the Device Discovery procedure at each stage of network formation so that the smartphones can discover each other.

Table 2: Time taken to discover smartphones

	Discovered smartphones			
Discovering smartphone	**1 Smartphone**	**2 Smartphones**	**3 Smartphones**	**4 Smartphones**
HTC One	1st sec	1st sec	1st sec	1st sec
Samsung Galaxy Note 3	2nd sec	2nd sec	2nd sec	2nd sec
Samsung Galaxy S4	2nd sec	2nd sec	2nd sec	2nd sec
LG G2	1st sec	1st sec	1st sec	2nd sec
Xperia Z1	3rd sec	3rd sec	3rd sec	3rd sec

7.2 Throughput of GO to a client data transfer

As shown in Figure 18 where the transfer is in the direction from the GO to the Client (whether it was connected through a P2P interface or Wi-Fi interface), a noticeable increase in throughput can be realized with the increase in the size of the transmitted file. The throughput is increased from 17 Mbps to 62 Mbps. The variation of the throughput is affected by the specifications of the smartphone that plays the role of the GO or client.

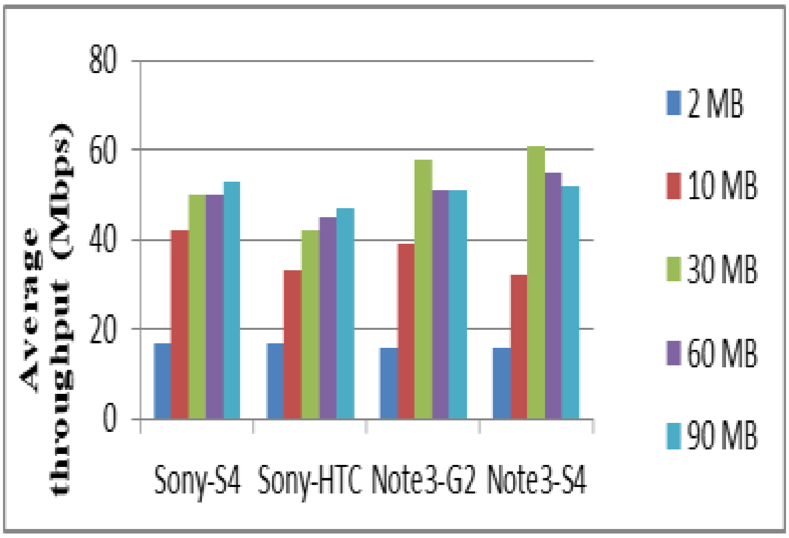


Figure 18: GO to Client throughput

7.3 Throughput of a client to GO data transfer

The maximum throughput in the direction from the client to the GO reached 72 Mbps, as shown in Figure 19. The increase of throughput from client to GO compared to the throughput from GO to a client is due to the specifications of the smartphone that acts as a GO or client.

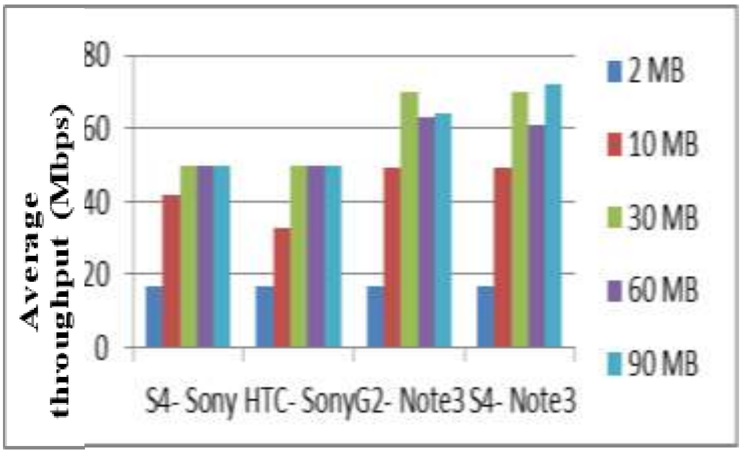


Figure 19: Client to GO throughput

7.4 Throughput of a client to client data transfer

The last possible transfer is the transfer from client to client. As shown in Figure 20 the maximum throughput is reached up to 24 Mbps, which is much less compared to if the transfer was direct between the GO and the client. Because although the client can send data to another client in the same group in one hop at the IP layer (client-client), the data is routed through their GO at the MAC layer in two hops (client-GO-client) and not one hop as in the previous two cases.

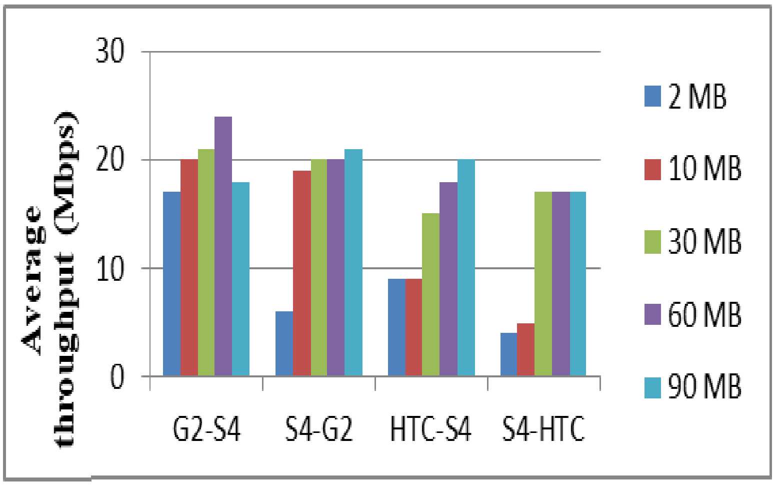


Figure 20: Client to Client throughput

7.5 Effect of distance on delay

The time taken to receive a 10 MB file was measured at different distances to see the effect of the distance as shown in Figure 18. There is an effect of distance where the time taken to receive the file increases with the increase of the distance. Because with the increase in distance, the possibility of data loss increases and since the transmission is through TCP, the lost data will be retransmitted. As well as this effect varies from one smartphone to another, so the time taken depends on the specifications of the receiving smartphone as well. Figure 21 shows the delay when 4 meters distance is in a line of sight. While greater than 4 meters distance is in no line of sight.

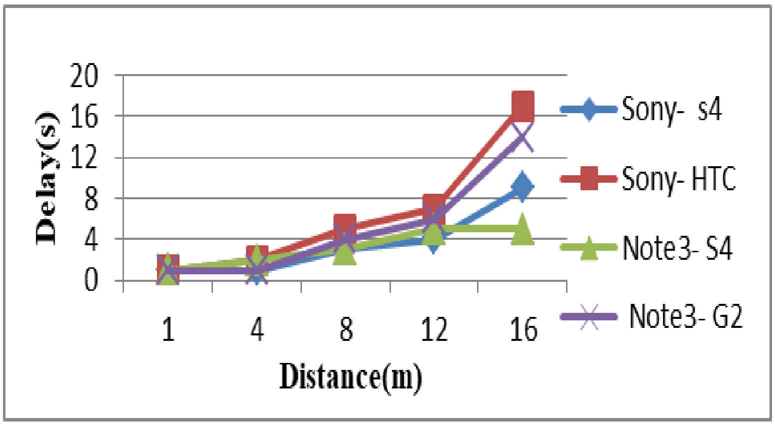


Figure 21: GO to Client delay

7.6 Inter-group throughput

Table 3 shows the inter-group throughput via the Link Client (S4). The highest throughput is obtained, which is 25 Mbps when the transmission is between Sony and Note 3 because the transmission is in the fewest number of hops. Two hops at both the IP and MAC layer (GO-Client-GO). The lowest throughput, which is 11 Mbps, is when the transmission is between HTC and G2 because the transmission is in the largest number of hops at the MAC layer. Two hops at the IP layer (client-client-client) and four hops at the MAC layer (client-GO-client-GO-client).

Table 3: Inter-group throughput

Between	Throughput (Mbps)
HTC One - LG G2	11
HTC One - Samsung Galaxy Note 3	16
Sony – LG G2	15
Sony - Samsung Galaxy Note 3	25

Intuitively, a smartphone in the network may receive/send from/to more than one source/destination at the same time, especially the Link Client here because it is the link between groups. The throughput was measured to receive/send the same file, which is 30 MB, by the Link Client (S4) from/to its two sides at the same time:-

- Received from the two GOs on both sides. The throughput from the Sony side is 25 Mbps. The throughput from the Note 3 side is 41 Mbps.
- Receive from HTC and G2. The throughput from the HTC side is 11 Mbps, and the throughput from the G2 side is 15 Mbps.
- Sent to the GOs on both sides. The throughput on the Sony side was 27 Mbps, and on the Note 3 side was 13 Mbps.
- Sent to HTC and G2. The throughput on the HTC side is 17 Mbps, and the throughput on the G2 side is 8 Mbps.

When sending and receiving from and to more than one destination, the throughput decreases due to working on the principle of time-sharing. As mentioned in Section 2, both the P2P interface and Wi-Fi interface are logically separated, but physically it is the same NIC. In addition to the factors mentioned, such as file size, distance, and smartphone specifications, the environment has an impact, as even light can affect the wireless signal.

7.6 Comparing the Results with Content-centric Routing in Wi-Fi Direct Multi-group Networks[13]

As shown in Figure 22, when GO1 and GO2 want to communicate, they must send the required message to Client 1, and then Client 1 sends it to GO1/GO2, although GO2 is a client of GO1, who can communicate with it in one hop. But in order to address the problem of IP address conflict, the communication was made through the Relay node (Client 1). So, two hops are required to transfer a message between GO and the connector between the groups (legacy GO). While in this work there is one hop required to transfer a message between GO and the connector between the groups (Link Client). Also, the transmission from the legacy GO to its clients, is done using broadcast transmissions in which the data rate is low in case of the increased loss of packets [13]. While in this work, only unicast transmissions are used to send data.

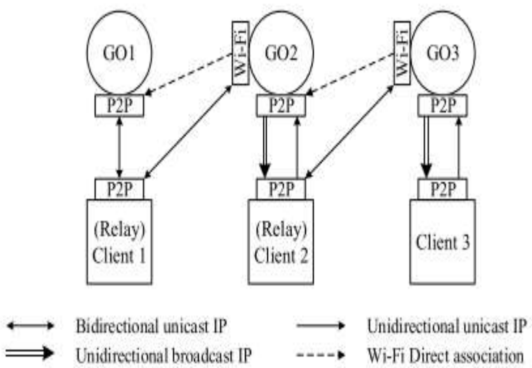


Figure 22: Example network with three groups in reference [13]

8. Conclusions

In this paper, a mechanism is proposed that addresses the Wi-Fi multi-group communication problems to construct an efficient Wi-Fi Direct ad hoc network. The proposed mechanism prevents IP address conflict problem from appearing in the network and addresses the interface priority problem to have reliable data communication depending on the TCP protocol, without resorting to the UDP protocol. Also, the proposed mechanism supports network expansion due to placing the GOs far away from each other. In other words, they are not in the Wi-Fi range of each other. As a consequence, most of the network edge smartphones will be GOs which in turn facilitates extending and joining the network smoothly. The network has been implemented on real, non-rooted Android smartphones. In future work, the mechanism should be developed to consider the mobility of smartphones in the network.

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