Wi-Fi Direct Multi-Group Communication: Connect different Wi-Fi Direct groups with Access Point

Thesis

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Abstract

Wi-Fi Direct is a new technology which establishes Wi-Fi peer to peer (P2P) connection between devices at the network layer. It is very similar to Bluetooth which could connect different devices without Wi-Fi or LTE network, but it is faster than Bluetooth. Systems above Android 4.0 provide the Wi-Fi Direct Application Programmer Interface (API) for Android devices to communicate in the same Wi-Fi Direct group. But currently Multi-Group communication (communication between the groups) can not be implemented directly by using Wi-Fi Direct API on Android system. This paper proposes a new topology for Wi-Fi Direct Multi-Group communication, and a new device Access Point is introduced as an intermediary to connect different Wi-Fi Direct Groups. If a Client (Client1) in one group wants to communicate with another Client (Client2) in another group, Client1 will first send the information to its Group Owner (GO1), and then GO1 will send the information to the Access Point. The Access Point can determine which Group Owner the Client2 connects with through the routing table information, and it will send the packets to the target Group owner (GO2). Finally, GO2 will send the packets to destination Client2, which finishes a complete Wi-Fi Direct Multi-Group communication.
Acknowledgments

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Chapter 1. Introduction

Wireless Fidelity (Wi-Fi) is a wireless interconnection technology. It converts wired network to wireless network through wireless transfer protocol and has a very high transmission speed (Wi-Fi 802.11n can reach up to 300Mbps theoretically). Traditionally, the Wi-Fi connection refers to a link from source point to the destination point, which is called the infrastructure connection. This infrastructure connection is a centrally controlled mode, and there is an Access Point as a data exchange hub for each node. This kind of infrastructure connection has been subjected to the limited numbers of Access Points, and for each regular Access Point, there is also a limitation for client’s numbers and area coverage distance.

Wi-Fi Direct is a new technology which establishes a Wi-Fi peer to peer (P2P) group at the network layer. It is very similar to Bluetooth which could connect different devices without Wi-Fi or LTE network. The comparison between Bluetooth and Wi-Fi Direct can be found at Table 1.
<table>
<thead>
<tr>
<th></th>
<th>Bluetooth 5.0</th>
<th>Wi-Fi Direct</th>
</tr>
</thead>
<tbody>
<tr>
<td>Speeds</td>
<td>1-3 Mbit/s</td>
<td>&gt;54Mbits/s</td>
</tr>
<tr>
<td>Range</td>
<td>100m</td>
<td>46-100m</td>
</tr>
<tr>
<td>Energy consumption</td>
<td>0.01–1.0 W</td>
<td>2 to 20 watts</td>
</tr>
<tr>
<td>Frequency</td>
<td>2.4Ghz</td>
<td>2.4 or 5.0Ghz</td>
</tr>
</tbody>
</table>

Table 1 Comparison between Bluetooth and Wi-Fi Direct

In Wi-Fi Direct group, it determines a node as the Group Owner based on some given rules, and the Group Owner is equivalent to the traditional Access Point in the traditional Wi-Fi connection infrastructure. Except for the Group Owner, all other remaining nodes in the Wi-Fi Direct group are regarded as the Clients. The Clients join the Wi-Fi Direct group by connecting with the Group Owner. In the meantime, the Group Owner provides DHCP services and MAC information for all clients. By using the Wi-Fi Direct technology, devices can connect with each other at any location without Wi-Fi or LTE network.

1.1 Wi-Fi Direct Application Programming Interfaces (API)

Currently, Wi-Fi Direct Application Programming Interfaces (API) are mainly available in the following three platforms:
1.1.1 Android platform

Systems above Android 4.0 provide Wi-Fi Direct API for developing Wi-Fi Direct related functions. The Wi-Fi Direct API can initialize the Wi-Fi Direct function, search the nearby available Wi-Fi Direct devices, connect or disconnects with other devices nearby, as well as get the timely feedback of the connection status on Android platform.

1.1.2 IOS platform

Airdrop can achieve an end to end connection between two IOS devices. The Airdrop uses Bluetooth for searching nearby devices, and uses Wi-Fi Direct for data transmission. Programmers could use Software Development Kit (SDK) above iOS to integrate the corresponding Wi-Fi Direct functions to the IOS applications.

1.1.3 Windows platform

Systems with Windows8 or above support the usage of Wi-Fi Direct functions.

1.2 Wi-Fi Direct API Multi-Group Communication Issues

The majority of existing Wi-Fi Direct related research focuses on Android platform, and the Android Wi-Fi Direct API makes it possible for devices to communicate within the Wi-Fi Direct group easily. However, there is a restriction on the number of Clients in a single Wi-Fi Direct Group. Most Group Owner only supports 6-10 Clients at the same time. Since the function of Group Owner is equivalent to the function of Access Point in Wi-Fi environment, the group members must be in the vicinity of Group Owner. Therefore, the transmission distance is also limited to a single Wi-Fi Direct group.
However, if different Wi-Fi Direct groups can communicate with each other, it is equivalent to increase the carrying capacity and the transmission distance in Wi-Fi Direct environment, because different Wi-Fi Direct groups can be regarded as a single group. But simply using the Wi-Fi Direct API in Android system, it is difficult to communicate among multiple Wi-Fi Direct groups, because of the following reasons:

1.2.1 The Group Owners of different groups can not communicate directly

Because the Internet Protocol (IP) addresses of different Group Owners in Wi-Fi Direct are the same: 192.168.49.1. This address is written to the source code of Android system, which means that it can not be changed. As a result, when one Group Owner wants to send data to another Group Owner, the data will be sent directly to the Group Owner itself.

1.2.2 A Client can not connect with two different Wi-Fi Direct groups at the same time

There will be no response if a Client wants to connect with a Group Owner when it has already connected with another Group Owner. Thus, a Client can not connect with two groups at the same time. Although the Wi-Fi Direct 802.1 protocol describes it as possible, it is not plausible in Android system, and it cannot be implemented in Android system.

1.2.3 The Group Owner of one group can not be the Client of another group

When the Group Owner of one group wants to connect with another group, it will automatically disconnect with the current Wi-Fi Direct group. When a Client in one group wants to establish a Wi-Fi P2P connection with another group at the same time, it will automatically disconnect with the current group and join another group as a Client.
1.3 Network Performance Factors

Typically, six important performance factors are used in evaluating network performance. [7-14]

1.3.1 Packets Loss Rate (Efficiency): it refers to the number of packets that are lost during the transmission, which equals to the number of packets the source device sends minus the number of packets the destination device receives. Packets loss reflects the network reliability, and smaller packets loss rate reflects better network performance.

1.3.2 Data Transmission Delay: it stands for the time it takes for packets to send from source device to the destination device, and usually in milliseconds. The delay reflects the speed of the network, and less delay reflects better network performance.

1.3.3 Network Bandwidth (throughput): it is regarded as the amount of data that is transferred per unit of time, usually in bits per second (denoted as bps). Bandwidth reflects the transmission capacity of the network, and larger bandwidth reflects better network performance.

1.3.4 Power Consuming: it refers to the electrical energy per unit time, supplied to operate something, such as a home appliance. Wi-Fi Direct is said to extend battery life by anywhere from 15 to 40 percent depending on factors such as file size, Wi-Fi protocol, range and device type.

1.3.5 Network Interference: Signals operating at similar frequencies can cause interference with each other and have a negative effect on the performance of the network.
1.3.6 **Network Channel:** Wireless Network Channel has five distinct frequency ranges: 2.4 GHz, 3.6 GHz, 4.9 GHz, 5 GHz, and 5.9 GHz bands\(^{14}\). All Wi-Fi Direct devices operate in the 2.4 GHz frequency band\(^{15}\).

The results in the present document mainly focus on the first three factors for performance testing, packets loss rate (efficiency), data transmission delay and network bandwidth (throughput).

1.4 **Work Outline**

There are some existing Wi-Fi Multi-Group communication solutions without rooting in Android devices. It is found that Casetti ’s\(^{16}\) work best meets this expectation and has very good network performance. In this document, after doing some basic performance test about Wi-Fi Direct, an optimized topology is put forward based on the principles of Casetti’s solution. The feasibility of the optimized topology is evaluated firstly. Then the performance of the optimized topology is evaluated, and the performance test results are compared with those of Casetti’s work. Lastly, some other existing Wi-Fi Multi-Group solutions are introduced and compared with this optimized topology.
Chapter 2. Wi-Fi Direct Performance Test

Wi-Fi Direct is a point-to-point connection technology, and it can establish TCP/IP link directly between two devices. Wi-Fi Direct is developed from Wi-Fi and it supports typical Wi-Fi speed (up to 250Mbps), so that its transmission speed will be faster than Bluetooth speed (up to 25Mbps). However, when the transmission distance is increased or interference by obstacles is presented, the transmission gets delayed, and the packets loss rate will increase significantly.

In order to have a more in-depth understanding of Wi-Fi Direct technology on Android platform, it is necessary to test the performance of Wi-Fi Direct from a different perspective.

2.1 Testing Principle

2.1.1 Packet loss and Delay testing principle

Because Android is an operating system based on the Linux kernel, the Ping Command was used to test the packet loss rate and delay of the network transmission in the performance testing.

The working principle of the Ping Command is shown in Figure 1. “Local” sends the packet to “Remote”. After Remote receives the packet, it sends the original packet back to the Local. The packet contains the serial number and timestamp information, and the
serial number is used to determine whether the packet is lost in the process. The timestamp is used to calculate the back and forth delay (blue part in Figure 1), and the delay equals to the receive time minus the packet’s timestamp.

![Figure 1. Ping Command Principle](image)

2.1.2 Network Bandwidth (Throughput) testing principle

Network Command Iperf was used to test maximum network bandwidth performance. When using the Iperf for testing, a host must be set as a client, and another host must be set as the server.

The working principle of the Iperf Command is shown in Figure 2. It can be seen from the Figure 2 that the Iperf Command sends a one-way packet. At the receiver side, it will not send the packet back to the sender as the PING Command. Therefore, it can not be used for measuring the delay.
After establishing a three-way handshake connection between the client and the server, the network bandwidth at the client side is calculated by the total amount of data it sends divides the total time it spends to send the data. The network bandwidth at the server side is calculated by the total amount of data it receives divides the total time it spends to receive the data.

![Diagram of network handshake](image)

Figure 2. Iperf Command Principle.\textsuperscript{20}

2.2 Testing Setup

Wi-Fi Direct performance is tested on Android platform in real scenery. Fix the location of two Clients in a Wi-Fi Direct group. By moving the location of the Group Owner device to change the distance between the Group Owner and two Clients. The performance test topology is shown in Figure 3. Three Android devices were used to compose a single Wi-Fi Direct group for performance testing. The GO is a LG device, and
two Clients are a HTC device and a SAMSUNG device. For network bandwidth, the data traffic and bandwidth were tested on two Clients. For transmission delay, the minimal delay (Min), average delay (Avg), maximum (Max) delay, modified allan deviation (Mdev variance) delay were tested on two Clients. For packet loss rate, it was tested on two Clients. By changing the distance between the GO and the Clients,

Figure 3 Wi-Fi Direct performance test topology.
2.3 Testing Results

Five different Cases were designed and tested. Below are the corresponding testing results.

2.3.1 Case 1: The distance between GO and Clients is 0 meter.

Table 2 shows the results for Case 1.

<table>
<thead>
<tr>
<th>Client Name</th>
<th>GO Name: LG</th>
<th>Network Bandwidth</th>
<th>Transmission Delay</th>
<th>Packet loss rate (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>HTC</td>
<td>33.2</td>
<td>27.9</td>
<td>1.8</td>
<td>25.0</td>
</tr>
<tr>
<td>SAMSUNG</td>
<td>23.0</td>
<td>19.2</td>
<td>2.3</td>
<td>19.0</td>
</tr>
</tbody>
</table>

Table 2. Wi-Fi Direct Performance Test Result (0 meter between GO and Clients)

2.3.2 Case 2: The distance between GO and Clients is 12.5 meters.

Table 3 shows the results for Case 2.

<table>
<thead>
<tr>
<th>Client Name</th>
<th>GO Name: LG</th>
<th>Network Bandwidth</th>
<th>Transmission Delay</th>
<th>Packet loss rate (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>HTC</td>
<td>24.9</td>
<td>20.9</td>
<td>2.1</td>
<td>24.4</td>
</tr>
<tr>
<td>SAMSUNG</td>
<td>20.8</td>
<td>17.4</td>
<td>15.4</td>
<td>43.6</td>
</tr>
</tbody>
</table>

Table 3. Wi-Fi Direct Performance Test Result (12.5 meter between GO and Clients)
2.3.3 **Case 3**: The distance between GO and Clients is 25 meters.

Table 4 shows the results for Case 3.

<table>
<thead>
<tr>
<th>Client Name</th>
<th>GO Name: LG</th>
<th>Network Bandwidth</th>
<th>Transmission Delay</th>
<th>Packet loss rate (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Data Traffic (Mbyte)</td>
<td>Bandwidth (Mbits/sec)</td>
<td>Min (ms)</td>
</tr>
<tr>
<td>HTC</td>
<td>10.23</td>
<td>7.99</td>
<td>30.1</td>
<td>45.2</td>
</tr>
<tr>
<td>SAMSUNG</td>
<td>7.9</td>
<td>5.8</td>
<td>5.4</td>
<td>33.5</td>
</tr>
</tbody>
</table>

Table 4. Wi-Fi Direct Performance Test Result (25 meters between GO and Clients)

2.3.4 **Case 4**: The distance between GO and Clients is 50 meters.

Table 5 shows the results for Case 4.

<table>
<thead>
<tr>
<th>Client Name</th>
<th>GO Name: LG</th>
<th>Network Bandwidth</th>
<th>Transmission Delay</th>
<th>Packet loss rate (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Data Traffic (Mbyte)</td>
<td>Bandwidth (Mbits/sec)</td>
<td>Min (ms)</td>
</tr>
<tr>
<td>HTC</td>
<td>2.05</td>
<td>1.50</td>
<td>7.1</td>
<td>45.7</td>
</tr>
<tr>
<td>SAMSUNG</td>
<td>4.32</td>
<td>3.88</td>
<td>5.2</td>
<td>39.2</td>
</tr>
</tbody>
</table>

Table 5. Wi-Fi Direct Performance Test Result (50 meters between GO and Clients)
2.3.5 Case 5: The distance between GO and Clients is 80 meters

Table 6 shows the results for Case 5.

<table>
<thead>
<tr>
<th>Client Name</th>
<th>GO Name: LG</th>
<th>Network Bandwidth</th>
<th>Transmission Delay</th>
<th>Packet loss rate (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>HTC</td>
<td>1.53</td>
<td>1.22</td>
<td>5.1</td>
<td>53.4</td>
</tr>
<tr>
<td>SAMSUNG</td>
<td>1.90</td>
<td>1.53</td>
<td>37.3</td>
<td>74.6</td>
</tr>
</tbody>
</table>

Table 6. Wi-Fi Direct Performance Test Result (80 meters between GO and Clients)

2.4 Test Results Analysis

2.4.1 After observing Case 1 (as shown in Table 2) and Case 2 (as shown in Table 3), it is found that Wi-Fi Direct signal strength is almost the same within a certain range. There is no significant change on throughput, packet loss rate and delay when the distance is smaller than 12.5 meters between the Group Owner and the Clients. In this case, GO and Clients can communicate with each other with a small packet loss rate, which is less than 1 percent.

2.4.2 After observing Case 2 to Case 4 (as shown in Table 5), it is found that within a certain range, the packet loss rate does not change significantly with the incensement of distance, and the bandwidth of the GO and the Clients will gradually decrease as the distance increases, and the average delay and maximum delay will gradually increase as the distance increases.

2.4.3 After observing Case 5 (as shown in Table 6), it is found that the packet loss rate for the two Clients is 5 percent and 18 percent, respectively. This is very high compared to
Cases 1 and 2, and can not guarantee a stable data transmission in a wireless network\textsuperscript{21}. And the maximum delay is nearly 1 second in the packets transmission. Therefore, there is no need to increase the distance to test the Wi-Fi Direct performance, since the performance is already really bad at this distance range. At this distance, the connection between the GO and the Clients is very fragile, and it is easy to be interrupted or lost.

2.5 Testing Conclusion

After analyzing the above Wi-Fi Direct performance test, it can be concluded that Wi-Fi Direct performs well at distances of 50 meters or lower, and does not perform well at distances of 80 meters or larger. When the distance between the Group Owner and the Clients is more than 80 meters, the Packet Loss Rate and Transmission Delay are already unacceptably high. Therefore, there is a need for Multi-Group communication in Wi-Fi Direct. If different Wi-Fi Direct groups can communicate with each other, it could significantly enlarge the Wi-Fi Direct communication distance. As a conclusion, Multi-Group communication is suitable for Wi-Fi Direct to cover a larger area.
Chapter 3. Analysis of Topology in Casetti’s Work

When the solution comes to Casetti’s work, it implements Wi-Fi Direct Multi-Group communication without rooting the Android devices. Android devices have a Wi-Fi interface for Wi-Fi connection, and there is also a P2P interface in Android devices above 4.9 system for Wi-Fi Direct connection. The Group Owner in Wi-Fi Direct group is equivalent to the Access Point in Wi-Fi group, and it can generate a SSID password. Android devices can use P2P interface to connect with the existing Wi-Fi Direct group as a P2P client (no password needed). And Android devices can also use the Wi-Fi interface to connect with the existing Wi-Fi Direct group as a Legacy Client by using the SSID generated by the Group Owner.

In order to achieve Wi-Fi Direct Multi-Group communication, the GO(GO2) in one Wi-Fi Direct group uses the Wi-Fi interface to connect with another GO (GO1) in another Wi-Fi Direct group. As a result, the GO2 is a Legacy Client of GO1. But in this situation, the GOs which belongs to different Wi-Fi Direct groups still have the same IP address. And because of the conflict of IP address, the GOs still can not communicate with each other directly. But the GO2 which is the Legacy Client of another Wi-Fi Direct group, can communicate with the Client (Client1) in that Wi-Fi Direct group. As a result, in Casetti’s work it chooses a Client in each group as the relay to communicate with the GO which is a Legacy Client of this group. In this way, it can achieve a Wi-Fi Direct Multi-Group communication.
3.1 Connection Procedure

The P2P IP address of the GO is always 192.168.49.1/24. And in the same Wi-Fi Direct group, the Legacy Clients and the P2P Clients will be assigned IP addresses with same network segment. In a typical topology connecting four devices, as shown in Figure 4, GO1 connects with Client1 through P2P interface, and GO2 connects with Client2 through P2P interface. But GO2 connects with GO1 through Wi-Fi interface.

![Diagram of Multi-group physical topology with four devices](image)

Figure 4. Multi-group physical topology with four devices on Casetti’s paper.

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3.2 Data Flow Analysis

When the source is Client 1 and the destination is Client 2, two Clients communicate with each other cross the group. Firstly, Client1 sends unicast packet to GO2 (In IP layer the data is from Client1 to GO2. In MAC layer the data is first from Client1 to GO1, and then from GO1 to GO2). Then GO2 sends broadcast packets to Client2 (In IP layer the data is from GO2 to Client2. In MAC layer the data is from GO2 to Client2).

When the source is Client 2 and the destination is Client1, two clients communicate cross the group. Firstly, Client2 sends unicast packet to GO2 (In IP layer the data is from Client2 to GO2. In MAC layer the data is from Client2 to GO2). Then GO2 sends broadcast packets to Client1 (In IP layer the data is from GO2 to Client1. In MAC layer the data is first from GO2 to GO1, and then from GO1 to Client1).

3.3 Software Analysis

A MGC software\textsuperscript{24} is developed in the Casetti’s work. There is an area on the MGC software User Interface(UI) that user could discover nearby devices and connect with them. By using the group button, user can get the current group information including SSID password. And with this password other devices can manually connect with this GO through its Wi-Fi interface as the Legacy Clients of this group. Each device can add files to its Wi-Fi Direct group. If a file is successfully added, other devices can request the corresponding file. And after a successfully requesting, the file will be sent from the source device to the request device. The paper\textsuperscript{25} gives a detailed introduction about this software.
3.4 Existing Problems

As a Legacy Client, GO2 must use broadcast to send packets to its group member Client2. Because only in this way, GO2 can send packets to its P2P client through P2P interface. The reason is that in this topology, GO2 uses Wi-Fi interface and P2P interface at the same time. And the IP addresses of these two interfaces are in the same network segment. If it sends unicast packets, the packets will choose the interface based on the interface ranking on the routing table in the Android device. In Android 4.4 system and system below the 4.4, Wi-Fi interface ranks before the P2P interface in the routing table. So that the unicast will always be sent from the Wi-Fi interface. As a result, by using unicast the group member Client2 can not accept packets sent from GO2. But after experiments it is found that the broadcast packets sent by GO2 will be sent through the P2P interface by default, regardless of the interfaces ranking on the routing table, which leads to that Client2 can receive the broadcast packets sent by GO2.

However, the use of broadcast transmission greatly limits the rate of data transmission in wireless network. Because under the 802.11 protocol, the maximum broadcast transmission rate is 6Mbps. But the normal Wi-Fi unicast transmission speed limit is 54Mbps. So how to make Wi-Fi Direct Multi-Group communication systems not use the broadcast becomes the focus of this study.
Chapter 4. Feasibility Verification of Optimization Topology

4.1 Optimization Principle

A new optimized topology is put forward in this paper based on Casetti’s work. In this optimized topology, a new device Access Point (AP) is introduced. Group Owners of different groups will connect with the the same Access Point. It is analyzed and tested whether the system can avoid broadcast for Multi-Group communication and the communication works well between the GOs and the Clients after AP is introduced. Through the study it can be found that if the IP address of P2P interface and the IP address of Wi-Fi interface are not at the same network segment, have different Mask code, have different destination address, the unicast will choose the interface which has the same network segment as the destination segment to send. In other words, if two interfaces have different network segment, the unicast will choose the right interface to send the packets, not based on the relatively ranking on the routing table in Android device.

By introducing an Access Point to the Wi-Fi Direct Multi-Group communication topology, it can be found that the IP address of P2P interface and the IP address of Wi-Fi interface on the same Android device are not at the same network segment. As a result, the new optimized topology can avoid broadcast.

4.2 Experiment Principle

Use an AP to connect different Wi-Fi Direct groups. As a result, the Group Owners of different Wi-Fi Direct groups are connected through the AP and they can communicate with each other directly. In the optimized topology of this paper, four mobile phones are
divided into two groups respectively for the experiment. And each group only contains a Group Owner and a single Client for simplifying the experiment. The first device is a Group Owner (GO1) of Group1. The second device is a Group Client (Client1) of Group1. The third device is a Group Owner (GO2) of Group2. The fourth device is a Group Client (Client2) of Group2. Two Group Owners are regarded as the intermediary for the information forward. And at the Access Point, it has a routing table\textsuperscript{26} which contains the routing information of two Group Owners.

The optimized topology is shown in Figure 5.
Figure 5. Optimized Multi-group physical topology with four devices of this paper.
4.3 Experiment Equipment

AP: TRENDNET N300

GO1: HTC device with 4.42 Android system, and Wi-Fi-Direct-Discovery application is installed.

CLIENT1: LG device with 4.42 Android system, and Wi-Fi-Direct-Discovery application is installed.

GO2: HTC device with 4.42 Android system, and Wi-Fi-Direct-Discovery application is installed.

CLIENT2: Samsung device with 5.01 Android system, and Wi-Fi-Direct-Discovery application is installed.

4.4 Software Introduction (Wi-Fi-Direct-Discovery)

The Wi-Fi-direct-discovery software application is written based on the google Wi-Fi Direct demo code. Four Android devices use the same software application to implement Wi-Fi Direct Multi-Group communication.

Followings are the steps about how to use this software: Firstly, click the icon in the right top corner, and it will search the nearby devices with Wi-Fi Direct function on and show a list of available devices in the list. After clicking a specific device’s name, the device that is clicked will receive an invitation and can decide whether accept this connection request. If two devices successfully connect with each other, they could send messages to each other bidirectional without Wi-Fi network or LTE network environment. Figure 6 shows the screenshots of the Wi-Fi-direct-discovery software.
Figure 6. The left part is the search result list, and the right part is the chat page after successfully connection.

4.5 Experiment Connection Process

In Figure 5, GO1 opens 5000 server port for P2P connection, and Client1 connects GO1 with P2P interface to implement bidirectional unicast TCP connection. GO2 opens 5000 server port for P2P connection, and Client2 connects GO2 with P2P interface to implement bidirectional unicast TCP connection. GO2 opens 5500 server port and waits for Wi-Fi connection, and GO1 connects GO2 with Wi-Fi interface to implement bidirectional unicast TCP connection.
4.6 Data Flow Analysis

The Receiver is Client2, and the sender is Client1. There are three hops data transfer in IP layer. The data in IP layer is firstly sent from Client1 to GO1, then from GO1 to GO2, and finally from GO2 to Client2. There are four hops data transfer in MAC layer. The data in MAC layer is firstly sent from from Client1 to GO1, then from GO1 to AP, then from AP to GO2, and finally from GO2 to Client2.

4.7 Experiment Analysis

In the above topology, it replaces GO1 with two different Android phones. One phone is installed with Android 5.0 system and another phone is installed with Android 4.4 system, which is to make sure that the topology can work well on devices with different Android systems. Figure 7 shows the Multi-Group Communication between two Wi-Fi direct groups by using four Android devices.
Figure 7. The Multi-Group communication among four devices. If one device sends a message, all the other devices can receive the message.

After completing the experiment, it is found that the IP address of GO1’s Wi-Fi interface is 10.177.19.82, and IP address of GO1’s P2P interface is 192.168.49.1. They are not on the same network segment, so that broadcast can be avoided at this topology.

The routing tables of two phones above are shown as below.

Figure 8 is the corresponding routing table in device with Android 4.4 system. It can be found that the Destination MTUs of Wi-Fi interface and P2P interface are different, the Masks of Wi-Fi interface and P2P interface are different too. P2P interface ranks after the Wi-Fi interface.
Figure 8. Routing table of device with Android 4.4 system.

Figure 9 is the corresponding routing table in device with Android 5.0 system. It can be found that the Destination MTUs of Wi-Fi interface and P2P interface are different, the Masks of Wi-Fi interface and P2P interface are different too. P2P interface ranks before the Wi-Fi interface.

Figure 9. Routing table of device with Android 5.0 system.
Even if the priority between Wi-Fi interface is P2P interface is different on two different Android systems, the GO1 can still send unicast packet to Client1 and GO2 successfully. It can be concluded that if IP address of Wi-Fi interface and IP address of P2P interface are not in the same network segment, unicast packet will be sent through the correct interface based on the destination IP address, rather than the interface ranking on the routing table. The experimental results also validate the previous conjecture.

4.8 Experiment Conclusion

In the optimized topology, Wi-Fi Direct Multi-Group communication can be implemented without using broadcast. Based on the routing tables shown in Figures 8 and 9, it is proved that Client1 can send packets to Client2 without using broadcast.
Chapter 5. Performance Testing of Optimization Topology

In this chapter, throughput and delay are tested in the topologies shown in Figures 4 and 5, which means that the performance are tested for both Casetti's topology and optimized topology, respectively. Different test Case s are designed and tested separately on both Casetti's topology, which means that different source device and destination device are chosen in the experiment. The test results are compared between the two topologies, and it is easy to find that the optimized topology in this paper has higher throughput and less delay than the topology of Casetti's Work.

5.1 Test Case s in Topology of Casetti's Work

(Each Case has a device as the source to send data, and a device as destination to receive data)

5.1.1 Case 1: One hop in IP layer, one hop in MAC layer. (Without Broadcast)

Source is Client1, and destination is GO1. There is one hop at IP layer and one hop at MAC layer between the source and destination.

5.1.2 Case 2: One hop in IP layer, two hops in MAC layer. (With Broadcast)

Source is GO2, and destination is Client2. There is one hop at IP layer and one hop at MAC layer between the source and destination.

5.1.3 Case 3: Two hops in IP layer, three hops in MAC layer. (Without Broadcast)
Source is Client2, and destination is Client1. There are two hops at IP layer (Client2-GO2-Client1) and three hops at MAC layer (Client2-GO2-GO1-Client1) between the source and destination.

5.1.4 Case 4: Two hops in IP layer, three hops in MAC layer. (With Broadcast)

Source is Client1, and destination is Client2. There are three hops at IP layer (Client1A-GO2-Client1B) and three hops at MAC layer (Client1-GO1-GO2-Client2) between the source and destination. The packets are sent from GO2 to Client2 by using broadcast.

5.2 Test Cases in Optimized Topology

(Each Case has a device as the source to send data, and a device as destination to receive data)

5.2.1 Case 1: One hop in IP layer, one hop in MAC layer.

Source is Client1, and destination is GO1. There is one hop at IP layer and one hop at MAC layer between the source and destination.

5.2.2 Case 2: One hop in IP layer, two hops in MAC layer.

Source is GO1, and destination is GO2. There is one hop at IP layer and two hops at MAC layer (GO1-AP-GO2) between the source and destination.

5.2.3 Case 3: Two hops in IP layer, three hops in MAC layer.
Source is Client1, and destination is GO2. There are two hops at IP layer (Client1-GO1-GO2) and three hops at MAC layer (Client1-GO1-AP-GO2) between the source and destination.

**5.2.4 Case 4:** three hops in IP layer, four hops in MAC layer.

Source is Client1, and destination is Client2. There are three hops at IP layer (Client1-GO1-GO2-Client2) and four hops at MAC layer (Client1-GO1-AP-GO2-Client2) between the source and destination.

**5.3 Performance Test Devices for Optimized topology and Casetti's topology**

Performance test devices for Optimized topology and Casetti's topology, as shown in Table 7\textsuperscript{27}.
Table 7 Performance test devices for Optimized topology and Casetti’s topology

<table>
<thead>
<tr>
<th>Devices name and system version</th>
<th>Optimized topology</th>
<th>Casetti’s topology</th>
</tr>
</thead>
<tbody>
<tr>
<td>Device1</td>
<td>HTC One M7 (Android 4.4.2 system)</td>
<td>Google Nexus 7 (Android 4.4.2 system)</td>
</tr>
<tr>
<td>Device2</td>
<td>HTC One M7 (Android 4.4.2 system)</td>
<td>ASUS Transformer Pad TF300 (Android 4.4.2 system)</td>
</tr>
<tr>
<td>Device3</td>
<td>LG G4 H810 (Android 4.4.2 system)</td>
<td>LG P700 (Android 4.0 system)</td>
</tr>
<tr>
<td>Device4</td>
<td>SAMSUNG S4 (Android 5.0.1 system)</td>
<td>Sony Xperia Miro ST23i (Android 4.2.1 system)</td>
</tr>
</tbody>
</table>

5.4 Throughput Test

5.4.1 Test principle

Verify the data transmission capacity in the optimized topology and the Casetti’s topology. Plot the throughput capacity graphs based on the throughput of the receiver side and the offer load of the sender side.

Offer load (x axis): Offer load equals to the amount of data sent by the sender divide the time it takes to send the data. The experiment data is divided into fixed chunks to send, and the size of each chunk is 1400bytes fixed. Each time the source device sends 18,000...
chunks, total 24M data to the destination. By adjusting the time interval between sending two consecutive chunks, the offer load can be controlled.

Throughput (y axis): Throughput equals to that the size of the data received by the receiver device divides the time it takes to receive the data. In the experiment record the time between receiving first packet and receiving total 2M data.

5.4.2 Optimized topology Throughput Test

Test the throughput based on the offer load. And Case 1, Case 2, Case 3, Case 4 in the optimized topology are tested separately. Figures 10 to 13 show the throughput capacity testing results, representing Case 1 to Case 4 in the optimized topology, respectively. The horizontal axis represents the offer load and the vertical axis represents the throughput.
Figure 10. Offer load vs Throughput. Case 1 of optimized topology. One hop in Mac layer.

Figure 11. Offer load vs Throughput. Case 2 of optimized topology. Two hops in Mac layer.
Figure 12. Offer load vs Throughput. Case 3 of optimized topology. Three hops in Mac layer.

Figure 13. Offer load vs Throughput. Case 4 of optimized topology. Four hops in Mac layer.
5.4.3 Optimized topology Throughput results analysis

Experimental results analysis: In Figure 10 (Case 1 in the optimized topology with one hop in MAC layer), the maximum throughput can reach 45Mbps. In Figure 11 (Case 2 in the optimized topology with two hops in MAC layer), the maximum throughput can reach 18Mbps. In Figure 12 (Case 3 in the optimized topology with three hops in MAC layer), the maximum throughput can reach 12Mbps. In Figure 13 (Case 4 in the optimized topology with four hops in MAC layer), the maximum throughput can reach 11Mbps.

From the above observations it can be found that: from one hop to three hops, the throughput is essentially proportionally reduced with the number of hops in MAC layer increasing. All the available Wi-Fi Direct interfaces are in the same frequency band. So the entire cross-group transmission devices are in the same conflict domain. But a single conflict domain will reduce its interference as the network reaching area becomes larger. When the transmitters or the source devices are far from the receivers or the destination devices, the interference will be greatly reduced. So from three hops to four hops, the throughput of the system does not decrease a lot.

5.4.4 Throughput capacity comparison between Optimized topology and Casetti’s topology

5.4.4.1 One hop in data transmission

The one hop data transmission Case in Casetti’s Work without broadcast can reach a maximum throughput about 19Mbps, as shown in Figure 14. However, the one hop data
transmission Case in the Optimized topology can reach a maximum throughput of about 50Mbps, as shown in Figure 15, which is a great improvement.

Figure 14. Offer load vs Throughput. Case 1 of Casetti’s topology. One hop in Mac layer.
Figure 15 Offer load vs Throughput. Case 1 of optimized topology. One hop in Mac layer.

5.4.4.2 Three hops in data transmission

The three hops data transmission Case in Casetti’s Work without broadcast can reach a maximum throughput about 5Mbps, as shown in Figure 16. However, the three hops data transmission Case in the Optimized topology can reach a maximum throughput of about 12Mbps, as shown in Figure 17, which is a great improvement.
Figure 16 Offer load vs Throughput. Case 3 of Casetti’s topology. Three hops in Mac layer.

Figure 17 Offer load vs Throughput. Case 3 of optimized topology. Three hops in Mac layer.
5.5 Efficiency Evaluation

5.5.1 Efficiency Test Principle

An efficiency figure of merit in network transmission may be defined by the throughput divided by the offer load\textsuperscript{28}. Offer load equals to the amount of data sent by the sender divided by the time it takes to send the data. Throughput equals to the amount of data received by the receiver device divided by the time it takes to receive the data\textsuperscript{29}.

5.5.2 Efficiency comparison between Optimized topology and Casetti’s topology

5.5.2.1 One hop in data transmission

For offer loads of less than 20Mbps, the average efficiency of Casetti’s topology (as shown in Figure 18) is larger than the average efficiency in Optimized topology (as shown in Figure 19). Therefore, Casetti’s work has a better efficiency performance in one hop data transmission when offer loads are less than 20Mbps.

For offer loads larger than 20Mbps, the efficiency was not evaluated on Casetti’s topology, because Casetti’s topology has an upper bound of about 20Mbps for offer loads due to its network traffic capacity\textsuperscript{30}. However, for the optimized topology the efficiency is consistently above 60% for offer loads of up to about 56Mbps.
Figure 18 Offer load vs Efficiency. Case 1 of Casetti’s topology. One hop in Mac layer.

Figure 19 Offer load vs Efficiency. Case 1 of optimized topology. One hop in Mac layer.
5.5.2.2 Three hops in data transmission:

For offer loads of less than 16Mbps, the average efficiency of optimized topology (as shown in Figure 21) is larger than the average efficiency in Casetti’s topology (as shown in Figure 20). Therefore, of optimized topology has a better efficiency performance in three hops data transmission when offer loads are less than 16Mbps.

For offer loads larger than 16Mbps, the efficiency was not evaluated on optimized topology, and it will be done in future work. However, for Casetti’s topology the efficiency is constantly above 25% for offer loads of up to about 20Mbps.

![Case3 in Casetti's topology (three hops without broadcast)](image)

Figure 20 Offer load vs Efficiency. Case 3 of Casetti’s topology. Three hops in Mac layer.
Figure 21 Offer load vs Efficiency. Case 1 of optimized topology. Three hops in Mac layer.

5.6 Delay Test

5.6.1 Delay Test Principle

A total of 1400 bytes packets are sent from the source device to the destination device. Record the time the source device sends the packet and the time the destination device receives the data, and also the transit devices receive the data (invoke the Android's API system.currentTimeMillis method to get current time). Then time difference is calculated for each hop by subtracting the arriving time between two devices. After 50 repeated experiments for each Case, average delay time is calculated as the final result.
5.6.2 Delay Test Principle

The delay test results for Casetti’s Topology and Optimized Topology are indicated in Tables 8 and 9, respectively.

5.6.2.1 Delay Test Results for Casetti’s Topology

<table>
<thead>
<tr>
<th>Transfer</th>
<th>Average time (ms)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Client1—GO1</td>
<td>250</td>
</tr>
<tr>
<td>GO1—GO2</td>
<td>304</td>
</tr>
<tr>
<td>GO2—CLIENT2</td>
<td>226</td>
</tr>
<tr>
<td>Client1—Client2</td>
<td>780</td>
</tr>
</tbody>
</table>

Table 8. Delay test for Casetti’s topology
5.6.2.2 Delay Test Results for Optimized Topology

<table>
<thead>
<tr>
<th>Transfer</th>
<th>Average time (ms)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Client1—GO1</td>
<td>87</td>
</tr>
<tr>
<td>GO1—GO2</td>
<td>66</td>
</tr>
<tr>
<td>GO2—CLIENT2</td>
<td>32</td>
</tr>
<tr>
<td>Client1—Client2</td>
<td>185</td>
</tr>
</tbody>
</table>

Table 9. Delay test for optimized topology

5.6.3 Delay Test Analysis for Optimized Topology and Casetti’s Topology

In the optimized topology, the delay for sending data from Client1 to the farthest node is only about 200ms. The delay time which is spent on the transmission part is really small, and the delay time which is spent on the data processing part at each node's application layer is much larger. The average delay time from Clien1 to GO1 is 87 ms, but the average delay time from Clien1 to GO1 is only 32 million seconds (ms). The reason is that Client1, Client2, GO1 and GO2 use different Android devices, and different Android devices may have different Wi-Fi Direct performance.

When compared with the Casetti’s topology, the optimized topology spends less time on processing the data. Both the GO1 and GO2 in the optimized topology use the Wi-Fi interface to transmit data, which reduces the percentage of using P2P interface in the entire data transmission circle.
Chapter 6. Conclusions

The results of implementing a bidirectional, multi-Group communication in Android devices, which supports the recent Wi-Fi Direct protocol have been presented in this document. The significant outcome relies on the possibility of enlarging the communication range and the clients number in Wi-Fi Direct without rooting the devices.

In particular, a new solution was proposed to overcome the limitations of the current Wi-Fi Direct network topology by introducing an Access Point. This topology can enable bidirectional inter-group and multi-group data transfers. An Android application (Wi-Fi-Direct-Discovery) was developed to implement this optimized topology.

The network performance of the optimized topology was tested, and the test mainly focused on network throughput, data transfer efficiency and delay. Then the network performance in the proposed optimized topology was compared with the corresponding results in Casetti’s topology.
Chapter 7. Future Work

This thesis report opens up several future research directions.

7.1 In the performance test, the positions of Android devices should be rotated or exchanged. Different Android devices may have different Wi-Fi Direct performance, so that each Android device should be placed at each position at least once for throughput test, efficiency test and delay test.

7.2 In the delay test, different size of packets should be used, because it may influence the final test results.

7.3 In the throughput test of optimized topology, broadcast performance should be tested, because in Casetti’s topology both broadcast and unicast are used for throughput test. Besides, different one-hop Cases (Figure 5, Client1 to GO1, GO1 to GO2 and GO2 to Client2 are three different one-hop Cases) should be chosen for throughput test, because different one hop Case s may have different throughput test results.

7.4 Obstacles may be added between the Group Owner and the Client, so that network interference can be tested for Wi-Fi Direct communication.

7.5 Additional tests under near-limit conditions of throughput may be evaluated to assess the critical distance and bandwidth related factors and thresholds associated with a Wi-Fi Direct communication.
### Table 10. Wi-Fi Direct Multi-Group Related Work Comparison

<table>
<thead>
<tr>
<th>Related Work</th>
<th>Technical innovation</th>
<th>Limitation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Casetti’s Work</td>
<td>Connect the GO to another Wi-Fi Direct group as the legacy client. And in each group select a client as the relay.</td>
<td>Must use broadcast, and structure is complex.</td>
</tr>
<tr>
<td>Teófilo’s Work</td>
<td>Choose two clients in each group as the relay. To avoid the broadcast, each group selects two clients as relay. To avoid the broadcast.</td>
<td>Structure is more complex, only theoretical analysis, lack of experimental verification.</td>
</tr>
<tr>
<td>Funai’s Work</td>
<td>Client could use Wi-Fi interface to connect with one Wi-Fi Direct Group, and use P2P interface to connect with another Wi-Fi Direct Group.</td>
<td>Must use multicast. And multicast is not unstable.</td>
</tr>
<tr>
<td>Shahin’s Work</td>
<td>Select a client intermediary point of two groups to achieve Wi-Fi Direct Multi-Group communication</td>
<td>Need rooted Android, and to change the Android source code</td>
</tr>
<tr>
<td>This Work</td>
<td>Use an AP to connect different Wi-Fi Direct groups. Improve throughput a lot and decrease the delay between the data transmission.</td>
<td>Need to introduce a new device to the Wi-Fi Direct group.</td>
</tr>
</tbody>
</table>
Bibliography


24 https://github.com/yufengduan/MGC.


