Increased Persistence of Wi-Fi Direct Networks for Smartphone-based Collision Avoidance

Priyanka Angadi

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Increased Persistence of Wi-Fi Direct Networks for Smartphone-based Collision Avoidance

by

Priyanka Angadi

A Thesis Submitted in Partial Fulfillment of the Requirements for the Degree of
Master of Science in Computer Engineering
Supervised by
Dr. Clark Hochgraf

Department of Computer Engineering
Kate Gleason College of Engineering
Rochester Institute of Technology
Rochester, NY
July 2014

Approved By:

__________________________
Dr. Clark Hochgraf
Primary Advisor – R.I.T. Department of Electrical, Computer and Telecommunications Engineering Technology

__________________________
Dr. Andres Kwasinski
Secondary Advisor – R.I.T. Dept. of Computer Engineering

__________________________
Dr. Amlan Ganguly
Secondary Advisor – R.I.T. Dept. of Computer Engineering
Dedication

I would like to dedicate this Research work to my parents,

Mr. A. Muni Krishna and Mrs. A. Sarath Chandrika
Acknowledgements

I would like to firstly thank my primary advisor Dr. Clark Hochgraf for his boundless support and motivation throughout my thesis journey. This research work has been a great learning experience, because of his constant guidance.

I would also like to thank my other advisors Dr. Andres Kwasinski and Dr. Amlan Ganguly for their suggestions that helped in improving my thesis work.

Lastly, I would like to thank my family and friends for their emotional support during the course of my research.
Abstract

Inter-vehicular communication is a promising technology to improve road safety. Inter-vehicular communication over a wireless medium can be used to exchange important information such as the speed, location, and headings of a vehicle with nearby vehicles. Using this information, it is possible to calculate if a collision is imminent and warn the driver to take action. Wi-Fi can also be used to share this information, however it requires an access point hardware to facilitate communication. Wi-Fi Direct enabled devices can share information without a hardware access point.

Wi-Fi Direct provides peer to peer communication by employing a software defined access point embedded within the system. Wi-Fi Direct is a technology that is present on many smartphones, eliminating the need for dedicated access point hardware. In collision avoidance application, Wi-Fi Direct maybe used to exchange safety-related information between vehicles. Collision avoidance systems developed using smartphones can also be extended to protecting pedestrians carrying a smartphone and in this role they could be a long-term solution for certain vulnerable road user collision scenarios. Smartphones with Wi-Fi Direct capability could provide a path to early, low-cost implementation of inter-vehicle communication for collision avoidance. However, there are many limitations to such a system that are addressed in this thesis.

Wi-Fi Direct functions by creating groups. One of the nodes in the group is elected as the group owner that acts as an access point and manages the communication between the nodes within the group. If the group owner moves out of range, reforming the group is a
lengthy process. This thesis proposes a new method for nomination of the group owner to reduce the likelihood that the group owner will move out of range.

This thesis introduces the concept of nominating a Backup Group Owner that can quickly replace the group owner if the group owner shuts down or moves out of range of the group. An orderly handoff from the group owner to the Backup Group Owner can prevent loss of communication among nodes. An analytical study of the amount of time saved by adopting the proposed method of electing the BGO is presented.
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Glossary

P2P - Peer to Peer

DSRC - Dedicated Short Range Communication

WAVE - Wireless Access in Vehicular Environment

GO - Group Owner

BGO - Backup group owner

RSSI - Received Signal Strength Indication

SOC - State of Charge

AP - Access Point

IVC - Inter-vehicular communication

OBU - On Board Unit

RSU - Road Side Unit

UI - User Interface.

WPS - Wi-Fi Protected Setup

AES - Advanced Encryption Standard

DHCP - Dynamic Host Configuration Protocol

MTU - Maximum Transmission Unit

SAE - Society of Automotive Engineers
LTE - Long term Evolution

UMTS - Universal Mobile Telecommunication Network
Chapter 1: Introduction

The use of wireless communication technology has expanded rapidly and is beginning to extend into applications such as inter-vehicular communication systems for crash avoidance. When vehicles exchange information such as GPS position, velocity, and heading, it is possible to calculate if a collision is imminent and warn the driver to take action.

1.1 Dedicated short range communication (DSRC)

Dedicated short range communication (DSRC) is one of the most popular technologies in inter-vehicular communication. DSRC is a wireless technology that is used to exchange safety information between vehicles. Each vehicle broadcasts a Basic Safety Message (BSM) that contains its speed, location, and heading. Using the information in the BSM, the DSRC devices in the cars can calculate the possibility of occurrence of collision. DSRC is based on IEEE802.11p standard also known as Wireless Access in Vehicular Environment (WAVE)[55].

Though DRSC provides a reliable means of inter-vehicular communication, the cost of DSRC hardware is high. Since DSRC requires dedicated hardware, it may not be the best solution to alert pedestrians of collisions, as this would require pedestrians to carry DSRC equipment along with them all the time. The motivation for this work is to evaluate alternate technologies such as Wi-Fi Direct that are potential contenders for inter-vehicular communication and where needed, provide enhanced solutions for the collision avoidance application.
1.2 Wi-Fi Direct

Wi-Fi Direct was introduced by Wi-Fi alliance to facilitate peer to peer communication through a software defined access point. It is based on the IEEE 802.11n standard. Although, Wi-Fi Direct was initially introduced for an infrastructure based network, this thesis analyzes the effectiveness of using Wi-Fi Direct in inter-vehicular communication (IVC) in an ad-hoc mode [54].

The idea here is to replace the DSRC hardware by using a smart phone that has Wi-Fi direct capability. The location, speed and headings of nearby vehicles and pedestrians can be exchanged with the aid of Wi-Fi Direct technology. The location information is obtained using the GPS technology built into the smart phone. In addition, if a mobile application that can make necessary calculations to predict the occurrence of the collision and alert the driver is programmed, this can be considered as an economical alternative to DSRC.

1.3 Thesis contribution

Some of the key issues that are discussed in this thesis are:

1. Since the Group Owner manages the communication between different devices in a Wi-Fi Direct group, this makes the GO a single point of failure of the group. In this thesis, a new method of nominating a backup group owner is introduced, if the GO no longer functioning, the BGO takes over the role of the GO, this increases the persistence of the groups formed, thus increasing the reliability of the Wi-Fi Direct groups, which is an important factor in IVC. The algorithm to nominate the BGO and the GO delegation process are discussed in chapter 4.
2. Wi-Fi Direct functions by forming groups. Each device that wishes to contend for the role of the group owner provides its intent value and using this intent value the group owner is determined. Chapter 5 proposes a modification to the intent value. In the new method, the intent value is generated based on the time the device will persist in the group which depends on several factors such as state of charge of the device, velocity with which the device is moving, and the number of neighbors seen by the device.

3. Chapter 6 discusses an experimental validation of group formation process between two Wi-Fi Direct devices. It also discusses the theoretical analysis of the amount of time saved in reformation of the group when a group owner fails. Further, this chapter also presents the effect of increase in the number of mobile vehicles on the saturation throughput of the channel and also the probability of successful transmission of the safety message. This provides a guideline for restricting the group size to ensure almost guaranteed delivery of the safety messages.

4. Some of the key issues that are yet to be addressed with Wi-Fi Direct technology in the ad-hoc mode are discussed in the final chapter.
Chapter 2: Dedicated Short Range Communication

Dedicated short range communication (DSRC) is a short range, high speed wireless protocol that is used for inter-vehicular communication [35]. DSRC can be used to establish secure connection between vehicles to exchange information between vehicles that travel at a maximum speed of 120mph and are within 1km radius from each other [38]. DSRC is built on IEEE 802.11p standard also known as WAVE technology [46].

It uses licensed spectrum over the 5.850 to 5.925 GHz frequency range. The frequency range is divided into 7 channels of 10MHz each with a data rate range from 3 to 27 Mbps [45]. The most relevant channel is 178 which is known as the control channel (CCH) where the BSM is broadcast [51]. The other channels 174,176,180,182 and 184 are called service channels (SCH) that can be used to transmit both safety and non safety messages. The remaining channel 172 is used for future research work [52].

<table>
<thead>
<tr>
<th>Reserved Channel</th>
<th>CH 172 Service Channel</th>
<th>CH 174 Service Channel</th>
<th>CH 176 Service Channel</th>
<th>CH 178 Control Channel</th>
<th>CH 180 Service Channel</th>
<th>CH 182 Service Channel</th>
<th>CH 184 Service Channel</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.850</td>
<td>5.855</td>
<td>5.865</td>
<td>5.875</td>
<td>5.885</td>
<td>5.895</td>
<td>5.905</td>
<td>5.915</td>
</tr>
</tbody>
</table>

Figure 1: Frequency band allocation in DSRC

DSRC also has the provision of aggregating channels to increase the data rate and bandwidth. Apart from safety application, DSRC system provides other applications such as navigation assistance, it can also be used to get traffic information [38]. The following
section briefly describes the network components of DSRC referring from [31] which describes how DSRC can be used to control congestion on the road.

2.2 DSRC system components

The system consists primarily of the DSRC On Board Unit (OBU), DSRC Road Side Unit (RSU) and User Interface (UI).

2.2.1 DSRC On Board Unit (OBU)

This is a mobile device that is placed in the moving vehicles [47]. It uses an Omni directional antennae for communication with RSU. The antennae is placed centrally on top of the vehicle to have a clear signal. The DSRC OBU establishes a link with the DSRC RSU. It scans for the DSRC RSU invitation messages to establish connection with DSRC RSU. The DSRC OBU sends the current location and speed of the vehicle to the DSRC RSU. The DSRC RSU processes this information and sends out broadcast messages containing this information to all the DSRC OBU devices within its range [37].

The DSRC OBU also processes the DSRC RSU broadcast messages and if it contains information that the driver should be altered of, then it would do so through the user interface. [31]

2.2.2 DSRC Road Side Unit (RSU)

The DSRC RSU is an immobile device that is placed alongside the road. The primary function of RSU is to collect the current location, speed and traffic information from all the DSRC OBU devices within its range. The RSU processes this information and broadcasts traffic information to all OBU devices in its range. Different RSU input variables are used
depending upon the parameter that needs to be measured, the RSU should be tuned to adapt to these input parameters prior to any communication with the OBU devices [31][46].

2.2.3 User Interface

The User Interface is used to communicate the traffic information to the driver. The User interface consists of the Communication Interface device (CID). There could be in-built displays in the car or a mobile phone or an add-on display. [31]

2.3 Operation

The BSM, which contains the speed, location and heading of the vehicle, are transmitted to the RSU by the OBU. The RSU broadcasts the current location, speed and heading of all the vehicles within its range. Based on this information, the DSRC equipment onboard computes and calculates the occurrence of a possible threat and alerts the driver. [46]

Development of DSRC has occurred over many years and the system’s communication protocols, messages, security methods, and potential for benefit are well defined [19]. However, the cost of the DSRC radio equipment remains high. Additionally, given the slow replacement cycle for automobiles, the timing of the widespread implementation of DSRC in vehicles remains uncertain, and could take more than a decade or two.

At the same time, over half of adults in the United States already have smart phones with Wi-Fi and GPS capabilities. Certainly, the performance of smartphone-based GPS and Wi-Fi today are not as good as the technology found in automotive-grade DSRC systems. However, new GPS algorithms are showing promise for creating highly accurate relative position estimates from consumer-grade GPS units. For example, researchers at Vanderbilt University have demonstrated mean relative positional errors of less 0.25m during high
speed driving, as well as in city driving with partially obscured views of the sky, using only consumer grade devices [48]. Given that smartphone technology evolves and is replaced at a much faster rate than vehicle technology, smartphones could potentially play a limited interim role in providing crash avoidance communications between vehicles. Collision avoidance systems developed using smartphones could also be extended to protecting pedestrians carrying a smartphone and in this role they could be a long-term solution for certain vulnerable road user collision scenarios.

The other technologies that can be used in smart phone based collision avoidance are Wi-Fi Direct and cellular technology like 3G/HSPA/LTE [49]. Cellular technology is implemented either using Long term Evolution (LTE) or Universal Mobile Telecommunication Network (UMTS). Both of these technologies have a centralized core server that manages communication. Due to this, there is an added network latency, which may be a concern when using them for safety applications. So, although cellular technology provides better coverage, its hierarchical based implementation does not make it the best option for implementing collision avoidance system when compared to DSRC, which has dedicated bandwidth allocated to send safety messages, and the communication is direct. [50]

One of the biggest shortcomings of using DSRC is the dedicated hardware required. The use of dedicated hardware in constructing the system architecture of DSRC adds additional cost on the vehicle. Wi-Fi Direct is a good contender to consider because Wi-Fi Direct eliminates the need for costly dedicated hardware. Wi-Fi Direct is a novel technology that implements Wi-Fi technology using a software based access point. The information is exchanged between the nodes through this access point. The idea is to use Wi-Fi Direct in smart phones to exchange BSM that would contain speed, heading and location of the vehicle and develop
a mobile application that would perform calculations and alert drivers or pedestrians prior to the occurrence of a collision. In the following section of thesis, the operation of Wi-Fi Direct technology is briefly discussed along with some of the key issues that need to be addressed to implement Wi-Fi Direct in smartphone based collision avoidance system.
Chapter 3: Overview of Wi-Fi Direct capabilities and its operation

3.1 Introduction

Wi-Fi Direct was popularly known as Wi-Fi peer to peer communication [6]. This was a standard introduced by Wi-Fi Alliance for fast file sharing in infrastructure networks. Wi-Fi Direct uses soft access point to facilitate communication between the nodes [6]. It is supported in IEEE 802.11 a/d/g/n wireless technologies [11]. Wi-Fi Direct is one of the most economical technologies, which can substitute DSRC in inter-vehicular communication.

3.2 Working

3.2.1 Wi-Fi Direct

Wi-Fi is a technology that enables devices to connect wirelessly to the Internet or with other networks. In Wi-Fi direct any node can act as a software defined access point (AP). The node that becomes the AP is called the group owner (GO). All the clients can communicate with each other through the GO.

Apart from Wi-Fi Direct devices, there can be legacy devices in the group but the legacy devices can never become the GO. Also, the GO and the clients can be part of more than one group. There could be a large variety of devices that could come together to form Wi-Fi Direct groups, which could be formed by a combination of Wi-Fi Direct devices and legacy devices. There can be two kinds of Wi-Fi Direct groups formed:

1) 1:1 P2P group: in this group there would be one client and one group owner.
2) 1: n P2P group: this group consists of one GO and many clients (these clients can either be legacy devices or Wi-Fi Direct devices) [11]. Figure 2 and 3 describes the two types of group formation in Wi-Fi Direct.

![Figure 2: P2P group formation in Wi-Fi Direct with two devices](image)

![Figure 3: P2P group formation in Wi-Fi Direct with multiple devices](image)
3.2.2 Wi-Fi Direct Group Formation

In Wi-Fi Direct, the group formation is divided into four different phases namely discovery, GO negotiation, WPS Provisioning and address configuration as shown in the figure 4.

Figure 4: Different working phases in Wi-Fi Direct connection process (Figure 2 from Camps-Mur et.al. [6]).

i. **Discovery**: the first phase is known as the device discovery phase.

![Device Discovery Phase Diagram](image)

Figure 5: Device Discovery Phase

In this phase the devices try to find other Peer to peer devices within its range. This is done by sending out probe requests and listening for probe responses. The devices switch between scanning and listening phases.
ii. **GO negotiation:**

In this phase the GO is elected using a three-way handshake, which comprises of request, response and confirmation signals. The GO owner is decided based on the intent value of each device. The intent value is determined based on the power left in the device, if the device is connected to the AC supply and also if the device is part of different groups and has the capability of cross connection. The devices that wish to form the group share their intent value. The device with the highest intent value becomes the GO. [11]

iii. **WPS provisioning**

Wi-Fi Direct uses Wi-Fi Protected Setup (WPS) for initial set up and authentication. WPS is based on WPA-2 security and uses Advanced Encryption Standard (AES)-CCMP as cypher and randomly generated pre-shared key for mutual authentication [11]. The group owner takes the role of registrar; the key responsibilities of the registrar are, granting and revoking network access for the client devices. It is also responsible for passing on the necessary information such as group ID, the operating channel, and the preshared key to the client devices. WPS provisioning is also divided into two phases: in the first phase the security keys are generated by the internal registrar and in the second phase the devices disconnect and reconnect using the key that is generated in the first phase [11].
iv. **Address configuration**

Finally, DHCP is used to assign IP addresses to the P2P devices. This phase is relevant only when devices are connected to the Internet. The GO acts as the DHCP server and assigns the clients IP addresses. In order to obtain an IP address, the client and the DHCP server exchange DHCP discover, offer, request and acknowledgement messages. [11]

Generally the group formation takes about 15 seconds and the Wi-Fi protected set up takes between 90 to 120 seconds. [11]

**3.3 Advantages and disadvantages of using Wi-Fi Direct in Inter-Vehicular Communication**

**Advantages**

i. Replaces the need of having dedicated hardware for inter-vehicular communication.

ii. Economical option as it would only need a smartphone that can support Wi-Fi Direct to share information between the vehicles.

iii. Backward compatibility: Wi-Fi Direct devices operate well with legacy Wi-Fi devices. However, these legacy devices can’t become the group owner.

iv. Wi-Fi Direct ensures secures data exchange and set up as it uses WPA-2 for security and AES protocol for authentication.
Disadvantages

i. Wi-Fi Direct uses Wi-Fi Protected Setup (WPS) with AES-CCMP encryption. This would require prior exchange of additional frames such as 4-way handshake to exchange encryption keys; this would use up some amount of channel bandwidth and increase the initial setup time of the network.

ii. Wi-Fi Direct works best in small groups of networks. To ensure lower probability of packet loss due to collisions and retransmissions, the number of nodes that form Wi-Fi Direct groups should be restricted. This thesis analyzes the probability of packet delivery with varying number of nodes and window size.

iii. In Wi-Fi Direct, the group owner facilitates communication between the nodes in a group. This makes the group owner single point of failure of the whole group. This is one of the setbacks of using Wi-Fi Direct in inter-vehicular communication, as the vehicles need to exchange road safety related information that are of high priority to avoid collision. Through this thesis a new concept of nominating the backup group owner is introduced.
Chapter 4: Backup Group Owner

4.1 Introduction

Wi-Fi Direct functions by creating groups. One of the nodes is elected as the group owner (GO) that acts as an access point and manages the communication between the nodes within the group. If for some reason the group owner fails or moves out of range of the group, the whole group falls apart. This makes the GO as the single point failure of the whole group.

Once the group falls apart, renegotiation of the GO needs to take place, which is time consuming and adds additional overhead on the network. To address this issue, once the GO is elected, a backup group owner is also elected based on the intent value. When the GO is no longer part of the group, the GO delegates the work to the BGO before it leaves the group.

Thus, introduction of backup group owner increases the reliability of a Wi-Fi Direct group; this is very essential in the application of collision avoidance as safety messages are exchanged at regular intervals. With experimental setup and mathematical calculations it is observed that, this concept replaces the entire Group negotiation phase by a couple of frames that need to be exchanged between the BGO and the current GO before the BGO takes over the group as the new GO. After this successful handshake, the GO leaves the group.
4.2 Algorithm to Nominate the Group owner and Backup group owner

The BGO is nominated at the time of the group formation and it is based on the intent value of the device. During the group formation phase all the devices that are going to be part of the group share their intent values. The intent value algorithm picks the best (highest) intent value. The device with the best intent value is assigned as the GO. Once the group is formed, a better choice for the BGO can be made using additional information derived from the position and velocity of the nodes. The revised intent value to nominate the BGO is based on additional parameter called time in group that is calculated based on the relative velocity and the direction in which the device is moving relative to the centroid of the group. The time in group parameter is an estimate of how long the device is going to be in the vicinity of other nodes.

Each device sends a tiebreaker bit along with its intent value. In case of tie, the tie breaker bit is observed and the device which sends the tie breaker as 1 is assigned as the GO. It is assumed that, at any given time no two devices that have the same intent value have their tie breaker bit equal to 1. The algorithm to nominate the GO and BGO is described in figure 6.
The algorithm to nominate the GO is presented in figure 6. This algorithm is a columniation of the work presented in [22], [1], [2], [3] and [4]. The algorithm to elect the GO and BGO has the same logic but the parameters used to elect each of them are different at the time of group formation and once the group is formed. At the time of group formation, the intent value is calculated using the state of charge of the device, number of Wi-Fi Direct groups the device is part of and the number of neighboring nodes seen by the client. Using this intent value, the GO and the BGO are nominated. Once the group is formed and the devices begin communicating with each other, the intent value requested is recalculated taking into account time in group parameter. If the GO leaves, the BGO elected using the time in
group parameter takes over the role of the GO. More details about intent value are described in the next chapter of the thesis.

Figure 7: BGO nomination algorithm taking into account Time in Group Parameter
4.3 Description of stages when the BGO takes over the group in the absence of the GO

Consider five devices device A, device B, device C, device D and device E. These devices exchange their intent values and device D is nominated as the GO as it has the highest intent value (IV=15). All the communication between these devices is done through device D. Figure 7.1 describes a fully formed Wi-Fi Direct group with device as the GO. Once the GO moves out of range of the current group the BGO takes over. This process of BGO taking over the group in the absence of the GO is helpful only when there is smooth transition of the GO from the group. In the case of smooth transition, the GO moves out of range of the group as opposed to abruptly shutting down. Before the GO moves beyond the critical distance (200 meters), the GO delegation process is triggered and completed and the BGO would have taken over the group. Figure 7.2 depicts this process.

![Diagram of Wi-Fi Direct group](image)

Figure 8: A fully formed Wi-Fi Direct group. The device with the highest invent value (IV=15) acts as the group owner.
Figure 9: In the left figure, stage 1, the GO Device D, is moving out of range of the group members. In the right figure, stage 2, the BGO Device E becomes GO after the timeout expires.
4.4 Group owner delegation in the presence of BGO

Once the GO decides to leave the group, the GO has to delegate the group ownership to the BGO or if the BGO fails to take up the group ownership then it has nominate a new GO from the other devices before it leaves the group. Referring to prior work from [56] on GO handoff process. This thesis theoretically explains the frames exchanged between the BGO and GO that comprise of the GO delegation process.

In the above figure, the different frames that are exchanged for group owner delegation are described.

1. **GO delegation announcement frame:** This frame is broadcasted by the GO informing that a new GO will be elected for the group.
2. **GO Delegation confirmation frame**: This is a unicast frame sent to GO; this frame is send as an acknowledgment for the GO delegation announcement frame and confirms that the BGO is ready to take over the role as the GO.

3. **Handshake for GO delegation**: There is handshake between the GO and BGO. During this time important information about the group such as the mac address of all the clients in the group is exchanged that would facilitate communication between the devices in the group.

4. **New GO advertisement**: This frame carries information about the new GO and this is a broadcast frame that is sent by the GO to advertise about the newly elected GO. After this frame is broadcasted, the GO leaves the group and the new GO takes over the group.

Since the GO owner delegation is done prior to the device leaving the group, change of GO will not cause any communication hiccups between the devices in the group.
4.5 Algorithm for group owner delegation

Below is the algorithm that is run before the GO moves out of range of the group. The new GO is nominated and announced before the GO moves out of range of the group. The GO also exchanges important information with the newly elected GO.

![Diagram of Algorithm for group owner delegation]

Figure 11: Algorithm for group owner delegation
4.6 Modification to Wi-Fi Direct state machine diagram with Backup Group Owner

The state machine diagram below describes the entities that constitute of the Wi-Fi Direct technology and the transition conditions. The state machine diagram is derived from prior work from [22]. The transition of the client that was assigned as BGO to operate as the GO is the new transition path introduced in this thesis that is contrary to the traditional Wi-Fi Direct operation.

Figure 12: Wi-Fi Direct State machine diagram with Back Group Owner
Chapter 5: Intent value calculation for collision avoidance application

5.1 Traditional Intent value generation

Intent value is an integer used to elect one of the nodes as a GO of the Wi-Fi group. Referring to prior work from [4] on traditional intent value calculation, each device shares its intent value, which is an integer value between 1 and 15. The Intent value is decided based on the battery run time left in the device, and the participation of the device in more than one group. Since, Wi-Fi Direct is going to be used in vehicles, it is important that the groups persist for a longer duration of time and if the GO leaves the group, the transition should be quick, smooth and effective. Through this thesis, it can be seen that, by nominating the right candidate as the GO, by considering additional factors such as state of charge and number of nodes that the device heard from, the groups can persist longer which makes the communication of critical information between the vehicles more effective.

5.2 Proposed Intent value generation

This thesis proposes a modification to the intent value so that it includes the time the device will last in the group, which depends on state of charge of the device and the speed with which the device is moving. It also takes into consideration if the device is part of more than one group and the number of nodes the device can serve based on its position. The intent value should be an integer value that is calculated giving all the above factors equal priority. The weighted factor is an integer value 1 through 15.

1. Number of neighbors seen by the client: A node is considered as a neighbor to the client only if the RSSI value is -80dbm or better. This is assuming the devices have
exchanged beacon frames to discover each other. The Received signal strength gives us an estimate of the link quality between the node and its neighbors. Based on the number of neighbors the node has, a weighted factor $W_n$ is assigned to it.

2. State of charge (SOC): this is quantity is the percentage representation of the charge left in the device against the maximum charge of the battery. This would help us estimate how long the device can run. Based on the SOC value a weighted factor $W_b$. If the SOC value is high this means the device can run longer.

3. Number of groups the node is part of: Based on the number of groups the node is part of a weighted factor $W_g$ is assigned. If the device is part of larger number of groups, the less likely the device will be chosen as the GO as it may not have enough resources to facilitate the communication between the clients in the group.

The above three weighted values are considered to calculate the intent value $I_{gn}$. The intent value $I_{gn}$ reported by any node $n$ is given by the average of the sum of the weighted factors $W_n$, $W_g$ and $W_b$.

$$I_{gn} = \frac{(W_n + W_g + W_b)}{3}$$

$I_{gn}$ is used to nominate the GO. By considering the average of the three factors, a GO with high availability,

Once the GO is decided, the BGO nomination needs an additional factor called time in group.

4. Time in group: This is a measure of the time the node would stay within the range of the group. Even if the GO leaves the group, it is important to nominate a BGO that would stay longer in the range of the clients in the group. By doing so, even if the GO fails the BGO that is nominated is the next best candidate to replace the GO. Since we
need additional information such as relative velocity, position of the node, which can be exchanged only after the group is formed, due to this, sometimes the BGO nominated may end up with better intent value as opposed to the GO.

5.3 Calculation of time in group

Time in group is an estimate of the time the node would stay within the critical distance from the centroid. Based on the time in group value, a weighted factor $W_t$ is assigned. To calculate the time in group, the centroid for all the devices is calculated using the co-ordinates of all the devices. Using the radial velocity of each of the devices relative to the group centroid and the critical distance, the time in group value is calculated.

![Diagram of centroid calculation](image)

Figure 13: Illustration of the centroid calculation for a group with five nodes.

1. Figure 12 shows the centroid $(x_c, y_c)$ for $n$ number of nodes with co-ordinates $(x_1, y_1), (x_2, y_2), (x_3, y_3), \ldots, (x_n, y_n)$ which is given by the formula:

   $\begin{align*}
   x_c &= \frac{(x_1 + x_2 + \ldots + x_n)}{n} \\
   y_c &= \frac{(y_1 + y_2 + \ldots + y_n)}{n}
   \end{align*}$

   The vector notation of $(x_c, y_c)$ is $R_c = x_c + y_c$

2. Consider a node with co-ordinates $(x_1, y_1)$ with velocity vector $V_1$ as shown in figure 13, where the node moves to a new position $(\Delta x, \Delta y)$ in $\Delta T$ seconds.
The distance to the centroid is given by:

$$|r| = \sqrt{(x1 - xc)(x1 - xc) + (y1 - yc)(y1 - yc)}$$

$$|r1| = \sqrt{(\Delta x - xc)(\Delta x - xc) + (\Delta y - yc)(\Delta y - yc)}$$

If $|r| > |r1|$, then the node is moving closer to the centroid.

$$\Delta R = |r1| - |r|$$

The radial velocity which is defined as the velocity with which the node is moving towards or away from the centroid, is denoted by $Vr$ and given by:

$$Vr = \frac{\Delta R}{\Delta T}$$

Critical distance is defined as the maximum distance the node travels from the centroid beyond which the node is no more part of the current group. The critical distance is assumed to be 200 meters for calculations. With the help of the radial velocity and the critical distance, time in group is calculated.

$$\text{Critical distance} = r + \frac{\Delta R}{\Delta T} \cdot Tg \quad \text{where } Tg \text{ is the time in group in seconds}$$

Solving for $Tg$ in the above equation, we get

$$Tg = \frac{200 - r}{\frac{\Delta R}{\Delta T}}$$
By considering all the four factors in the BGO nomination, the intent value for each device is calculated and the device with the higher intent values (\(I_{\text{bgn}}\)) are considered as strong contenders as BGO and the device with the highest intent value is chosen as the BGO.

\[ I_{\text{bgn}} = \frac{(Wn + Wg + Wb + Wt)}{4} \]

<table>
<thead>
<tr>
<th>Weighted factor</th>
<th>Number of Neighbors</th>
<th>Time in group based on State of charge (measured in hours)</th>
<th>Number of groups the node is part of</th>
<th>Time in group based on relative velocity (in seconds)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Less than 5</td>
<td>Less than 0.05</td>
<td>14 and above</td>
<td>2 seconds and below</td>
</tr>
<tr>
<td>2</td>
<td>5-10</td>
<td>0.05-0.1</td>
<td>13</td>
<td>2-5</td>
</tr>
<tr>
<td>3</td>
<td>11-15</td>
<td>0.2-0.1</td>
<td>12</td>
<td>5-10</td>
</tr>
<tr>
<td>4</td>
<td>16-20</td>
<td>0.3-0.2</td>
<td>11</td>
<td>10-20</td>
</tr>
<tr>
<td>5</td>
<td>21-25</td>
<td>0.4-0.3</td>
<td>10</td>
<td>20-30</td>
</tr>
<tr>
<td>6</td>
<td>26-30</td>
<td>0.5-0.6</td>
<td>9</td>
<td>30-35</td>
</tr>
<tr>
<td>7</td>
<td>31-35</td>
<td>0.6-0.7</td>
<td>8</td>
<td>35-40</td>
</tr>
<tr>
<td>8</td>
<td>36-40</td>
<td>0.7-0.8</td>
<td>7</td>
<td>40-45</td>
</tr>
<tr>
<td>9</td>
<td>41-45</td>
<td>0.8-0.9</td>
<td>6</td>
<td>45-50</td>
</tr>
<tr>
<td>10</td>
<td>46-50</td>
<td>0.9-1</td>
<td>5</td>
<td>50-55</td>
</tr>
<tr>
<td>11</td>
<td>51-55</td>
<td>1-2</td>
<td>4</td>
<td>55-60</td>
</tr>
<tr>
<td>12</td>
<td>56-60</td>
<td>2-3</td>
<td>3</td>
<td>60-120</td>
</tr>
<tr>
<td>13</td>
<td>61-65</td>
<td>3-4</td>
<td>2</td>
<td>120-180</td>
</tr>
<tr>
<td>14</td>
<td>66-70</td>
<td>4-5</td>
<td>1</td>
<td>180 and above</td>
</tr>
<tr>
<td>15</td>
<td>Above 70</td>
<td>5 and above</td>
<td>0</td>
<td>Stationary node relative to centroid</td>
</tr>
</tbody>
</table>

Table 1: Weighted factors for calculating intent value

If a device which is part of 2 groups, hears from 20 neighbors, reports state of charge of 1 hour and time in group of 120 seconds will have the following intent value:
Intent value reported for GO nomination = \(\frac{13 + 4 + 11}{3} = 9.33\) which is approximated to 9.

Intent value reported for BGO nomination = \(\frac{13 + 4 + 11 + 13}{4} = 10.25\) which is approximated to 10.

From table 1, it can be inferred that a device that has more neighbors, fewer groups and has a longer predicted time in group, is the best candidate for becoming the BGO.

### 5.4 Comparison of intent value calculation with the traditional method and new proposed method

Consider the following devices A, B, C, D that are forming a Wi-Fi Direct group.

<table>
<thead>
<tr>
<th>Device</th>
<th>((W_n))</th>
<th>((W_g))</th>
<th>((W_b))</th>
<th>(W_t)</th>
<th>(I_{gn} = \frac{(W_n + W_g + W_b)}{3})</th>
<th>(I_{bgn} = \frac{(W_n + W_g + W_b + W_t)}{4})</th>
</tr>
</thead>
<tbody>
<tr>
<td>Device A</td>
<td>4</td>
<td>10</td>
<td>1</td>
<td>5</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>Device B</td>
<td>4</td>
<td>4</td>
<td>1</td>
<td>15</td>
<td>3</td>
<td>9</td>
</tr>
<tr>
<td>Device C</td>
<td>4</td>
<td>14</td>
<td>1</td>
<td>3</td>
<td>6</td>
<td>3</td>
</tr>
<tr>
<td>Device D</td>
<td>4</td>
<td>15</td>
<td>1</td>
<td>1</td>
<td>7</td>
<td>4</td>
</tr>
<tr>
<td>Device E</td>
<td>4</td>
<td>2</td>
<td>1</td>
<td>2</td>
<td>2</td>
<td></td>
</tr>
</tbody>
</table>

Table 2: Devices A, B, C, D, and E with their weighted factors and calculation of weighted sum of intent values to nominate the GO and BGO.

From the above diagram it is clear that device D is nominated as the GO as it has the highest intent value and the device C would be nominated as the BGO. At this point the time in group information is not exchanged. After the GO and BGO are nominated and the communication between the devices in the group begins, the time in group information is exchanged between the nodes. Using time in group, \(I_{bn}\) is calculated and the device with the highest \(I_{bn}\) is nominated as the new BGO. In the above example, based on the calculations, device B is the nominated as the BGO. Once device D decides to leave the group, device B takes over the role of the GO.
Chapter 6: Experimental setup and results

In this section, group formation delay is studied and evaluated with the prior results presented in [7]. This helps in understanding the frame exchange and assessing the delay involved in group formation.

6.1: Experimental Setup

To understand the process of group formation and to quantify the delay associated with group formation, an experiment was set up using two Android devices. In this scenario two Google Nexus tablets were used. The experiment was conducted in an environment free from Wi-Fi signals. The two devices communicated using an application called SuperBeam that uses Wi-Fi Direct technology.

The packets exchanged during the process of device discovery and group formation were captured on channels 1, 6, and 11 using sniffing software called aircrack-ng [34]. The packet captures were analyzed in detail using Wireshark.

From the time stamp using wireshark captures, the time taken for group formation was calculated and verified with prior work presented in [7].

An example of a wireshark capture is shown above. The important fields in the wireshark capture are as follows:

No. : This represents the serial number of the packet that is sent.
Time: This represents the time stamp when the packet was sent.

Source: This represents the MAC address of the device sending the packet.

Destination: This represents the MAC address of the device receiving the packet. If the packet is received by all the devices, the destination is a broadcast with a MAC address of FF:FF:FF: FF:FF:FF.

Protocol: This represents the name of the protocol used.

Length: This represents the length of the packet that is being exchanged.

Info: This provides information of the type of packet that is being exchanged, it also contains information pertaining to communication using TCP and other additional information such as SSID of the wi-fi networks.

Figures 16 and 17 are screenshots of packet captures showing the probe requests being broadcasted by each of the devices with source MAC address 62:a4:4c:9a:b9:9d and 52:46:5d: c8:a5:83 and unicast probe response messages are exchanged between the two devices, this is part of the device discovery phase, where the devices are scanning channels and listening to discover other devices.

Once the devices have discovered each other, P2P-P2P invitation request and response messages are exchanged between the devices.
Figure 16: Probe request messages being broadcasted by each of the devices.

Figure 17: Probe request/response messages and P2P-P2P invitation request/reply packets
Figure 18: Group formation phase

In capture 4.1 we see probe responses being sent by both the devices and the P2P-GO negotiation request, reply and confirmation messages. To initiate a P2P connection, P2P-GO negotiation request message is sent. The device 62:a4:4c:9a:b9:9d sends a P2P-GO negotiation confirmation message with success status to 52:46:5d: c8:a5:83. Which implies the group is formed between the two devices.
The two devices share the same intent value in this case 7 in GO negotiation process. But the since the tie breaker bit is set to 1 for device with MAC address 52:46:5d: c8:a5:83, it is chosen has the GO.
Figure 21: Authentication process

Capture 5 shows the authentication process and capture 6 shows EAP 4 way handshake.

During this process the keys for encryption are exchanged. The GO takes over the role of the authenticator and the client the role of supplicant.
6.2: Experimental validation of group formation process between two Wi-Fi Direct devices

The diagram in figure 8 depicts the data capture between the two devices and the time they spend in each phase.

![Diagram of Wi-Fi Direct group formation process](image)

Figure 23: Timing diagram for Wi-Fi Direct group formation
Time taken to elect the GO = 2.23 seconds

Phase 1 of authentication process = 0.6 seconds

Time taken to exchange WPS frames = 1.2 seconds

Phase 2 of authentication process = 0.6 seconds

Total setup time taken for Wi-Fi Direct group = 2.23 + 0.6 + 1.2 + 0.6 = 4.63 seconds

The total setup time measured aligns well with the results demonstrated in [7]. With traditional Wi-Fi Direct technology, the entire group disbands when the group owner leaves the group. It takes about 4.6 seconds for the group to reform, after which the devices can again communicate. However, with the use of a BGO, the time to reform the group upon the departure of the GO can be reduced. The GO to BGO delegation process takes place in the background, ensuring continuous connectivity between the devices in the group. This can save up to 4.6 seconds if no additional handshake messages are used, or if four handshake messages are used in the group reformation, it can save an estimated 3.2 seconds.
6.3: Analytical study of saturation throughput

Wi-Fi direct must share spectrum with other Wi-Fi devices, limiting the number of nodes that can effectively exchange information due to bandwidth limitations. In order to ensure guaranteed delivery of safety messages, it is important to study the effect of increasing the number of nodes on the channel utilization. It is recommended that the transmission delay for a basic safety message for safety applications be within 100 milliseconds[57]. From the channel utilization calculation, the maximum number of nodes that can transmit within 100 milliseconds is calculated. Calculations are made with RTS/CTS and without RTS/CTS method. This provides a guideline on sizing the Wi-Fi direct groups.

Referring to bianchi’s model for modelling the CSMA/CA mechanism presented in [43], we calculate the throughput of the 802.11n system.

The throughput $S$ for the channel measures the fraction of time the channel is used for success transmission of payload bits.

$$S = \frac{E[\text{payload information in a slot time}]}{E[\text{length of slot time}]} \text{ where } E[.] \text{ represents expected value.}[43]$$

$E[\text{payload information in a slot time}] = P_{tr} \cdot P_s \cdot E[.]$ [43]

$E[.]$ represents the average packet payload size, for Wi-Fi direct the BSM size is 50 bytes.

$P_{tr}$ represents the probability of at least one transmission in the time slot of intercept.

$$P_{tr} = 1 - (1 - \tau)^n \ [43]$$

$\tau$ represents the probability that the station will transmit at some randomly chosen time.

$P_s$ represents the probability of a successful transmission.

$$P_s = \frac{n \tau (1-\tau)^{n-1}}{[1-(1-\tau)^n]} \ [43]$$
\[
S = \frac{\text{Ps.Ptr.E[P]}}{(1 - \text{Ptr})\sigma + \text{Ptr.Ps.Ts + Ptr(1 - Ps)Tc}} [43]
\]

\(\sigma\) represents single slot time size for calculations we assume a slot time of 50 microseconds.

\(T_s\) represents the average time a slot lasts when there is a successful transmission.

\(T_s\) without RTS/CTS = PHY header size + MAC header size + E[P] + SIFS + propagation delay + ACK + DIFS + propagation delay

\(T_s\) with RTS/CTS = RTS + SIFS + propagation delay + CTS + SIFS + propagation delay + PHY header size + MAC header size + E[P] + SIFS + propagation delay + ACK + DIFS + propagation delay

\(T_c\) represents the average time a slot lasts when there is a collision.

\(T_c\) with RTS/CTS = RTS + DIFS + propagation delay

\(T_c\) without RTS/CTS = PHY header size + MAC header size + E[P] + DIFS + propagation delay

Transmission bit rate = 6 Mbps

Packet payload = 50 bytes = \((50 \times 8) / 6\) Mbps = 66.67 microseconds

ACK = 14 bytes = \((14 \times 8) / 6\) Mbps

RTS = 20 bytes = \((20 \times 8) / 6\) Mbps

CTS = 14 bytes = \((14 \times 8) / 6\) Mbps

DIFS = 50 micro seconds

SIFS = 50 micro seconds

\(\sigma\) i.e. slot time = 9 micro seconds
Propagation delay = 10 micro seconds

We substitute all the above values in equation below to compute the value of S.

\[ S = \frac{E[P]}{Ts - Tc + \left( \frac{(1 - P_{tr})\sigma}{P_{tr} + Tc} \right) / P_s} \]  \[ 43 \]

The saturation throughput is calculated for \( n = 50, 500 \) and \( 1000 \) nodes.

Since it is suggested to have a maximum transmission delay of 100msec for all safety applications in inter-vehicular communication applications [57]. Using this reference transmission delay, we calculate the maximum of nodes that can send safety messages within 100 milliseconds tasking into account occurrence of collisions in the system. It is given by the equation:

Required BW = (\( N \times 50 \times 8 \)) Mbits/100msec = \( N \times 0.004 \)Mbps

The solid black increasing curve represents the bandwidth required, if each of the \( N \) nodes need to be able to transmit their message in 100 msec.
Figure 24: Saturation throughput of the channel as the number of nodes increases up to 50.

Figure 25: Saturation throughput of the channel as the number of nodes increases up to 500.
Figure 26: Saturation throughput of the channel as the number of nodes increases up to 1000.

In all the three graphs above and from table 3, it is observed that when we compare the saturation throughput is better with RTS/CTS as opposed to without RTS/CTS for any window size and for any number of retransmissions.

The x coordinate of the intersection point of each of the colorful curves with the solid black curve represents the maximum number of nodes the system can support to keep the transmission delay within 100 milliseconds. These values are tabulated in table 3.
Figure 27: Maximum number of nodes that can be accommodated for window sizes 16, 32, 64.

<table>
<thead>
<tr>
<th>W</th>
<th>with RTS/CTS m=4</th>
<th>No RTS/CTS m=4</th>
<th>with RTS/CTS m=5</th>
<th>NO RTS/CTS m=5</th>
<th>with RTS/CTS m=6</th>
<th>NO RTS/CTS m=6</th>
<th>with RTS/CTS m=7</th>
<th>NO RTS/CTS m=7</th>
</tr>
</thead>
<tbody>
<tr>
<td>16</td>
<td>180</td>
<td>153</td>
<td>213</td>
<td>194</td>
<td>237</td>
<td>225</td>
<td>252</td>
<td>249</td>
</tr>
<tr>
<td>32</td>
<td>112</td>
<td>88</td>
<td>132</td>
<td>105</td>
<td>152</td>
<td>123</td>
<td>166</td>
<td>134</td>
</tr>
<tr>
<td>64</td>
<td>83</td>
<td>66</td>
<td>94</td>
<td>74</td>
<td>102</td>
<td>79</td>
<td>108</td>
<td>82</td>
</tr>
</tbody>
</table>

Table 3: Maximum number of nodes that can be accommodated for window sizes 16, 32, 64.

The minimum window size is 16 and the maximum window is 1024 for 802.11n[58]. This sets the upper limit for the number of retransmission represented by the quantity m.

To stay within the maximum allowable transmission delay for safety applications, the maximum number of nodes that can be accommodated are 252 as opposed to 363 presented in the thesis work [59]. If the number of vehicles goes beyond 252, new mechanisms to split the group should be incorporated that can be considered for future work.
Chapter 7: Conclusion and Future work

This thesis introduces the concept of defining a backup group owner in inter-vehicular communication system using Wi-Fi Direct. The backup group owner would quickly replace the group owner when the group owner can no longer serve the group. This increases the persistence of the group and availability of the communication between the devices by reducing the time to reform a group when the group owner leaves the group.

Modifications to the traditional intent value calculation are made and new parameters are proposed. By considering additional parameters such as relative velocity there is less chance of the group falling apart because of the GO moving out of range of the group. By considering the state of charge of each smartphone and the number of neighbors seen by the node in nominating the group owner, there is an increased chance of that a GO will last longer in group and also have higher availability for communication of devices within the group.

Analytical study suggests that nominating a backup owner creates the potential to avoid a considerable amount of downtime that would otherwise occur due to renegotiation of the group owner. Smartphone implementation of the proposed backup group owner mechanism and modification to the calculation of intent value is one of key scopes of future work in this field. To improve the collision avoidance system performance further, alternate mechanisms to reduce this larger setup time in Wi-Fi Direct group formation, will facilitate in faster transmission of safety messages between devices.
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