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Optimal Group Formation in Dense Wi-Fi Direct Networks for Content Distribution

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ABSTRACT Wi-Fi Direct enables direct communication between Wi-Fi devices by forming Peer to Peer (P2P) groups. In each P2P group, one device becomes the Group Owner (GO) and serves as an access point (AP) to connect the remaining devices. The group formation in Wi-Fi Direct has two major limitations. Firstly, it is initiated between two P2P devices only. It does not define any mechanism to allow more than two devices to contend for becoming GO. Secondly, it does not include a selection criteria for the GO (to allow vendor-specific implementation). These limitations can significantly reduce the performance of the Wi-Fi Direct networks. Earlier works addressed these issues using heuristic approaches which do not guarantee optimum performance. Furthermore, the selection of multiple GOs (in dense networks) has not been rigorously investigated in the literature. This paper proposes a modified group formation scheme among multiple devices. The proposed scheme formulates the GO selection problem as an optimization problem which is solved using integer programming (IP). The GOs are selected based on link capacities with the objective to maximize the overall network throughput. In multicast applications, the proposed scheme is implemented such that the minimum achievable rate by any device is maximized. The performance of the proposed GO selection scheme is extensively evaluated through realistic simulation performed in ns-3. The results reveal significant performance gains in terms of group formation time and network throughput. For instance, a throughput gain of 19.8% is achieved using a single GO. The gain is further improved by using a higher number of GOs. In multicast applications, a Packet Loss Ratio (PLR) of 2.8% is maintained. Detailed performance evaluation is presented for several scenarios considering different network sizes, number of GOs, and distribution of user's locations. Moreover, a comparison with state-of-the-art schemes is presented to validate the advantages of the proposed scheme.

INDEX TERMS Wi-Fi direct, peer-to-peer, access point, group owner, network simulators.

I. INTRODUCTION

Many technology and industry experts speculate that Device-to-Device (D2D) communication to become the main choice for content delivery in both long-range (LR e.g. 4G, 5G) and short-range (SR e.g. Wi-Fi) communication networks. The potential benefits of D2D communications in LR communication networks include: lower spectrum utilization, higher throughput, and enhanced energy efficiency. Additionally, in SR communication networks, D2D can be used to scale up the network by enabling multi-hop connectivity [1].

The key enabling technology for D2D communication in Wi-Fi networks is Wi-Fi Direct [2], which was first introduced by the Wi-Fi Alliance in 2010. The key motivation behind introducing the Wi-Fi Direct technology is to allow users to connect and share contents using standard Wi-Fi rates, without the need to connect to a Wi-Fi access point. However, since the release of Wi-Fi Direct specifications in 2010, a significant amount of research has proposed to extend the use of Wi-Fi Direct beyond the basic direct users connectivity to various real-world applications such as, opportunistic networking [3], [4], collaborative data off-loading [5], and extending cellular networks coverage such as LTE [6], [7]. Our recent survey paper [1] reports several potential applications using Wi-Fi Direct.

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In content distribution networks, Wi-Fi Direct can be used to enable multi-hop Wi-Fi networking to scale up the networks by connecting a larger number of users without compromising the performance. For instance, considering the scenario of having a group of users who are streaming videos and are in need to connect to the Internet through an AP. Assuming that the AP is capable of connecting to only a limited number of users, or if some users are located at far distances, which results in having some users with low connection rates. Thus, Wi-Fi Direct can play a vital role to improve users' experience in this case. Using Wi-Fi Direct, the devices that are closely located to the AP can act as relays to cross connect the distant users to the AP. Consequently, all devices would ultimately connect to the AP and will not suffer from poor quality links.

The extended applications of Wi-Fi Direct require several functional and design improvements in the standard Wi-Fi Direct technology. The first detailed study to evaluate the standard Wi-Fi Direct performance can be found in [8]. The study investigates various novel features defined in Wi-Fi Direct such as device discovery, group formation and energy efficiency schemes. In addition to evaluate the default features, several enhancements are proposed in [1], [9]–[12].

In [10], [12] the authors proposed an inter-group routing scheme for communication between multiple Wi-Fi Direct groups. In [1], [13], authors proposed modifications to enhance the group formation procedure. In [9], the authors proposed algorithms to achieve energy efficiency using the power saving schemes defined in Wi-Fi Direct specification [2].

Despite the efforts made to enhance the Wi-Fi Direct features and to improve the protocol's operation in real-world implementations, there are still some unresolved issues which need further consideration. For instance, in content distribution over Wi-Fi networks, the optimum selection of the GO is of high importance. As the GO is the intermediate device which relays the contents to all the group members, it is desired that the GO maintains strong connection with the AP as well as with its group members. Ideally, the GO selection should be based on several network parameters such as the Signal-to-Noise Ratio (SNR), and the achievable transmit rates parameters. Secondly, in video streaming applications, multicasting is an important feature. Thus, any proposed GO selection scheme is required to incorporate efficient and reliable multicasting support. In classic multicasting applications in Wi-Fi networks, the AP, by default, uses the lowest available rates to send multicast traffic to clients [14], causing lower network throughput. To mitigate this issue, several solutions were proposed including More Reliable Groupcast (MRG) [15], Leader Based Protocol with Acknowledgment (LBP-ACK) [16], [17], Pseudo-Broadcast approach [18], [19] and LBP with Negative Acknowledgements (LBP-NACK) approach [20], [21].

The proposed scheme in this paper aims to improve the overall performance of the content distribution network by providing optimal group formation and GO selection schemes. The proposed scheme allows the multicast traffic to be sent at higher possible bit-rates without compromising the Packet Delivery Ratio (PDR). The proposed scheme operates in a similar way to LBP in multicast applications, i.e. the selected GO acts as a multicast leader and acknowledges all traffic destined to the clients associated with the GO.

A. MAIN CONTRIBUTION

The contributions of the paper can be summerized as follow:

- A modified group formation scheme is proposed to replace the standard group formation procedure in Wi-Fi Direct. The proposed scheme eliminates the limitation of the standard group formation by allowing all network devices to participate in the GO selection, which increases the likelihood of the best GO selection, and consequently the overall network performance.
- The GO selection problem in Wi-Fi Direct networks is solved using integer programming, to achieve throughput gains. The proposed solution for the GO selection takes into account both homogeneous as well as heterogeneous traffic destined to different users. In the case of heterogeneous traffic, the proposed scheme ensures that the demand of each Wi-Fi station (STA) is met, while maximizing the overall network throughput.
- The proposed GO selection scheme incorporates multicast applications to achieve higher throughput while maintaining low packet loss, which helps to realize efficient multimedia content distribution.
- The claimed performance benefits of the proposed scheme are tested and validated by extensive realistic simulations performed in ns-3.

B. PAPER ORGANIZATION

The rest of the paper is organized as follows: Section II presents an overview of the Wi-Fi Direct technology including the network architecture, device discovery and group formation procedures. Section III briefly explains the GO selection problem and its potential benefits in terms of the overall network performance. Section IV discusses relevant research contributions that address the GO selection problem in Wi-Fi Direct networks. The proposed group formation scheme is explained in Section V. Section VI presents the system model and the proposed optimization problems for the GO selection. Section VIII discusses in details the simulation parameters, evaluation of the proposed scheme and the acquired results. Lastly, conclusions are drawn in Section IX.

II. THE Wi-Fi DIRECT TECHNOLOGY

Wi-Fi Direct technology was first introduced by the Wi-Fi Alliance [1] in 2010 to enable Wi-Fi devices to directly connect to each other without connecting to an AP. Wi-Fi Direct, initially called Wi-Fi Peer-to-Peer (Wi-Fi P2P), is built upon the IEEE 802.11 *infrastructure* mode to offer device to

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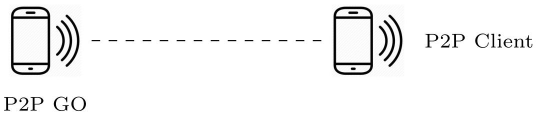
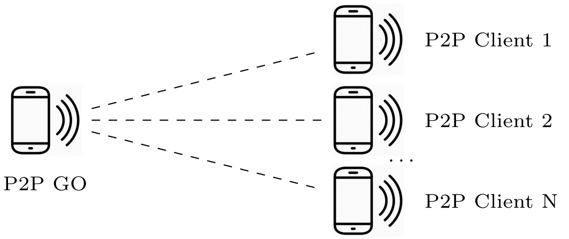
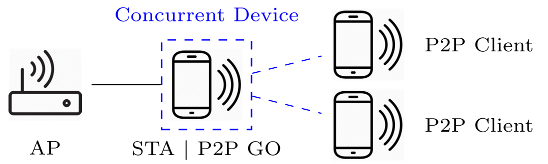
[1] http://www.wi-fi.org/



(a) 1:1 P2P group.



(b) 1:N P2P group.



(c) P2P group with concurrent P2P device..

FIGURE 1. **Wi-Fi Direct Architecture.**

device communication. The latest Wi-Fi P2P Technical specification [2] was released in 2016 (version 1.7). Wi-Fi Direct enabled devices (also called P2P devices) can discover each other to form a P2P group. In each P2P group, one P2P device assumes the role of the P2P GO and acts as an AP.

Wi-Fi Direct is becoming an interesting and suitable candidate technology for communication in several application domains including content distribution, resource sharing, multi-player online gaming, emergency alert dissemination and proximity based advertising.

Wi-Fi aware services include connecting with people nearby to play favorite games, managing meeting schedules and locations, receiving coupons and notifications from selected retailers while traversing a shopping mall, finding friends at a concert and sharing photos or location coordinates [22].

The functional entity of Wi-Fi Direct architecture is called a ''P2P group'' that is functionally equivalent to a Basic Service Set (BSS) in *legacy* Wi-Fi networks. Figure 1 illustrates different forms of P2P groups in Wi-Fi Direct networks. A P2P group consists of a P2P GO and zero or more P2P Clients. The P2P GO (sometimes referred to as ''GO'') is also called a *Soft-AP*. AP-like functions are implemented within the P2P devices. A P2P device can dynamically take the role of an AP or a client. The roles of P2P devices (i.e. P2P GO and P2P Client) are usually negotiated before creating a P2P group which remains fixed until the P2P group is inactive.

By using the proposed scheme which eliminates the standard GO negotiation phase, two benefits can be achieved: Firstly, the group formation delay between multiple devices is reduced [11]. Secondly, the best GO from more than two neighboring devices is selected.

Device discovery is a mandatory feature to be supported by all P2P devices. Prior to forming a P2P group, a P2P device runs the device discovery procedure to detect the presence of other P2P devices in its wireless range. In this procedure, P2P devices exchange *Probe Request* and *Probe Response* frames.

A P2P GO can also search on other channels to find desired devices or services. Service discovery is an optional procedure in Wi-Fi Direct. The procedure starts after the device discovery and prior to the group formation procedure. It allows a P2P device to connect to other P2P devices only if the latter offers the intended service. Using service discovery procedure, a P2P device advertises available services using link layer Generic Advertisement Service (GAS) protocol [23]. Following a successful device discovery, P2P devices can establish a P2P group. During the group formation, the device that will act as a GO is determined. Three types of P2P group formation schemes are employed in Wi-Fi Direct: standard group formation, autonomous group formation, and persistent group formation.

In *standard* group formation, two P2P devices negotiate the role of the P2P GO. The GO negotiation is a three-way handshake. During the handshake, the two devices send to each other a randomly chosen numeric value called ''intent value''. The intent value ranges from 0 to 15, and it measures the desire of the P2P device to become the P2P GO. The P2P device sending the higher intent value shall become a GO. In case both P2P devices send equal GO intent values, a tie breaker bit is used for decision and the device with tie breaker bit set to 1 shall become a GO. The P2P device selected as P2P GO shall start a P2P group session. The other P2P device can then connect to the P2P GO to obtain credentials, and exchange data. Similarly, other P2P devices and legacy Wi-Fi devices can join the P2P group as clients. In *autonomous* group formation, the role of a GO is not negotiated. Instead, a P2P device announces itself as a GO and starts sending Beacons. This process is much similar to the legacy Wi-Fi in which an AP directly sends Beacons into the network to become discoverable. The autonomous group formation is simpler and faster than the standard group formation. In *persistent* group formation, a P2P device sends an invitation to another P2P device, which was previously connected to it in a P2P group, in order to re-instantiate the P2P group. This is accomplished using *P2P Invitation Request* and *P2P Invitation Response* frames. The role of each P2P device shall remain the same as in the previously formed P2P group. To establish a persistent group, the P2P devices must declare the P2P group as persistent during the standard or autonomous formation of the group. A flag bit inside the P2P Beacons, Probe Response and GO negotiation frames is used to indicate that the P2P group is persistent or not. If the flag is not set during the group formation procedure, the P2P devices cannot re-instantiate a persistent group in the future and must start a standard or autonomous group.

The Wi-Fi Direct technology has been widely adopted in smartphones and other Wi-Fi enabled devices. However, there are still several open research problems as addressed in [1], [12], [24]–[32]. For instance, the work in [25] proposes multi-hop group-less communication in Wi-Fi Direct. The authors propose a scheduling algorithm to form emergency networks by modifying the Probe Request and Probe Response frames in the original Android Wi-Fi Direct API. In [27], the authors used SDN (Software Defined Network) based method to organize the Wi-Fi Direct groups to reduce the overall interference in a Wi-Fi network. The authors in [29] propose to build multi-hop ad-hoc networks using Wi-Fi Direct. A similar approach is adopted in [30] for inter-group communication to build multi-hop networks in Wi-Fi Direct networks. In [32], the authors propose an algorithm to dynamically change the operating channel for efficient use of spectrum and to reduce the congestion. A careful review of those studies motivates the need to propose novel approaches to standard Wi-Fi Direct functions for performance improvements.

III. THE GO SELECTION PROBLEM

Wi-Fi Direct in its standard form poses several restrictions which limit the performance of Wi-Fi Direct in several applications. Our recent study in [1] addresses the potential benefits of Wi-Fi Direct technology and the related challenges. Among others, the selection of most capable device as GO is of critical importance in several applications. Two inherent restrictions contribute to the challenge of selecting the best GO. Firstly, the standard group formation mechanism which is restricted to take place only between two devices. In our earlier work in [13], an enhancement to the Wi-Fi Direct group formation was provided by improving the selection of the GO and allowing multiple devices to form a P2P group with reduced delay. It was proposed that P2P devices can share their own intent value as well as the intent values used by their discovered neighbors using the Probe Request and Probe Response frames in the P2P Information Element (IE) attributes. Each device, and on receiving the Probe Request/Probe Response frame, updates and synchronizes its list with the neighbors. The second challenge in performing GO selection among several candidate devices is the capability of the selected GO. Several parameters define the capability of a GO including device's battery level, the strength of connection to the AP, the CPU power, the amount of RAM, and the number of neighbors the GO can connect to [1], [12]. It is very difficult to find the suitable device while optimizing over all these parameters. However, the selection of the GO can be done using weighted values of any subset of these parameters of interests in a given application. For instance, to enable short term network connections such as for data transfers, the battery level is of little importance. Similarly, to enable data transfer between two devices, the number of neighbors becomes trivial.

In content distribution applications, where the content on a local or remote server is intended to be distributed to a group of local users in the same network, the most significant parameter is the link quality between the AP and the GO as well as the link quality between the GO and the clients.

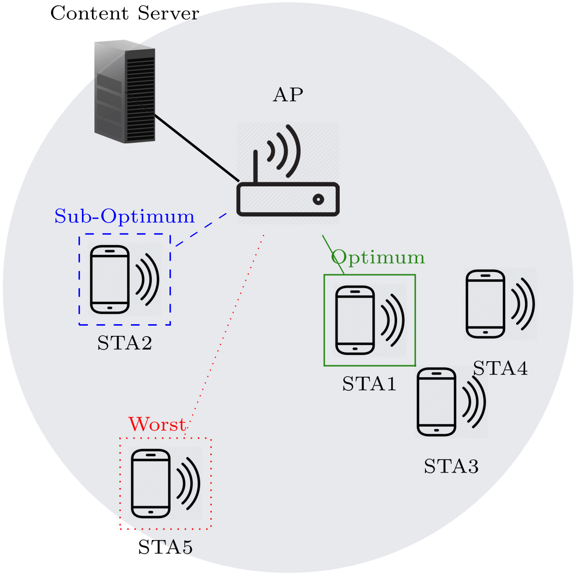


FIGURE 2. Illustration of group owner selection problem.

Multicast over Wi-Fi can be significant in several applications, such as emergency communication (push-to-talk), video distributions in enterprises, lectures delivery in classrooms, and streaming live TV channels over Wi-Fi [33]. Multicast over Wi-Fi experiences high level of Packet Error Rate (PER) due to lack of retransmission as well as low data rates, which reduces the network throughput.

IV. RELATED WORK

The GO selection problem has been of significant interest in several works [11], [12], [34], [35] due to its direct impact on the performance and persistence of the P2P group. Our previous work in [11] proposed a scheme in which P2P devices compute their intent values based on device capabilities. Four parameters were considered, namely, Received Signal Strength Indicator (RSSI), remaining battery level, number of neighbors and processing power. The intent value is calculated as the weighted sum of those parameters. Ultimately, the device with the highest intent value becomes the GO using the standard group formation scheme. However, the proposed scheme in [11] has three limitations. Firstly, the RSSI parameter of the link is a poor estimate of the link capacity. Secondly, only the link capacity of the AP-GO link is considered whereas the link capacities between the GO and the clients are ignored. Lastly, the equally weighted parameters for computing intent values provides a selection of the GO that is always merely non-optimum. Authors in [34] proposed an algorithm called "Mutual RSSI" to compute intent Values and then to perform GO selection similar to [11] to increase the average per-node throughput. However, the performance of the proposed scheme is severely impacted when the GO selection is required for connectivity to the Internet through a Wi-Fi AP or a cellular Base Station (BS). One reason of the possible poor performance of this method is that the link quality between the GO and the AP/BS imposes a bottleneck on the average network throughput. Furthermore, the work is limited to single group formation and the proposed scheme can not be used for creating multiple P2P groups to connect densely populated users.

Authors in [35] proposed a multi-hop network architecture in Content Centric Networks (CCN) using Wi-Fi Direct. In the proposed scheme, a content server which is a P2P device assumes the role of a GO in a similar way as the autonomous group formation procedure defined in [2]. The devices interested in the content become the Group Clients (GCs). The authors also stated that a GC in one P2P group can use concurrent mode to become a GO in another group. The study involves random GO selection based on the node's requirement to publish contents. A slightly different and simpler method for GO selection is proposed in [36] that is based on the amount of data load for each device. The device which has the largest data to transmit is selected as a GO.

Authors in [12] presented a distributed algorithm named "Smart Group Formation (SGF)" for group formation. The SGF algorithm performs GO selection based on a metric "GO Ability Index (GOAI)" which is very similar to [11]. The GOAI is computed as a weighted sum of parameters such as battery level, availability of Internet connection, CPU maximum frequency, amount of RAM and of non-volatile storage, etc. The weights of those parameters are tailored by the choice of application. The GOAI parameter replaces the standard intent value parameter in Wi-Fi Direct and is calculated by each device using a distributed approach. The SGF scheme consists of three distinct steps. In step 1, each node determines its bidirectional neighbors. In step 2, the nodes decide whether they can become candidate GO or not. A node marks itself as a candidate GO if it can connect to all the nodes that are connected to any of its neighbors and additionally to at least one more node. As a result, several GOs can be selected in the network. Lastly in step 3, a candidate GO unmarks itself if it has at least one bidirectional node, which is a candidate GO and has higher GOAI value than itself. Authors in [37] solve the problem of AP to STAs association to maximize the overall network throughput. The authors use heuristics to determine the optimal AP-STAs associations. Other closely related research works can be found in [38], [39].

The works in [13] and [40] propose back-up GO selection and redundant group formation respectively in scenarios where the P2P group is frequently terminated due to network dynamics. The works stated earlier [1], [11]–[13], [34], [36] requires the modifications of standard Wi-Fi Direct functions to improve the performance. The work in [25] further supports our idea of modifying the Probe Request and Probe Response frames, in their work to implement Wi-Fi Direct based multi-hop emergency communication network.

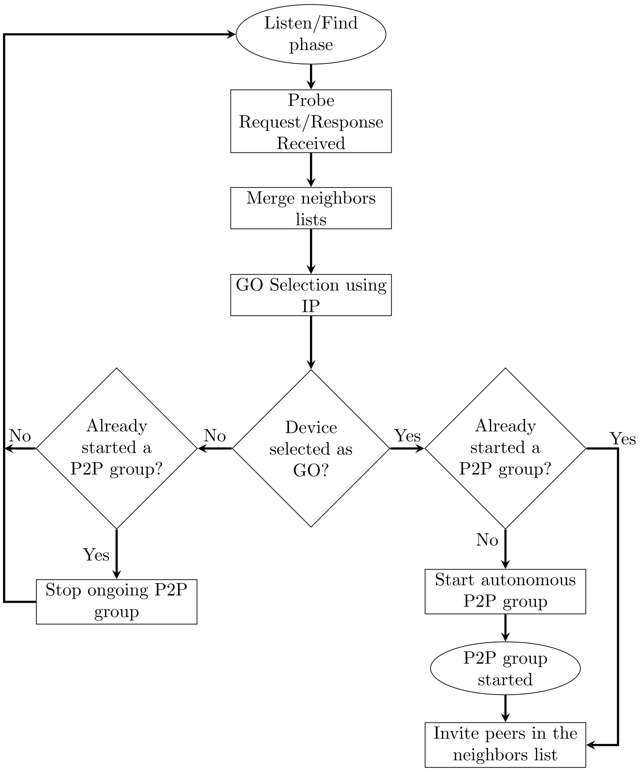


FIGURE 3. **Device state diagram.**

V. PROPOSED SCHEME

In a given set of STAs[2] randomly located in a shared wireless range and an AP that has a limitation on the maximum number of associated STAs, the AP can only connect to a few number of those STAs. However, to connect all STAs to the Wi-Fi network, the Wi-Fi Direct technology can be used to select one or more STAs to act as intermediate (or relay) devices and connect the remaining STAs to these intermediate devices.

The proposed scheme eliminates the 3-way handshake in GO negotiation which takes place between two P2P devices only. The proposed scheme preserves the intent value attribute defined in the Wi-Fi Direct specifications [2] to select the GO, however the highest intent value is now used by the device selected by the proposed scheme.

We propose to modify the standard functionality of the P2P devices as illustrated in Figure 3. In the proposed state diagram of the P2P device, each P2P device, when receives a Beacon frame from the AP, records the SNR of the link to the AP. The P2P device also sends Probe Request frames which are received by other P2P devices in its range. A P2P device on receiving the Probe Request frame records the MAC address and the SNR to the sender of the Probe Request frame. All the P2P devices which receive the Probe Request frames, reply with the Probe Response frames. The sender of the Probe Request frame, and after receiving the Probe

[2] "STA" is a device which supports Wi-Fi only, while a "P2P device" supports legacy Wi-Fi as well as Wi-Fi Direct. In this paper, the terms "STA" and "P2P device" are used inter-changeably, until explicitly mentioned

Response frames from all its neighbors, records the MAC addresses with their respective SNR values. This device then sends a second Probe Request frames and insert its complete neighbors list (i.e. MAC addresses and SNR values). Hence, all P2P devices share their complete neighbors lists. A P2P device on receiving neighbors' lists from its neighbors, combine those lists into a master adjacency matrix. The master adjacency matrix contains a list of SNR values from each P2P device to every other P2P device in the network.

Every device then runs the GO selection algorithm to determine the best GO. If a device determines itself as the best GO, it sets its intent value to 15, otherwise 0. The device with the highest GO intent value then starts an autonomous group formation and invites all the discovered devices to join the newly created P2P group.

ASSUMPTIONS

The implementation of the proposed scheme assume the following listed conditions to be always true:

- Each device shall always enable the "PROBING" feature, i.e. each STA constantly sends Probe Request frames and Probe Response frames (in response to Probe Request frames) until each device has discovered its neighbors. The Probe Request and Probe Response frames are shared during the standard device discovery phase, and no modification in the standard functions is required.
- In the proposed scheme, the Probe Request and Probe Response frames are sent with the maximum achievable transmit rates in order to calculate the link data rates used in the proposed scheme.

The proposed scheme aims to select a subset of STAs to act as relays between the AP and the GO, thus creating one or more clusters which are called P2P groups. A P2P GO for each P2P group is selected to connect the STAs in the P2P group to the AP.

We discuss two cases for the selection of candidate GOs:

- *Optimal selection* in which the selection is based on the link quality of both links (AP-GO and GO-STAs links) and
- *Sub-optimal selection* in which the selection of the GO is based on the link quality of the first hop (AP-GO) only.

For comparison purpose, we also consider a third case involving worst selection of the GO in which the GO has the poorest link quality over both hops (AP-GO and GO-STAs). In the subsequent sections, the detailed system model for the GO selection schemes is presented. All notations used in this paper are listed in Table 1.

VI. SYSTEM MODEL

Consider a Wi-Fi network where C and G denote the set of Wi-Fi clients (or STAs) and candiate GOs respectively. Let $n = |C|$ and $m = |G|$ denote the total number of STAs and candidate GOs respectively. The STAs are randomly placed around an AP. As discussed in Section V, each STA in the network computes the SNR to all the discovered devices using Probe Request and Response frames, in an array N_j, where j is the index of the node.

TABLE 1. List of key notations.

Variable	Description
j	Index of STA
i	Index of candidate GO
C	Set of STAs in the network
G	Set of Candidate GOs
n	Number of STAs in the networks
m	Number of candidate GOs in the network
D_j	Demand (i.e. Application data generating rate) of STAs
W_j	weight assigned to each STA's demand
S_{ij}	SNR of every STA to every other STA
Si	SNR of every STA to AP
U_{ij}	Link capacity between i^{th} GO and j^{th} STA
U_i	Link capacity between i^{th} GO and AP
X_{ij}	Decision variable to indicate GO-STA association
Y_i	Decision variable to indicate a candiate GO is selected as GO

$$N_j = \begin{bmatrix} id_0 & S_{(0)} \\ id_1 & S_{(1)} \\ id_2 & S_{(2)} \\ \vdots & \vdots \end{bmatrix}$$

where, id_0, id_1, .. are the MAC addresses of the devices, and S_0, S_1, ... are the respective SNR values to those nodes. The first value in the array (S_0) denotes the SNR to the AP.

Each Node share this array using the Probe Request to all of its neighbors. Each node on receiving the Probe Request frame reply with the Probe Response frame, in which it sends its own neighbors list.

Once the discovery phase is completed and all nodes have shared their neighbors lists, the next step is to transform the neighbors lists in the appropriate form required in the IP. Each node creates two arrays, a (1 × n) 1D array S_i and an (n x n) array S_{ij}. The S_i array contains the SNR of each link between the AP and each candidate GO (note: we assume that that every device is a candidate to become a GO).

$$S_i = \begin{bmatrix} S_{(0)} \\ S_{(1)} \\ \vdots \\ S_{(n)} \end{bmatrix}$$

The S_{ij} array contains the SNR values of each link between the STAs.

$$S_{ij} = \begin{bmatrix} S_{(1,1)} & S_{(1,2)} & S_{(1,3)} & \cdots & S_{(1,n)} \\ S_{(2,1)} & S_{(2,2)} & S_{(2,3)} & \cdots & S_{(2,n)} \\ \vdots & & & & \\ S_{(n,1)} & S_{(n,2)} & S_{(n,3)} & \cdots & S_{(n,n)} \end{bmatrix}$$

Although the SNR parameter is well-known and easily measurable, it is not a good estimate of the actual link data rates in Wi-Fi networks. In practical Wi-Fi implementations,

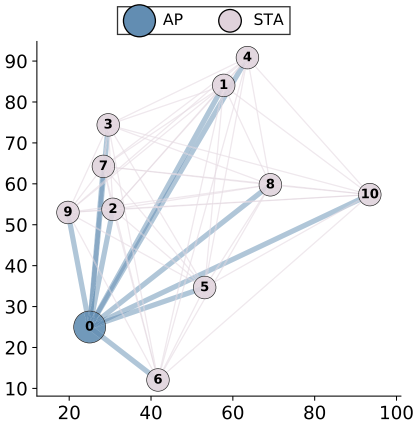


FIGURE 4. **Network topology for GO selection.**

rate adaptation algorithms [41], [42] are used instead of simple rate selection based on SNR. Hence, the S_i and S_{ij} matrices are converted into matrices of actual rates i.e. U_i and U_{ij}. The matrices U_i and U_{ij} are used in the optimization problem for GO selection.

VII. GO SELECTION ALGORITHMS

A. SINGLE GO SELECTION

Consider the case when the AP has a limit on the number of connected clients denoted as k. If the AP is already connected to $(k-1)$ STAs and has only one more STA to connect to, the proposed scheme shall select a single GO from the set of remaining STAs (denoted as n) as illustrated in Figure 4. The goal of the GO selection is to maximize the total throughput of the network. The network throughput depends on: (i) the application generation rates (D_j), (ii) the achievable link rates of STAs to AP (U_i) and (iii) the achievable link rates of each STA to its neighboring STAs (U_{ij}).

In several real world scenarios, users run different applications such as streaming audio and videos, web browsing, online gaming etc.

- If all STAs are running the same application, all STAs transmit at equal rates, and hence STAs have ''Equal Demands'' i.e. D_j becomes trivial.
- If STAs are running different applications, the data generation rates are unequal. STAs have ''Unqual Demands'' in this case and D_j shall be incorporated in selecting the optimal GO.

Due to the restriction on the number of GOs (only one), the GO selection is formulated as an un-capacitated location allocation problem with the objective to maximize the network throughput.

To formulate the problem, two decision variables are defined:

$$X_{ij} = \begin{cases} 1 & \text{if STA j is associated to } i^{th} \text{ GO} \\ 0 & \text{otherwise} \end{cases}$$

$$Y_i = \begin{cases} 1 & \text{if } i^{th} \text{ candidate GO is selected} \\ 0 & \text{otherwise} \end{cases}$$

where X_{ij} and Y_i are both binary variables.

$$X_{ij} = \{0, 1\}$$
$$Y_i = \{0, 1\}$$

The objective function is defined as a function which maximize the total link rates over both hops, i.e. the link rate on AP-GO link (U_i) and the sum of link rates of GO-STAs links (U_{ij}). It is mathematically formulated as:

$$\max \left\{ \sum_{i=1}^{m} U_i Y_i + \sum_{i=1}^{n} \sum_{j=1}^{m} U_{ij} X_{ij} \right\} \tag{1}$$

$$\text{subject to} \sum_{i=1}^{n} Y_i = 1 \quad \forall j \in C \tag{2a}$$

$$\sum_{i=1}^{m} X_{ij} = 1 \quad \forall j \in C \tag{2b}$$

$$X_{ij} = 0, 1 \quad \forall i \in G,\ j \in C \tag{2c}$$

$$Y_i = 0, 1 \quad \forall i \in G \tag{2d}$$

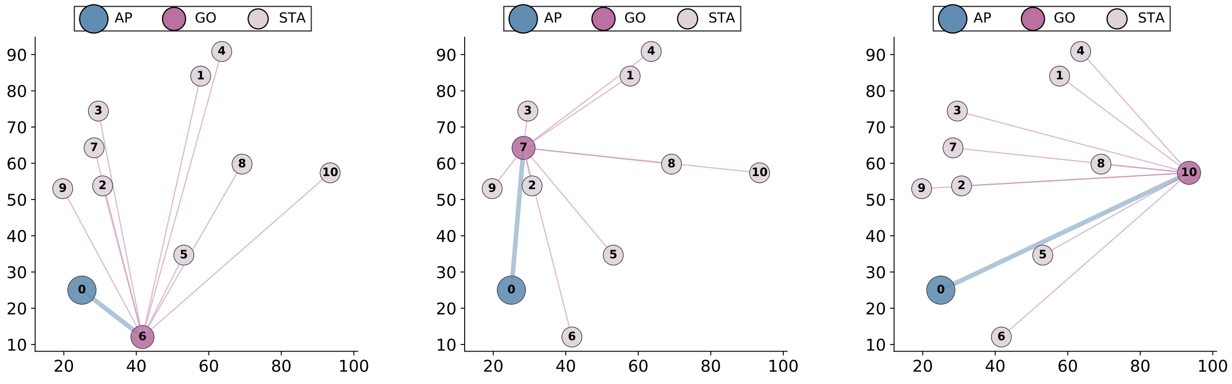
Constraint (2a) ensures that only one GO can be selected. The constraint is explicitly required in the case of single GO selection. Constraint (2b) ensures that every STA j can only connect to one GO.

In addition to the aforementioned optimal selection scheme, two other selection schemes are also presented. A sub-optimal selection and worst GO selection: In sub-optimal selection of the GO, the objective is to maximize the link rates of the AP-GO link (U_i) only. The objective function for sub-optimal selection eliminates the second part of the aforementioned optimization equation 1 and includes the first part $\max \sum_{i=1}^{m} U_i Y_i$ only. This type of sub-optimal selection is applicable to all other schemes in the subsequent sections of this paper. In the worst GO selection scheme, the optimization problem always minimizes equation 1. The worst GO selection scheme is used for comparison to assess the maximum possible benefit of the optimal selection.

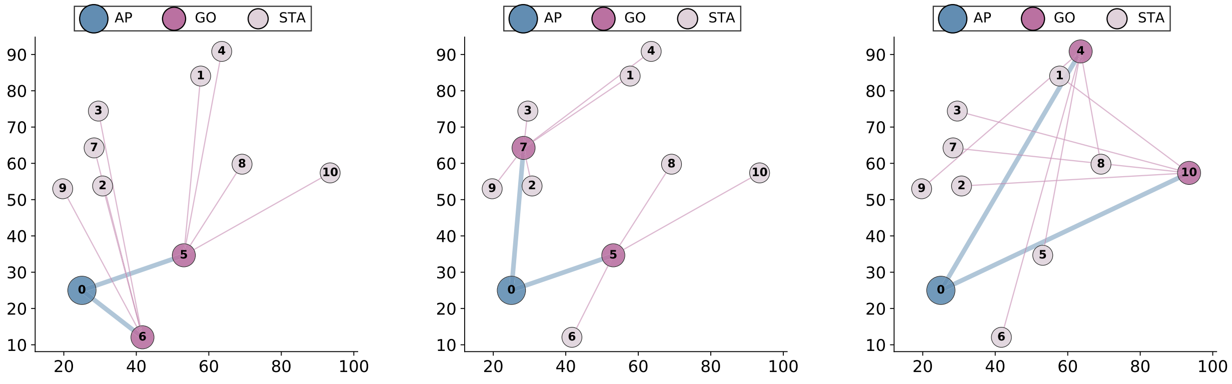
The three GO selection schemes, sub-optimal, optimal and worst GO selection are illustrated in Figure 5a, 5b and 5c respectively. The algorithm produces a full adjacency matrix X_{ij}^* and Y_i^*. The X_{ij}^* and Y_i^* matrices are of the same shapes as X_{ij} and 1D matrix Y_i. Each element in Y_i^* that is equal to 1 indicates the index of the node which is selected as GO.

B. MULTIPLE GO'S SELECTION

The theoretical maximum number of clients that a GO can support (in a single P2P group) depends on the Wi-Fi Direct implementation. For instance, the implementation of Wi-Fi Direct in Android OS allows up to 254 clients to connect to a single GO, however this is not practical for a resource-limited wireless device. For a large set of STAs, a single GO may not be capable to meet the demands of all STAs, and hence



(a) Sub-Optimal GO **(b)** Optimal GO **(c)** Worst GO



(d) Sub-Optimal GOs (Multiple) **(e)** Optimal GOs (Multiple) **(f)** worst GOs (Multiple)

FIGURE 5. GO Selection usiIP (a) single sub-optimal GO: highest rate on AP-GO link (b) single optimal GO: highest rates on both AP-GO and GO-STA links (c) single worst GO: lowest rates at all links (d) multiple sub-optimal GOs: highest rates on AP-GO links (e) multiple optimal GOs: highest rates on both AP-GO and GO-STA links (f) multiple worst GOs: lowest rates at both AP-GO and GO-STA links.

multiple GOs need to be selected to form several P2P groups. In multiple GO selection problem, the achievable link data rates between the GO and the AP impose an upper bound on the amount of data that it can serve without significant packet delay or packet loss. Hence, this upper bound shall be applied as a constraint to formulate a constrained optimization problem for multiple GOs selection.

In a P2P group that has N P2P clients connected to the GO, each device can roughly utilize $1/N$ of the total transmission time. Given the channel capacity for a single user j to GO i is U_{ij}, the total GO throughput can be calculated as:

$$U_i^{DL} = \sum_{n=1}^{N} U_{ij}^{DL} \tag{3}$$

The objective of the optimization problem is a function that maximize the achievable channel capacity (or achievable data rates) over two hops, i.e. AP-GO links (U_i) and GO-STA links (U_{ij}). The problem can be exactly formulated as:

$$\max \left\{ \sum_{i=1}^{m} U_i Y_i + \sum_{i=1}^{n} \sum_{j=1}^{m} U_{ij} X_{ij} \right\} \tag{4}$$

$$\text{subject to } \sum_{i=1}^{m} X_{ij} = 1 \quad \forall j \in C \tag{5a}$$

$$\sum_{j=1}^{m} X_{ij} D_j' U_{ij} \leq (U_i Y_i - D_i' Y_i)$$

$$\forall i \in G, \ \forall j \in C \tag{5b}$$

$$X_{ij} = 0, 1 \quad \forall i \in G, \ \forall j \in C \tag{5c}$$

$$Y_i = 0, 1 \quad \forall i \in G \tag{5d}$$

Constraint 5a ensures that each STA can only connect to a single GO. Constraint 5b ensures that the sum of effective throughput of STAs connected to a GO i shall be equal or less than the GO effective throughput to the AP.

C. GO'S SELECTION FOR MULTICAST APPLICATIONS

In a typical Wi-Fi implementation, multicast traffic is sent at the lowest available rates in the AP. The lowest rate is chosen to ensure reliability of the transmission as the multicast traffic is not acknowledged by the recipients. This leads to severe degradation of the achievable network throughput.

In a classic downstream content distribution scenario, which involves contents delivery to a number of STAs as depicted in Figure 2, the lowest link rate of an STA j to a candidate GO i is denoted by r and is defined as "the minimum link rate achieved by a device (usually device with the lowest SNR value to the AP) in the network". The proposed scheme aims to maximize the minimum transmit rate between the GO and STAs. The optimization problem is known as "Max-Min" problem.

The modified Max-Min objective function is defined as:

$$\max (r) \tag{6}$$

$$\text{subject to} \sum_{i=1}^{m} X_{ij} = 1 \quad \forall j \tag{7a}$$

$$X_{ij} \leq y_i \quad \forall i \in G,\ \forall j \in C \tag{7b}$$

$$X_{ij} = 0, 1 \quad \forall i \in G,\ \forall j \in G \tag{7c}$$

$$Y_i = 0, 1 \quad \forall i \in G, \tag{7d}$$

Constraint 7a ensures that each STA can connect to only one GO, while constraint 7b forces every GO to connect to at least one STA.

The data rate to send multicast traffic over the AP-GO link is selected based on the SNR of the link, whereas constant multicast rate is used at the GO to send multicast traffic to the clients. The multicast rate is selected as the minimum rate supported by an STA which is connected to the GO.

VIII. SIMULATION RESULTS

To implement the proposed scheme, we deploy a single AP and a number of STAs. Each node in the simulation model is identified by its *node_id*. The AP ($node\_id = 0$) is positioned at $(25, 25, 10)$, whereas the STAs ($node\_id = i, where\ i = 1, 2, ...n$) are randomly positioned at (x_i, y_i, z_i). The coordinates of STAs (x_i, y_i, z_i) are randomly chosen from Uniform and Gaussian (Normal) distributions. The positions of the AP and STAs remain fixed throughout the simulation.

The optimization problems are solved in the convex optimization tool CVXPY [43], [44]. The proposed scheme explained in the previous section is evaluated using ns-3 simulations. The simulation parameters used for evaluation are listed in Table 2.

TABLE 2. Simulation parameters.

Parameter	Single GO	Multiple GOs
Network Topology		
Topology (m x m)	multiple	multiple
No. of APs	1	1
No. of GOs	1	2, 3
No. of STAs	5, 10, 15, ..30	10, 15, 20, .. 50
Position of AP	Fixed	Fixed
Distribution of STAs	Random	Random
PHY Layer		
Transmit Power (dbm)	16	16
Transmit gain	0	0
Receive gain	0	0
Channel	1	1, 6, 11
Propagation Model	LogNormal	LogNormal
Spatial streams	1	1
Transmit Antennas	1	1
Receive Antennas	1	1
MAC Layer		
MAC standard	802.11n	802.11n
RTS/CTS	Disabled	Disabled
Rate Adaptation	Minstrel HT	Minstrel HT
Application		
Payload size (Bytes)	1400	1400
Application rate (Mbps)	1	1
Simulation		
Simulation Time (s)	100	100

A. THROUGHPUT PERFORMANCE

The proposed scheme is first evaluated for improvement in the overall network throughput. A network of 10 STAs is deployed where the STAs are randomly distributed in an area of 50 × 50 (m^2). The AP is located at position (25,25,10). In the first scenario, a single STA is selected as GO and the remaining STAs are connected to the GO to form a P2P group. The GO also associates to the AP to cross-connect the STAs to the AP. Three different simulations are performed. In each simulation, a GO is selected using the Optimal, Sub-optimal and Worst selection schemes as defined in Section VII-A. In the second scenario, 20 STAs and 2 GOs are selected in each simulation using the Optimal, Sub-optimal and worst selection. The purpose is to evaluate the significance of the proposed scheme in dense networks using higher number of GOs. The parameters related to topology, Physical layer, MAC layer, application and simulation are given in Table 2.

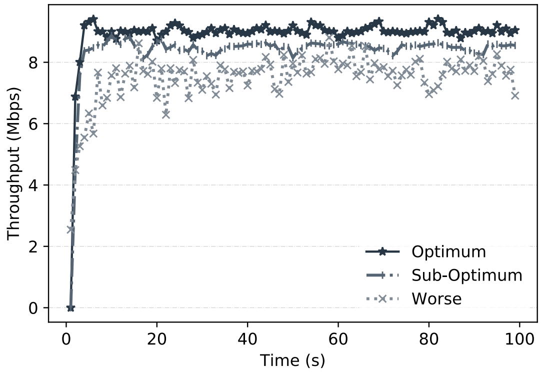


FIGURE 6. Network throughput (Mbps) using Single GO (Optimal Vs. Sub-optimal Vs. Worst GO selection).

The throughput gains for the three GO selection schemes are presented in Figure 6 considering q single GO. It can be observed that the worst selection of GO can significantly degrade the throughput performance. As the worst GO is the one which has poorest link quality to the AP as well as to the STAs in the network, it uses lower MCS values for transmissions. The throughput is also more random and varying over time. On the other hand, the proposed optimal selection provides more stable and higher throughput over time. The sub-optimal selection is relatively higher than the worst case, but lower than the optimal selection as expected. The average

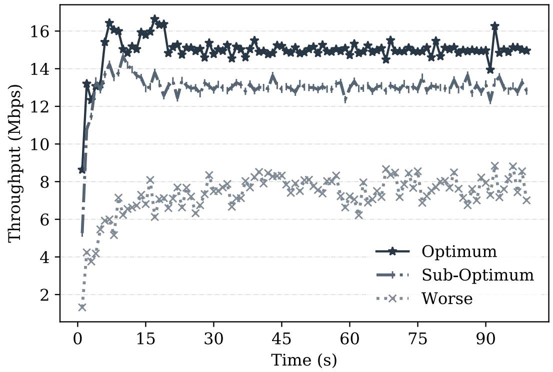


FIGURE 7. Network throughput (Mbps) using Multiple GOs (Optimal Vs. Sub-optimal Vs. Worst GOs selection).

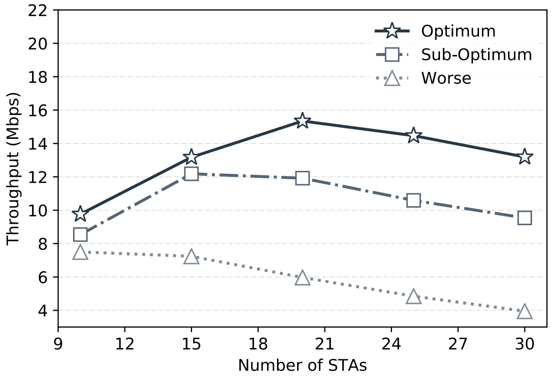


FIGURE 8. Average network throughput versus varying number of STAs while considering single GO. (Optimal Vs. Sub-optimal Vs. Worst GO selection).

throughput of the network is 8.97 Mbps, 8.53 Mbps and 7.49 Mbps for optimal, sub-optimal and worst GO selection respectively. Thus the optimal selection of GO has the potential of achieving throughput gain of 19.8% as compared to the worst selection. The throughput performance of the proposed scheme using multiple GOs is given in Figure 7. The throughput gain of the proposed scheme is more evident for multiple GOs. In this scenario, the throughput using the optimal and sub-optimal selection is increased by 1.8x and 1.6x as compared to the worst selection respectively.

The reason for the higher throughput gain in the optimal selection scheme, is the the selection of the best GO by taking into account the link quality over all links. It ensures to select the GO which has (i) highest SNR value to the AP, and (ii) highest SNR values over all links to STAs connected to it. The set of two conditions is mandatory for optimum performance. For instance, if only the first condition is met, i.e. the device with the highest SNR to the AP is selected (sub-optimal selection), it is likely that the device may be closely placed to the AP but have relatively large distances from other devices, and hence poor link qualities over those links. Thus the GO has the capacity to transmit to the AP at a much higher data rates but on the other hand, the STAs transmit at much lower rates to the GO which causes the effective throughput to decrease. The combination of the two conditions ensures that the device which achieves higher link rates to all STAs shall be selected provided that it has enough link rate to the AP as well, to transmit its own data as well as the data transmitted by all STAs connected to it, without any delay. Thus, the optimal selection scheme avoids congestion in the network and improves the effective link capacities or throughput.

B. THROUGHPUT VERSUS NUMBER OF STAS

The performance of the proposed scheme is further investigated by changing the number of users in the network. When the number of STAs in the network is increased, the network performance is impacted in two ways. Firstly, the increase in number of STAs increases the traffic volume in the network which will increase the throughput to some extent. However, as the network becomes saturated, the throughput begins to decrease. The point of interest in this evaluation is the time duration of non-saturation. If the GO can maintain better connections over all links, higher data rates are used and saturation can be avoided for a relatively higher number of STAs.

In Figure 8, the performance of the proposed optimal and sub-optimal selection is compared against the worst selection of the GO. The number of STAs in the network is increased from 10 to 30 and the throughput is computed. It can be observed that the throughput decreases in the worst GO selection case when the network has more than 10 STAs. The throughput is minimum at 30 STAs which indicates a congestion state. In comparison, in the sub-optimal GO selection, the throughput increases significantly until the network has 15 STAs and remains nearly constant till 20 STAs. A slight reduction in throughput is observed after the number of STAs increases from 20 to 30. The performance of the optimal selection provides the highest throughput gain, as expected, for all numbers of STAs. For 10 to 15 STAs, the difference in throughput for optimal and sub-optimal selection is small, but which increases afterwards. The throughput decreases when the number of STAs becomes more than 20. The rational behind the better performance of the optimal selection scheme at relatively higher number of STAs is the capability of the GO to attain higher data rates for a large subset of STAs connected to it. The capability is relatively less in the sub-optimal selection.

The superior performance of the optimal GO selection is evident in Figure 8, however, it is further investigated using more than one GOs. Intuitively, if a single GO is optimally selected, the throughput gain improves due to the capability to attain higher data rates. Consequently, the performance gain should become more evident as the number of GOs increases. More precisely, while increasing the number of STAs, the higher number of GOs shall push the saturation point towards the right. To verify the impact of the higher number of GOs in the network of different sizes, the proposed optimal selection scheme is evaluated at 1, 2 and 3 number of GOs, while increasing the number of STA from 10 to 50.

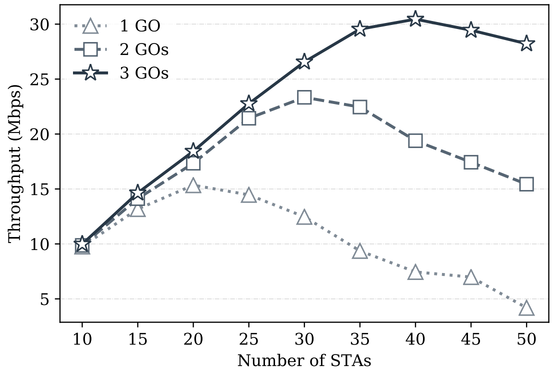


FIGURE 9. **Average network throughput versus Varying number of STAs using Multiple GOs (1, 2 and 3).**

The results are presented in Figure 9. It can be observed that the higher number of GOs not only increases the throughput but also pushes the saturation point towards higher number of STAs.

The intuition behind the higher throughput gains following an increased number of STAs is clearly the more amount of data being transmitted by the STAs. However, when the number of STAs is further increased (i.e. more than 10 in the worse case, 15 in the sub-optimal case and 20 in the optimal case), throughput drops. At this stage, the total amount of data transmitted by the STAs in a given time becomes higher that the uplink capacity of the GO which causes congestion, and thus a drop in throughput. The GO cannot transmit the data it receives from the STAs and its own data in the given time. The difference between the uplink rate and the effective downlink rates of the GO becomes less when multiple GOs are implemented. With a higher number of GOs, the congestion can be avoided for a higher number of STAs in the network. The reasons are two-fold. The primary reason is that using a higher number of GOs means more links are available to transmit the same amount of data to the AP. Secondly, multiple groups are formed which increase the link rates on the GO-STAs links.

C. THROUGHPUT VERSUS STAS DISTRIBUTION

In real Wi-Fi deployments, users distribution vary in different scenarios. To show the impact of user distribution on the performance of the proposed scheme, the three GO selection schemes are first evaluated with STAs positions following a uniform random distribution. Furthermore, three independent scenarios with area sizes of 50 × 50, 70 × 70 and 100 × 100 (m^2) are simulated and throughput is computed to validate the performance of the proposed scheme. The results are presented in Figure 10. It can be observed that the proposed scheme using optimal selection produces the highest throughput gains in all scenarios as compared to the sub-optimal and worst selection schemes. This validate the benefit of the proposed scheme. Another observation is that the throughput gain decreases with increasing the area size. The reason behind this is that, by increasing the area, the inter-STAs distances increase and consequently the attained data rates are decreased. To further quantify the results, the average throughput gains in all scenarios are computed. The results show that the optimal selection achieves average throughput gains of 6.5% and 17.5% as compared to the sub-optimal and worst selection cases, respectively. Similarly, the sub-optimal selection scheme achieves 10.3% higher throughput gain as compared to the worst selection scheme.

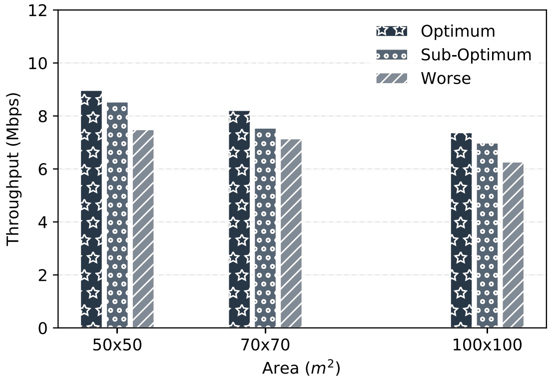


FIGURE 10. **Evaluation of Network Throughput versus STAs Distributions (STAs are uniformly distributed in areas of various sizes (m^2)).**

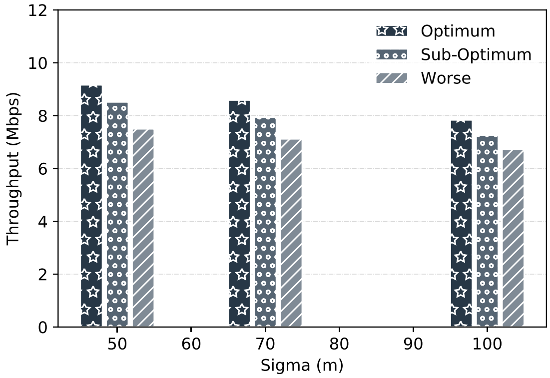


FIGURE 11. **Evaluation of Network Throughput versus STAs Distributions (STAs are normally distributed with different scale parameter).**

The proposed scheme is then evaluated with STAs positions distributed as a Gaussian random variable. Thus a higher number of STAs are located closer to the AP. Three scenarios with different values of the Scale (σ) parameter i.e. 50, 70 and 100 are deployed. The simulation results are presented in Figure 11. The analysis of results show that the optimal selection achieves average throughput gains of 7.9% and 19.8% as compared to the sub-optimal and worst selection cases, respectively. Similarly, the sub-optimal selection achieves 11.1% higher throughput gain as compared to the worst selection of the GO.

D. THROUGHPUT AND PACKET LOSS USING MULTICASTING

The proposed scheme for GO selection using multicast downlink traffic is given in Section VII-B. Multicasting can increase throughput dramatically, however, it causes higher packet loss. The proposed scheme aims to benefit from

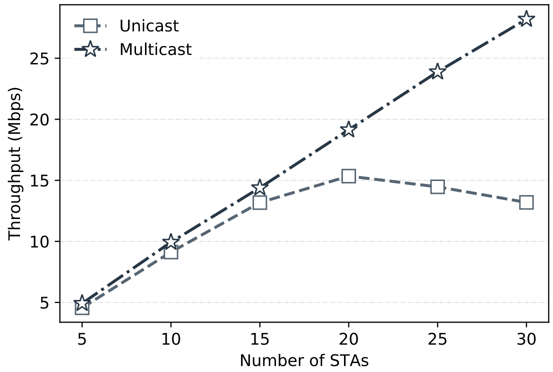


FIGURE 12. Network Throughput using Unicast and Multicast Traffic (STAs are uniformly distributed in 70 × 70 grid).

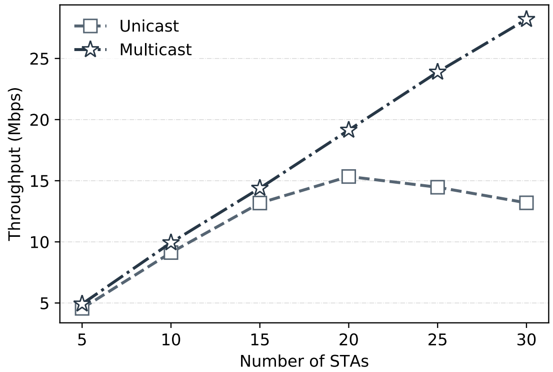


FIGURE 13. Network Throughput using Unicast and Multicast Traffic (STAs are normally distributed with Scale = 70m around AP).

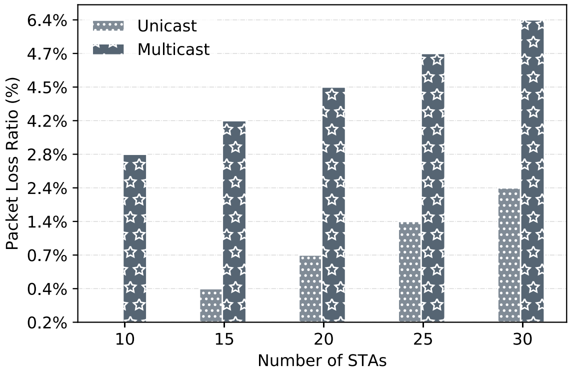


FIGURE 14. PLR using Unicast and Multicast Traffic (STAs are uniformly distributed in 70 × 70 grid).

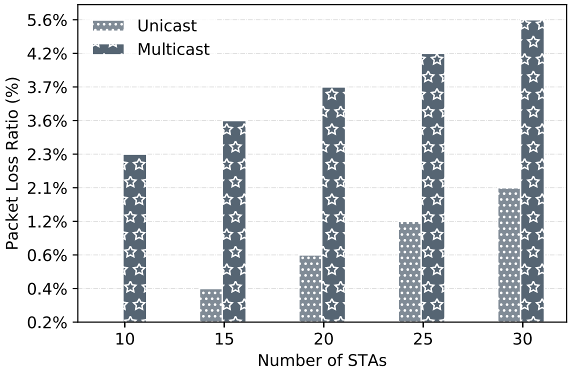


FIGURE 15. PLR using Unicast and Multicast Traffic (STAs are normally distributed with Scale = 70m around AP).

multicasting to achieve higher throughput without compromising packet loss. The performance of the proposed scheme is first evaluated by computing the throughput gains for a single GO using unicast and multicast traffic scenarios. In the first scenario, the positions of STAs are distributed as a uniform random variable, whereas in the second scenario, the positions of STAs are following Gaussian distributions. The throughput gains are computed for different number of STAs and the results are presented in Figure 12 and 13. The throughput for multicast traffic as compared to unicast traffic is evident in both figures. It is not an unexpected result as multicasting can achieve a similar throughput performance due to the fact that all STAs in the multicast group receive the same data. The relative benefit of the proposed scheme using multicast traffic increases as the number of STAs increases in the network. The only reduction in the throughput is due to packets' loss that occurred at some STAs which is reflected in the figures.

The analysis of throughput gains in Figure 12 show that the proposed scheme with multicast can increase the throughput by 8% as compared to unicast. The throughput gain increases by 2.1× when the number of STAs increases to 30 STAs. Similarly, Figure 13 shows a throughput gain of 1.97× for 30 STAs, when the positions are Gaussian distributed.

The prime concern in multicast over Wi-Fi networks is the packet loss i.e. Higher packet loss is intolerable in delay sensitive applications. It is therefore necessary to evaluate the packet loss performance of the proposed scheme. Ideally, the PLR in multicast should be close to unicast transmission, which is practically not achievable. However, the proposed scheme aims to achieve a reasonably low PLR using multicast transmission. In Figure 14 and 15, the PLR of the proposed scheme using unicast and multicast traffic is evaluated for a varying number of STAs, randomly placed using uniform and Gaussian distributions, respectively. The figures show an incredibly higher PLR (%) for multicast traffic as compared to unicast traffic. The rational behind high packet loss is well-known in the literature, which is caused by the lack of acknowledgments in multicasting. However, the PLR is significantly controlled for a smaller number of STAs (i.e. 2.8% and 2.3% for uniform and Gaussian distributions, respectively).

The intuition behind achieving a reasonably lower packet loss in multicast traffic is the objective function which selects the device that maximizes the minimum link rates to all STAs. Thus, the selected GO sends multicast traffic not at the lowest link rate (in the MAC implementation), but at the lowest rate supported by the STA with poorest link quality. If the STA is just located at the edge, it can only support the lowest link rate (in the MAC implementation), otherwise the multicast rate would be higher than the lowest available rate in the MAC.

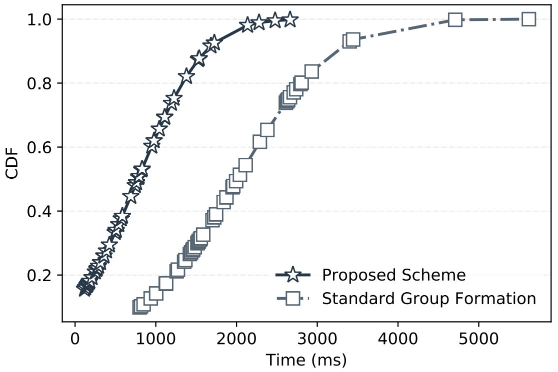


FIGURE 16. **Comparison of group formation delay.**

E. PERFORMANCE COMPARISON

1) GROUP FORMATION DELAY

One of the clear advantages of the proposed scheme is having a faster group formation as compared to the standard group formation scheme. The intuition behind this potential advantage is that the proposed scheme eliminates the 3-way handshake procedure for sharing the intent values, and instead shares the attributes in the device discovery process using the modified Probe Request and Probe Response frames. A comparison of the group formation delay of the proposed scheme versus standard group formation in Wi-Fi Direct is presented in Figure 16.

Figure 16 clearly shows a faster group formation using the proposed scheme as compared to the standard formation. The figure shows that the group formation delay using the proposed scheme is somehow random between 1 to 3 seconds, whereas it is between 1 to 5 seconds in standard group formation. Additionally, it shows that in 80% of the time, the proposed scheme takes less than 3 seconds to form the group.

2) THROUGHPUT GAIN

To validate the benefit of the proposed scheme in terms of throughput gain, the proposed scheme is compared with other methods discussed earlier in Section IV, i.e. standard group formation [2], RSSI based scheme [34] and load-based scheme [36]. To perform the comparison, multiple simulations are performed using random STAs' placement. The STAs are configured with different data generation rates, randomly chosen between 512 Kbps and 1 Mbps. Several simulations are run and the results are plotted in Figure 17 to show a comparison of the throughput gains achieved using the proposed scheme, versus the related works.

The results show that the proposed scheme outperforms the standard scheme by achieving 65% more gain in the average throughput. The proposed scheme improves throughput gain by 18% and 54% as compared to RSSI-based and load-based schemes. The reason for higher throughput gains using the proposed scheme is that it considers the actual link rates available at each STA as well as the amount of data load, thus combining the benefits of both the RSSI-based scheme [34] and load-based selection scheme [36]. On the contrary, the RSSI based scheme ignores the data load of the devices. This limitation can lead to the selection of a GO which has the highest RSSI to the AP, but lowest date load, and other devices with higher loads can achieve low link rates to the GO, thus lowering the throughput. Similarly, the load-based scheme does not consider the link rates. A device with highest load is selected as a GO, which can benefit the device itself to transmit at a higher rate on the single hop link, however other devices with even slightly less load achieves low link rates on the dual-hop links which significantly reduces the throughput. In the case of standard group formation, the GO is selected randomly and thus the throughput is always random. The throughput vary from a minimum (when the worse GO is selected) to a maximum value (when the optimum GO is selected).

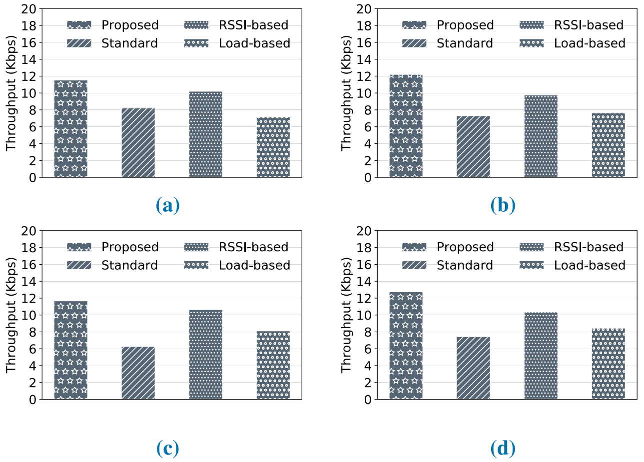


FIGURE 17. **Throughput Comparison of Proposed Scheme versus standard group formation, RSSI-based selection and Load-based selection schemes.**

F. OVERHEAD AND COMPLEXITY ANALYSIS

The computational complexity and overhead of the proposed scheme is evaluated to validate its significance in practical networks. It is worthy to note that the proposed scheme does not increase any significant overhead as compared to the standard group formation in Wi-Fi Direct [2]. The proposed scheme collects the information about its neighbors using the standard Probe Request and Probe Response frames that are transmitted in the device discovery phase. Thus, it does not cause any additional overhead. Furthermore, the GO negotiation procedure is replaced by the proposed GO selection scheme. The intent value parameter in Wi-Fi Direct standard is kept unchanged by the proposed scheme. The device selected as a GO by the optimization algorithm simply sets its intent value to the maximum (i.e. 15) and announces itself as a GO similar to the autonomous group formation.

The computational complexity of the proposed scheme to find the set of optimal GOs is evaluated in Figure 18. The GO selection algorithm (for single GO and multiple GOs) is run for different network sizes to compute the run time of the algorithm. Moreover, monte carlo simulation with

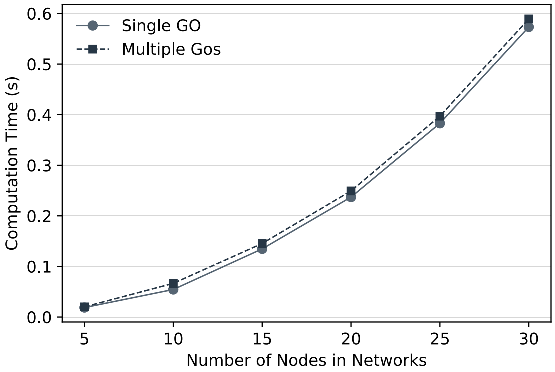


FIGURE 18. **Computational complexity.**

100 iterations is performed to calculate the average run time. The results are plotted in Figure 18.

It can be clearly observed in Figure 18 that the computation time increases by increasing the number of nodes in the network due to increase in the solution space i.e. the size of X_{ij} and Y_i arrays. However, even for a network size of 30 nodes, the algorithm takes an average time of 0.6 seconds. Recalling the group formation time of the proposed scheme (approximately 3 seconds) in Figure 16, it can be concluded that solving the optimization problem takes very little time in the GO selection process and that most of the time is taken by frames exchange to establish the connections between the GO and the P2P devices.

IX. CONCLUSION

The paper proposes an optimal group formation scheme to form optimal Wi-Fi Direct groups. The proposed scheme in this paper can be used in applications such as content distribution over Wi-Fi networks using unicast and multicast traffic. The performance of the proposed scheme is evaluated and validated using ns-3 simulations. Simulation results report performance gains in terms of throughput and PLR in several scenarios. The proposed scheme is used for optimal and sub-optimal selection of the GO. In small networks with fewer devices and single GO, a throughput gain of 19.8% is achieved using the proposed scheme as compared to the worst selection of GO. In large networks, the throughput gain is increased by 2.4 times using a single GO. The performance gain using multiple GOs is also validated. The performance evaluation of the proposed scheme shows high throughput gains when the users are uniformly distributed as compared to when they are normally distributed. In addition, the proposed scheme can be efficiently used with multicast applications to benefit from the higher throughput gains in multicasting while maintaining a fair PLR. Lastly, the computational complexity analysis shows that the overhead caused by the proposed scheme is minimum which makes it suitable for practical implementation.

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