IEEE Access
Multidisciplinary ⋮ Rapid Review ⋮ Open Access Journal

Received April 7, 2019, accepted May 1, 2019, date of publication May 10, 2019, date of current version June 5, 2019.

Digital Object Identifier 10.1109/ACCESS.2019.2916041

A Novel UAV-Aided Network Architecture Using Wi-Fi Direct

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This work was supported by the NPRP through the Qatar National Research Fund (a member of Qatar Foundation) under Grant NPRP 8-627-2-260.

ABSTRACT The use of unmanned aerial vehicles (UAVs) in future wireless networks is gaining attention due to their quick deployment without requiring the existing infrastructure. Earlier studies on UAV-aided communication consider generic scenarios, and very few studies exist on the evaluation of UAV-aided communication in practical networks. The existing studies also have several limitations, and hence, an extensive evaluation of the benefits of UAV communication in practical networks is needed. In this paper, we proposed a UAV-aided Wi-Fi Direct network architecture. In the proposed architecture, a UAV equipped with a Wi-Fi Direct group owner (GO) device, the so-called Soft-AP, is deployed in the network to serve a set of Wi-Fi stations. We propose to use a simpler yet efficient algorithm for the optimal placement of the UAV. The proposed algorithm dynamically places the UAV in the network to reduce the distance between the GO and client devices. The expected benefits of the proposed scheme are to maintain the connectivity of client devices to increase the overall network throughput and to improve energy efficiency. As a proof of concept, realistic simulations are performed in the NS-3 network simulator to validate the claimed benefits of the proposed scheme. The simulation results report major improvements of 23% in client association, 54% in network throughput, and 33% in energy consumption using single UAV relative to the case of stationary or randomly moving GO. Further improvements are achieved by increasing the number of UAVs in the network. To the best of our knowledge, no prior work exists on the evaluation of the UAV-aided Wi-Fi Direct networks.

INDEX TERMS Access point, group owner, NS-3, unmanned aerial vehicle, Wi-Fi Direct.

I. INTRODUCTION

The desire for higher throughput and extended coverage in dense Wi-Fi networks has triggered the evolution of device-to-device (D2D) communication. In 2010, Wi-Fi Alliance released the first specification of Wi-Fi Direct (also called Wi-Fi Peer-to-Peer or Wi-Fi P2P) for direct communication between Wi-Fi devices. The specification was later revised in 2016 (version 1.7) [1]. The Wi-Fi Direct technology was originally promoted to enable direct connectivity among home appliances for simple applications such as file transfer, printing and screencasting. However, new attractive applications have been proposed in the literature [2]–[4]. Wi-Fi Direct can be used to extend network coverage by deploying multi-hop networks.

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 network [5]. A P2P Group consists of a P2P Group Owner (P2P GO) and zero or more P2P Clients. The P2P GO (sometimes referred to as ‘‘GO’’) is also called a *Soft-AP* [1]. All AP-like functions are implemented within the Wi-Fi P2P device and a P2P device can dynamically take the role of a P2P GO or P2P Client. The roles of P2P devices (i.e. P2P GO and P2P Client) are usually negotiated before creating a P2P Group and remain fixed until the P2P Group is active.

A P2P device with dual interfaces can simultaneously connect to two different networks. Such a device is called Concurrent P2P device. A Concurrent P2P device can be used in two different ways to create multi-hop networks: (i) simultaneously connect to a Wi-Fi access point (AP) and serves as a legacy client and as a Soft-AP in a Wi-Fi Direct

The associate editor coordinating the review of this manuscript and approving it for publication was Mubashir Husain Rehmani.

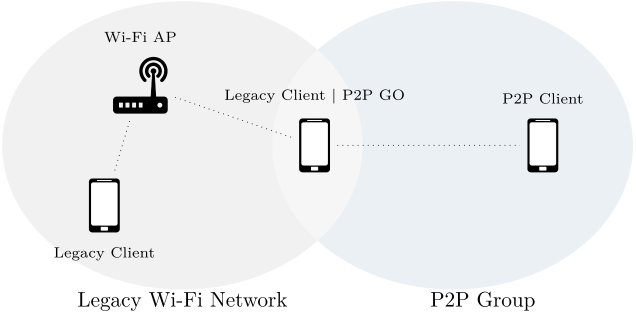


FIGURE 1. **A Wi-Fi direct P2P group.**

network (P2P Group) (ii) simultaneously connect to a Wi-Fi Direct Soft-AP (P2P GO) as a P2P client and as a Soft-AP (P2P GO) in another Wi-Fi Direct network (P2P group). Fig. 1 shows a P2P Group with a Concurrent P2P device with two interfaces. The multi-hop Wi-Fi Direct networks not only enable large-scale deployments but also has the potential to improve the aggregate throughput of the network. Hence, such deployments are very attractive for content distribution in densely populated areas.

In addition to the extending scale of the network and achieving higher network throughput, Wi-Fi Direct also has the potential of energy-efficient communication. The advanced power saving schemes introduced in the Wi-Fi Direct specifications [1] enables the battery-powered Soft-AP (P2P GO) to save energy using two sophisticated algorithms called Opportunistic Power Saving (OppPS) and Notice of Absence (NoA) schemes. In OppPS scheme, the GO is allowed to save power when its clients are in the *Sleep* mode. The GO announces its presence period called "CTWindow". At the end of the CTWindow, if all nodes are in *Sleep* mode, the GO can also go to *Sleep* mode until the next Beacon. However, at the end of CTWindow, if one of the P2P Client nodes is in *Active* mode, then the GO must remain Active until the next Beacon. In the NoA scheme, the GO announces via Beacons and Probe Response frames an "absence period". During the absence period, its clients cannot access the channel, thus the GO shut down its radio to save energy used in transmission or reception. The absence period is announced in Beacons using NoA schedule, consisting of four parameters:

1) *Duration* - the length of absence period,
2) *Interval* - the time between two consecutive absence periods,
3) *Start Time* - the start time of the first absence period after the current Beacon, and
4) *Count* - the number of absence periods in the current NoA schedule.

It is worthy to mention that the Wi-Fi Direct specification does not define the values of these parameters.

The aforementioned advantages pose Wi-Fi Direct as an attractive technology for multi-hop D2D networks. However, since the release of the first specification in 2010, Wi-Fi Direct has no commercial deployments. One of the reasons is the lack of efficient group formation mechanism in the standard Wi-Fi Direct to quickly deploy a Wi-Fi Direct network [2], [4], [6], [7]. The efficient group formation involves the selection of the most capable device in the network as the Group owner (GO) or Soft-AP to improve the network throughput which extends the coverage by connecting more devices and increase network lifetime. The selection of the best candidate device as GO and enhancement of group formation scheme is proposed in [3] and [4] respectively. These and other state-of-the-art proposals which focus on the efficient group formation and intra-group communication aim to select the best device from a pool of Wi-Fi Direct enabled devices as the P2P GO. However, although the selected GO is instantly capable to meet the requirements of the network, it is a user-owned device and subject to mobility. The mobility of the user handling the GO device can cause significant disruption of the group connections, achieve poor throughput if it moves to low SNR regions and has battery constraints. Hence, a logical desire is that GO device shall be owned and fully controlled by the network to cope with these challenges.

Recently, researchers have proposed the use of UAVs (Unmanned Aerial Vehicles) in future communication networks [8]–[13]. UAVs in communication networks are favored for their advantages such as reduced cost due to on-demand operation, more swift and flexible deployments, and controlled mobility [14]. The use of UAVs as network relay has been proposed in [8], [15], [16]. Similarly, UAVs as a mean to extend network coverage has been proposed in [12], [13].

Earlier studies on UAV-aided communication focus on the UAV placement and trajectory optimization problems in generic network scenarios. Very few studies are found in the literature which study the UAV-aided communication in practical networks such as Wi-Fi, cellular and IoT networks. The existing studies on UAV-aided Wi-Fi networks have several limitations. Hence, it motivates to further investigate the potential benefits of UAV aided communication in Wi-Fi and other short-range (SR) communication networks.

In this paper, we propose the use of UAVs to unveil the potential advantages of Wi-Fi Direct technology. We propose a UAV-aided Wi-Fi Direct network architecture in which the P2P GO is installed over the UAV. The P2P GO receives the location information from all the nodes and sends to the central controller which then controls the movement and placement of the UAV. The central controller dynamically determines the optimal location in the 3D network space and move the UAV to the new location. The proposed scheme can be efficiently used to improve network coverage by connecting more devices and achieve higher network throughput by maintaining relatively strong connections to all network devices. Typically UAVs have limited on-board energy and hence energy efficient communication is desired in UAVs. By determining the optimal placement of the UAV, the distance between user devices and the GO can be reduced which results in low transmit power and reduced number of

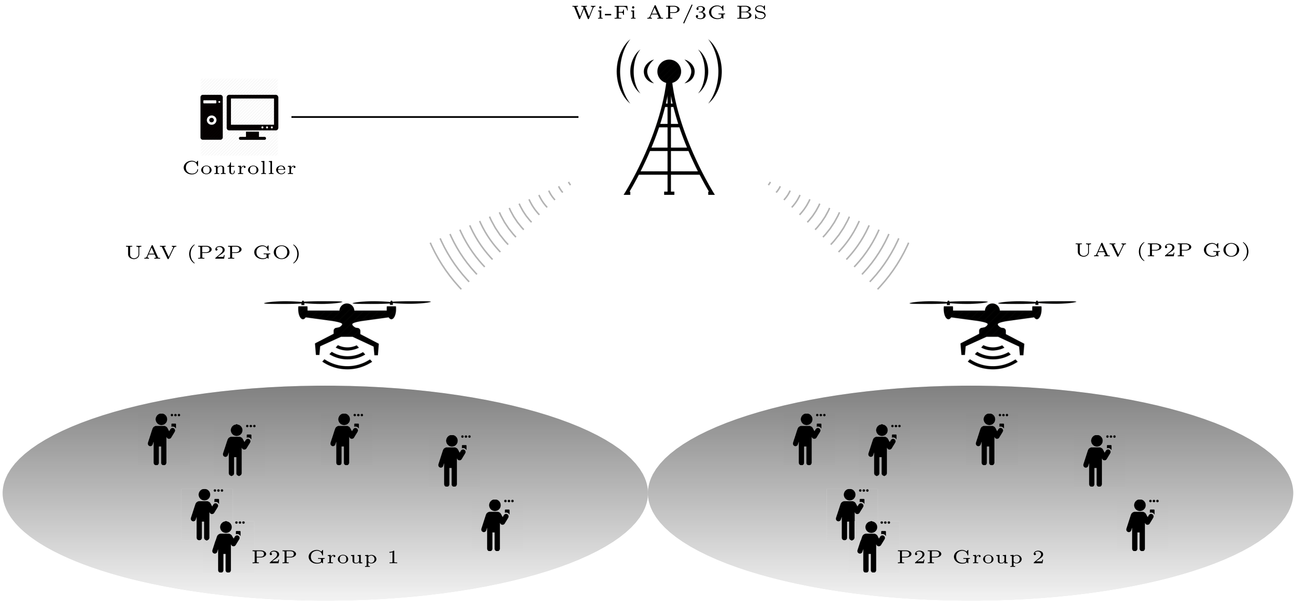


FIGURE 2. UAV-aided Wi-Fi direct network.

retransmission. Limiting the retransmissions, and lowering the transmit power can help to reduce energy consumption of the P2P GO. The Wi-Fi Direct default energy saving mechanisms further aid to energy efficient communication, which pose the use of such architecture more attractive from the perspective of energy efficiency. To the best of our knowledge, no prior work exists which proposes the UAV-aided Wi-Fi Direct networks, at the time of writing this paper.

The main contributions of this paper are:

- The paper proposes a novel UAV-aided Wi-Fi Direct network architecture. Wi-Fi Direct technology introduces enhanced features such as power saving, and dynamic service discovery which has the potential to bring several benefits.
- A simple yet efficient algorithm is used to optimally place UAVs in the network to improve the overall network performance.
- Existing works on the use of UAVs in Wi-Fi networks have several limitations. The paper presents a detailed investigation on the use of UAVs and their impact on the overall network performance. Realistic simulations in NS-3 network simulator are performed instead of analytical models which pose several limitations. NS-3 simulator implements network protocols similar to the standard Linux kernel and is a de-facto standard for network simulations.
- The paper presents an interesting case of UAVs placement in forbidden mobility regions, where the UAV's movement is restricted to a single dimension, following a straight path. The impact of such restrictions on the UAV-aided networks is investigated in this paper.

The rest of the paper is organized as follow: Section II discusses the state-of-the-art of UAV-aided communication networks. Section III presents the proposed scheme. Two distinct cases are studied in which the UAVs have full or limited mobility. Section IV discusses the system model. Section V includes a detailed investigation of the proposed schemes using simulations performed in Network Simulator-3 (NS-3). Conclusions and future research directions are drawn in Section VI.

II. RELATED WORK

UAVs in communication networks are preferred due to their mobility, flexibility, and adaptive altitude [17]. Authors in [18] proposed 3D placement of UAVs to maximize the total coverage area using circle packing theory [108]. The normalized results obtained in this study exhibits a general coverage performance versus the number of UAVs deployed in the network. Authors in [19] formulated the placement of the base station in 3-dimensional space as a Mixed-Integer Non-Linear Problem (MINLP), with the objective to maximize the coverage of the base station. The proposed scheme considers cellular networks and it uses the Air-to-Ground (ATG) model proposed by ITU in [20] which is a function of the altitude of the UAV and the horizontal distance between UAV and mobile stations. In [21], authors used reinforcement algorithm to find the optimum placement of the UAV in 3D space to increase the coverage and throughput. In the proposed scheme, an aerial base station is deployed to assist several ground base stations. In case, the QoS on a ground base station is not met due to user mobility, it triggers the aerial base station to find and move to the optimum location in the air and take over the respective ground base station to serve users connected to it. In [8], authors studied the optimum placement of UAV-aided relay along the altitude to improve the reliability of dual-hop communication networks. Three performance metrics, bit error rate, outage probability and total power loss are studied and numerical approximations are provided. However, the study is limited to a single user connected to UAV-aided relay. Moreover, the study considers a numerical approximation of the physical layer metrics which might not exhibit the actual network performance and the QoS delivered to the end user. Authors in [15] showed that the end to end network throughput with UAVs as mobile relays can be significantly improved with optimum trajectory design. The authors performed Monte-Carlo simulations of the physical-layer model only.

The proposed schemes in [8], [19], [21] consider a cellular architecture where the UAV is deployed at relatively high altitudes.

Unlike cellular networks, UAVs in SR communication networks such as IoT and Wi-Fi networks are placed at very low altitude due to short communication range (5-10 meters usually). Apart from the range limitation in Wi-Fi networks, the altitude in UAV placement is also considered less significant in Wi-Fi networks. For instance, according to [20], the coverage increases by 1-2% for each meter of altitude increase. Hence, slight changes in UAV altitude poses less impact on the coverage of Wi-Fi networks. The authors in [22] further demonstrated that by decreasing the UAV altitude, the SNR does not improve significantly.

UAV-based communication in SR communication networks has been studied in [18], [22]–[26]. Authors in [17] stated that UAVs can be used in SR communication networks such as IoT scenarios [27], [28] where the devices cannot communicate over long distances. Three potential benefits of UAV communication in SR communication networks are discussed in the state-of-the-art, i.e. improved coverage, high throughput and energy efficiency.

In [26], authors propose the use of UAV communication to extend the coverage of Wi-Fi networks. Authors in [22], propose to deploy UAVs as Wi-Fi hotspots to extend the coverage of the cellular networks. The UAVs are placed in 3D space such that it maximize the aggregated SNR of all nodes. The study claimed upto 44% throughput gain. However the authors did not consider the mobility of nodes.

Authors in [23] investigated the throughput performance of point-to-point aerial links in 802.11n Wireless LANs. The results show that throughput is not improved significantly. However the authors in [24] further investigated the use of UAVs in infrastructure Wi-Fi networks and evaluated network throughput. The results obtained in [24] show significant increase in the network throughput of IEEE 802.11n. The results also show that the mobility of users greatly affects the transmission rates and thus the network throughput.

Authors in [25] studied the throughput of UAV-aided wireless networks as an optimization problem. The aim is to maximize the minimum average throughput of all users by jointly optimizing the UAV trajectory and OFDMA resource allocation.

A recent study on the UAV positioning in Wi-Fi networks is conducted in [29]. The authors proposed a tabu search-based algorithm to determine the optimal position for the UAVs to improve the network throughput. The study report 26% improvement in the average network throughput using the proposed scheme for UAV positioning.

One of the benefit of UAVs in Wi-Fi networks is the potential to reduce energy consumption. The first logical reason to reduce energy consumption is UAV networks is the reduction in transmit power of the devices if the distance between them is shortened. Authors in [30], [31] show that the total transmit power of the devices can be minimized by placing the UAVs in the center of the optimal clusters. Secondly, at short distances, the frame loss can be reduced which decreases the retransmissions, thus resulting in energy efficiency [32].

Authors in [11] further investigated the energy efficiency in IoT network. The authors showed that the average transmit power of devices can be reduced by optimal deployment of the UAVs. Authors in [18] studied the UAV-aided Internet-of-Things (IoT) to enable energy efficient networks. The study considered K-means clustering algorithm to optimally cluster the network devices and find the optimal location of the UAVs. The study shows a reduction in total energy consumption.

III. PROPOSED SCHEME

Consider the case where a P2P GO is installed over a UAV which connects several Wi-Fi clients (STAs) to form a single P2P Group. All the STAs are mobile and hence they randomly move in the network. The random movement of the STAs tend to increase the distance between the UAV and the STAs large enough so that to cause de-association of the STAs from the network. To avoid STA's de-associations and maintain a relatively strong network connection to all nodes, it is desired that the P2P GO shall be placed in a location which reduces the distances to all Wi-Fi stations. Furthermore, when the STAs move around and change their relative positions, the UAV shall automatically re-calculate the new optimum location and relocate immediately.

In the subsequent subsections, two distinct network deployment are discussed in which the optimal location for the P2P GO is to be determined.

A. UAV MOVING IN 3D SPACE

Consider the scenario in Fig. 3, a number of STAs are deployed randomly in euclidean-plane. A UAV initially located at position $C_{x,y,z}$ can move freely in 3D space. This scenario is common and can be applied in several applications i.e. Internet connectivity and content distribution in large conference halls and exhibitions centers.

The optimal placement of the UAV which involves the minimization of the sum of distances to a set of points is a classical problem in operational research and location theory known as Weber Problem [33], [34].

In the proposed model, initially all the STA's are randomly placed at locations $p_i = (x_i, y_i, z_i)$, where i is the index of STA. The initial position of the P2P GO is $C_{(x,y,z)}$. Our goal is to find an optimal position $C^*_{(x,y,z)}$ in space for the P2P GO to

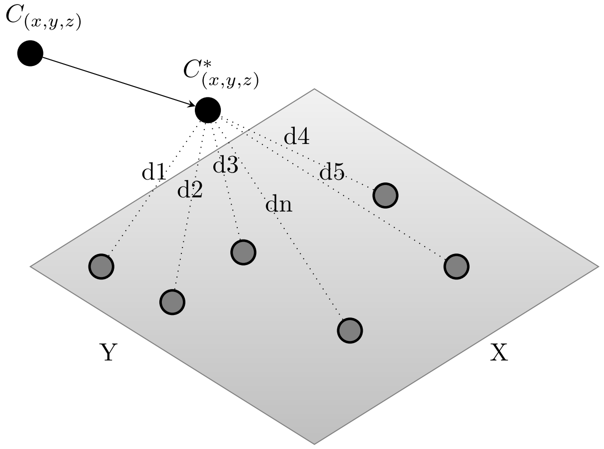


FIGURE 3. Moving UAV in 3D-space.

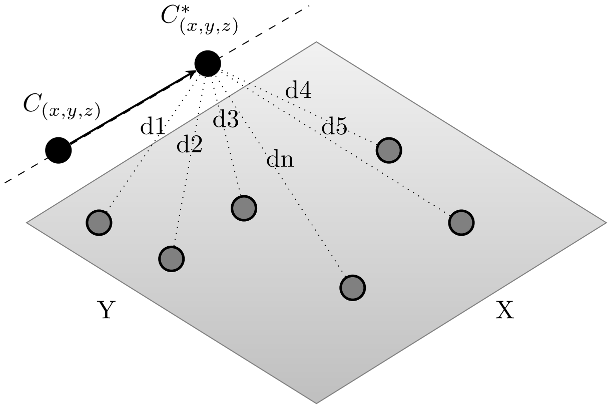


FIGURE 4. Moving UAV along a straight path.

maintain a fair connection with all STA's and achieve higher aggregate throughput at the cost of less energy consumption.

The Euclidean distance between the UAV and each STA is calculated in Eq. 1 [35]:

$$d(C, p) = \sqrt{(C_x - p_x)^2 + (C_y - p_y)^2 + (C_z - p_z)^2}. \quad (1)$$

where, C_x, C_y and C_z are the coordinates of the P2P GO, and p_x, p_y and p_z are the coordinates of a STA p_i in 3D space.

The Euclidean distance in Eq. 1 can be modified to compute the weighted Euclidean distance in Eq. 2 [36] to address the axis scales.

$$d'(C, p) = \sqrt{w[(C_x - p_x)^2 + (C_y - p_y)^2 (C_z - p_z)^2]}. \quad (2)$$

Eq. 2 is also referred to as "weighted $l2$-norm" or more generally "kl_p-norm" in [37] where k refers to the weight w_i. A minisum location model using weighted Euclidean distances between P2P GO and each station is given in Eq. 3 [38]:

$$f(C) = \sum_{i=1}^{n} w_i d_i(C, p_i) \quad (3)$$

where, w_i is the weight assigned with each station. For more distant stations, the weights w_i can be assigned higher values so that the UAV can be moved closer to serve better these stations. Eq.3 is known as *Weber Equation*. To find the optimum location for the UAV, is the same as to reduce the sum of distances to all STAs. The optimum location finding implies the minimization of the Weber equation 3 and this distance minimization problem is called the Weber problem (also known as the Fermat-Weber problem). Weber problem is an unconstrained optimization problem which can be written as in Eq. 4 [36]:

$$\begin{aligned} &\underset{x}{\text{minimize}} \ f(C) = \sum_{i=1}^{n} w_i d_i(C, p_i) \\ &\text{subject to} \ \{x, y, z\} \in R^n. \end{aligned} \quad (4)$$

A well-known approach to solve this optimization problem in Eq. 4 is known as Weiszfeld algorithm, presented in Algorithm (1). The Weiszfeld algorithm is an iterative approach based on the first order necessary conditions for a stationary point of the objective function. The convergence of weiszfeld algorithm has been proved in [39]. It is worthy to mention that the weiszfeld algorithms has a serious implication, if any of the p_i accidentally lands in a vertex C. However, it can be solved with a simpler modification as proposed in [40].

B. UAV MOVING ALONG A STRAIGHT PATH

In Section III-A, we assumed that the UAV can move freely in space along any direction and we aimed to find a point (C*) in 3D space which has the minimum sum of distances to all Wi-Fi stations. In this section, we consider a special case, where the UAV can't move freely. Instead, the movement of UAV is restricted to only a straight path. The straight path represents a line in Euclidean space and is illustrated in Fig. 4. A practical application of UAV mobility restricted to a fixed straight path can be UAV deployments in large indoor exhibition centers, conference halls and sports arena. The UAVs movement is usually restricted due to several barriers and hence these can be safely deployed to move along hazard-free straight paths to avoid collisions with other objects.

The optimal placement of UAVs with path barriers in the aforementioned example can be formulated as a special case of the unconstrained optimization problem in Eq. 4 which is referred to as an optimization problem with distance constraints i.e. with a barrier or forbidden region. Constrained optimization problems with barriers are studied in [41]–[43]. To find the optimal point over the straight path that minimizes the sum of distances to all points in the networks, we are using the modified Weiszfeld algorithm proposed in [38]. The proposed method uses "Weighted Euclidean distance" between STAs, which is slightly different from Eq. 2. The weights assigned to each axis is set equal to the inverse of the variance or the allowed scale to move along the respective axis as given in Eq. 5 [36].

$$d'(C,p) = \sqrt{w_x(C_x - p_x)^2 + w_y(C_y - p_y)^2 + w_z(C_z - p_z)^2}. \tag{5}$$

C. MULTIPLE UAVs PLACEMENT IN 3D SPACE

In the previous sections, i.e. III-A and III-B, we discussed the problem of finding an optimum location for single UAV. However, in most practical scenarios, such as dense networks in sports stadiums and large exhibition centers, multiple UAVs have to be deployed to form several network clusters. In this section, we discuss the case of multiple Wi-Fi Direct networks (called as P2P groups) as shown in Fig. 2, using UAVs each equipped with a P2P GO device. We keep the same assumption as in the case of single UAV, that the Wi-Fi stations are initially associated to the GO. However, due to the mobile nature of the stations, the deployed UAVs have to frequently move to the optimum locations to maintain strong connections. This problem is primarily studied as "multiple facility location" problem in location theory [44], and most recently known as clustering [45]–[48] in machine learning.

The multiple UAV placement problem can be solved using two different approaches. Firstly, by considering each P2P group independently and placing a UAV in each P2P group, using the single facility location problem as discussed in Section III-A and III-B. This approach is significant if the requirement is to avoid connection loss for the stations. However, if the temporary network connection loss is not a problem, a more useful approach is to use a combined approach to place multiple UAVs at optimum locations. The logical benefit of the second approach is that each STA is independently allocated to the closest UAV than to the rest of the UAVs in the network.

The problem of placing k UAVs in optimum locations is similar to forming k clusters or P2P groups. Given $P = p_1, p_2, p_3, ..p_n$ Wi-Fi stations and k UAVs, the multiple facility location problem is to determine the locations $C^* = C_1^*, C_2^*, ..C_k^*$ for the UAVs and the allocations of $X_1, X_2, ..X_k$ stations to each UAV, such that the total sum of distances of each stations to its assigned UAV is minimized. It can be represented mathematically [49]:

$$\min_{C_1,C_2,\ldots C_k} \; \min_{X_1,X_2,\ldots X_k} \sum_{j=1}^{k} \sum_{p_i \in X_k} w_i \left\| C_j - X_i \right\|. \tag{6}$$

The optimization problem given in Eq. 6 can be solved using k-median clustering [50]. The k-median clustering algorithm can be used to partition the set of Wi-Fi stations into k clusters and finding the optimal locations for the UAVs in each cluster. The k-median clustering process is given in Algorithm 1.

Algorithm 1 Optimal Placement of UAVs

```
Inputs: $p_i[x_i, y_i, z_i]$, $C_i(x, y, z)$
Outputs: $C_j^*, C_2^*, ..C_k^*, X_1, X_2, ..X_k$
switch $j$ do
    case $j = 1$
        Initialize cluster centroids at $C_j(x_j, y_j, z_j)$
        while
            error is too small do {
            $d_i^t = \left\| p_i - C^t \right\|^2$
            $C^{t+1} = \frac{\sum_{i=1}^{n} w_i a_i / d(p_i, C)}{\sum_{i=1}^{n} w_i / d(p_i, C)}$
            $error = \left\| C^{t+1} - C^t \right\|^2$
        end while
        return $C^*(x, y, z)$                                  ▷ Single location
    case $j \geq 2$
        Repeat until convergence: {
        For each i, set:
        $C^{*(i)} = \arg\min_j \left\| p^{(i)} - C_j \right\|^2$
        For each j , set:
        $C_j := \frac{\sum_{i=1}^{m} \{C^{(i)}=j\} p^{(i)}}{\sum_{i=1}^{m} \{C^{(i)}=j\}}$          ▷ Multiple locations
```

D. UAV TRAJECTORY AND SPEED

In the proposed schemes discussed in Section III-A and III-B, the Weiszfeld algorithm computes the optimal position denoted as $C*_{(x,y)}$ for the UAV at scheduled time denoted as T. The minimum distance covered by the UAV to travel from the present location $C_{(x,y)}$ to the new location $C*_{(x,y)}$ is calculated as:

$$d_{min} = \sqrt{(C_x^* - C_x)^2 + (C_y^* - C_y)^2 + (C_z^* - C_z)^2}. \tag{7}$$

The minimum speed S of the UAV to reach the new location within the time constraint T is calculated as:

$$S = d_{min}/T$$

The value of S should be typically chosen higher than d_{min}/T, so that the UAV can reach the new location before the start of the next T which trigger again the UAV to move to another point. After every time T, the UAV determines a new optimal location and calculate the minimum distance d_{min} and velocity V. The value of T generally depends upon the mobility of users. In a highly dynamic network where users are frequently moving, the value of T should be chosen small, to quickly optimize distances. In contrast, in a less dynamic environment, a larger value of T should be chosen to avoid variations in the channel caused by the unnecessary mobility of the UAV.

The proposed scheme presented in this section is different form the aforementioned studies [11], [15], [18], [22], [29] in Section II from several perspectives.

Firstly, the proposed scheme uses simpler yet efficient algorithm for the placement of UAVs which minimize only the distance between devices at regular intervals.

The simplicity of the algorithm make it suitable for use in practical deployments and experimental testbeds.

Secondly, the proposed scheme incorporates an interesting use case of restricted UAV mobility which has not been studied in any of these works.

Thirdly, the works in Section II that study the UAV-aided Wi-Fi and IoT networks have several limitations. For instance, the works in [22]–[25], [29] study the coverage and throughput, but does not investigate the impact on energy performance. Similarly the works [11], [26] focuses on the energy efficiency but does not study the throughput and coverage. Another major limitation which is common over all these studies except [11], [29] is the mobility of ground devices. The mobility of ground devices leave a strong impact on the network behavior and the overall performance. The impact of network size and the number of UAVs is significant, which is not studied in [22]–[24], [26]. In this study, we aim to cover all these missing aspects to provide a detailed insight of the performance of UAV-aided Wi-Fi Direct networks.

Fourthly, an important consideration of major significance is the evaluation methodology used across the aforementioned works. A common trend in these studies is the formulation of an optimization problem with a limited set of mandatory constraints and then solving the problem with a software package. The limitation of such approaches is the lack of evaluation with realistic conditions of practical wireless networks such as the intra-BSS interference, the impact of devices contention and back-off process, hidden and exposed terminal problems, network overhead caused by control and management frames, packet losses due to network congestion and retransmissions of frames. Ignoring all these parameters can have serious implications and the expected results might be altered hugely when such schemes are implemented in network simulators or actual networks. In contrast, the proposed scheme is implemented and evaluated in NS-3 network simulator to evaluate in more realistic environment without ignoring important conditions of real networks. The use of network simulators provides a unified approach to evaluate and compare the obtained results.

Lastly, this study proposes the use of UAVs in Wi-Fi Direct networks instead of Wi-Fi networks used in [23], [24], [29] or IoT used in [11], [28], or generic wireless networks used in [15], [51], [52]. The Wi-Fi Direct technology has additional benefit of power saving which are not available in legacy Wi-Fi networks as explained in Section I in details. The use of UAVs in Wi-Fi Direct networks is more attractive due to fact that the P2P GO (also called GO or Soft-AP) in Wi-Fi Direct network is a wireless device which can be equipped with multiple wireless interfaces or TDMA (Time Division Multiple Access) schemes for more efficient design of the communication strategy. These potential benefits are inherent in Wi-Fi Direct and no modifications are required in the protocol stack for deploying test-beds or real systems.

A comparison of the proposed scheme with previous related works is given in Table 1.

IV. SYSTEM MODEL

To evaluate the performance of the proposed scheme, four distinct scenarios are created. In scenario 1 and 2, the placement of single UAV is controlled in 3D and 1D space respectively using Algorithm 1. The proposed placement of the UAV in both cases is expected to improve network throughput and coverage while simultaneously achieve energy efficiency. To evaluate the performance of the proposed scheme, two other typical use cases are modeled. In the first case, the P2P GO is kept fixed which is equivalent to a fixed access point (AP) in legacy Wi-Fi. In the second case, the P2P GO is implemented as a randomly moving device in 3D space equivalent to a user-owned P2P GO device offering network connections. The four distinguished cases: (i) fixed mobility, (ii) random mobility, (iii) controlled mobility in 3D space and (iv) controlled mobility along a straight path (1D) are modeled.

The performance of the proposed scheme is further investigated by increasing number of UAVs (1,2 and 3) with their optimal placements in 3D space and 1D space respectively using Algorithm 1.

A. SINGLE UAV

Thirty (30) Wi-Fi stations are placed in the 300 x 300 (m^2) grid. The UAV is initially placed at position (100, 100, 15) and then it is allowed to move or remain fixed according to the mobility model.

- In the fixed UAV scenario, the UAV remained fixed throughout the simulation at position (100,100,15). This is identical to the fixed access point in legacy Wi-Fi networks.
- In the randomly mobility (unrestricted) UAV scenario, the UAV is allowed to move freely in the network during the simulation. This is identical to the P2P GO being a user-owned devices.
- In the controlled mobility (3D) case, the UAV is allowed to move in 3 dimensional space, however the mobility is controlled i.e. after each time T, the UAV is moved towards the new position computed using Algorithm 1.
- Lastly, in the controlled mobility (1D) case, the movement of the UAV is restricted to a single dimension (X-axis) i.e., movement along a straight path (X,100,15). Furthermore, the movement along the X-axis is controlled using Algorithm 1.

B. MULTIPLE UAVs

Two distinct scenarios are considered with two UAVs and three UAVs. In both cases, thirty (30) Wi-Fi stations are placed in the $(300, 300)(m^2)$ grid. In the first scenarios, the two UAVs are initially placed at positions (100, 100, 15) and (150, 101, 15) whereas in the second scenarios, a third UAV is placed in the network at (200, 102, 15) and then their

TABLE 1. Related works: Summary and comparison.

Proposal	Network Size	Analytical Tools	Evaluation Method	Performance Metric	Advantages	Limitations
[22]	1 UAV 1-7 STAs	–	Experimental	Throughput	Experimental Testbed produces more realistic results.	Study is limited to one UAV and static clients.
[23]	2 UAVs 1 STA	–	Experimental	Throughput Packet Loss	Realistic results can be achieved using testbed.	Considers aerial links only. Does not study energy efficiency.
[24]	2 UAVs 1 STA	–	Experimental	Throughput	Both indoors and outdoors tests are tested.	Study is limited to 2 UAVs only. Analyze only network throughput.
[26]	1 UAV	–	Experimental	Throughput Coverage Energy Consumption	Study UAV performance in both infrastructure and ad-hoc modes.	UAV is not optimally placed. Impact of No. of UAVs and clients is not studied. Energy consumption of the UAV does not provide insight on the energy consumed for data transfer.
[53]	5 UAVs 100 devices	Location Theory	Numerical simulations	Throughput Energy consumption	UAVs placed optimally in 3D space. Both Fixed and Mobile networks are studied.	STAs association is not studied. Need evaluation in realistic network simulator like NS-3.
[29]	25 UAVs	Tabu Search	Numerical simulation	Throughput	Maintain STAs connectivity.	Slow algorithm convergence. Posed to high energy consumption which is not evaluated. High performance degradation in mobile environment.
Proposed Scheme	1-3 UAVs 30 STAs	Location Theory	NS-3 Simulations	STAs association Throughput Energy Efficiency	UAVs placed optimally in 3D space. A special use-case of UAV placement in 1D space (restricted mobility) is studied. Presents a detailed analysis over three metrics. Realistic simulations in NS-3 is performed.	UAV trajectory optimization is not addressed.

positions are updated using the proposed scheme. Similar to the single UAV case, the placement of all UAVs is controlled using Algorithm 1.

V. SIMULATION RESULTS

The system model described in Section IV is evaluated in network simulator-3 (NS-3) [54]. We choose NS-3 for several reasons. Firstly, NS-3 is a well-known and de-facto standard for performing networks simulations. Secondly, NS-3 is an open source software and it provides full access to the protocol stack. It is enriched with trace sources which provide access to low-level protocol's and network parameters that are usually not accessible in other network simulators. Additionally, NS-3 based simulations are more realistic due to its Linux-like protocol stacks.

We used the Minstrel rate control algorithm [55] which is the default rate control algorithm in the Linux kernel. The minstrel rate control algorithm is originated from MadWifi project [56]. The project was initiated to develop Linux drivers for Wireless LAN cards based on Atheros chipsets. The Minstrel algorithm keeps track of the probability of successfully sending a frame of each available rate. Minstrel then calculates the expected throughput by multiplying the probability with the rate. This approach is chosen to make sure that lower rates are not selected in favor of the higher rates (since lower rates are more likely to have higher probability). In Minstrel, roughly 10 percent of transmissions are sent at the so-called lookaround rate. The purpose of using the lookaround rate is to force the algorithm to try a higher rate than the currently used rate, thus automatically selecting higher data rates when the SNR increases.

To evaluate the energy performance of the network, we use the "WiFi Radio Energy Model" of NS-3 which computes the energy consumption of a Wi-fi interface in each state of the PHY layer (Idle, Busy, Transmit, Receive, Channel Switching, Sleep, Off). The default values of these parameters are defined in [57].

The simulation configurations listed in Table 2. We used three performance metrics over which the performance of the proposed scheme is evaluated, i.e. number of associated stations, network throughput and energy efficiency. The performance over these metrics is evaluated and separately presented in the subsequent subsections.

A. NUMBER OF ASSOCIATED STATIONS

A primary benefit of the proposed scheme is to increase the number of associated stations and maintain fair connections to all clients by moving the UAV to the optimal location. As the network consists of mobile nodes, the network topology as well as the parameters are always changing. The quality of the wireless signal (i.e. SNR) degrades as the stations move away from the GO. However, the GO constantly moves to the optimal location determined by the proposed scheme. When the UAV moves to the new optimum location, the distance to each STA is reduced, thus avoiding stations to de-associate from the GO. The proposed scheme does not guarantee 100% STAs association, however the association ratio can be much improved using the proposed scheme.

TABLE 2. Simulation Parameters.

Parameter	Value
Area (squared meters)	300 x 300
No. of UAVs	1/2/3
No. of stations	30
STAs initial placement	Random (uniform distribution)
STA mobility model	Random way-point
GO mobility model	Fixed/Random/Proposed scheme
WLAN standard	IEEE 802.11n (5GHz)
Propagation model	Log-distance propagation-loss model
Simulation duration	600 seconds
Application	Constant bit rate
Payload size	1472 Bytes
Application data rate	1024 Kbps
Battery Model	Wifi Radio Energy Model of NS-3

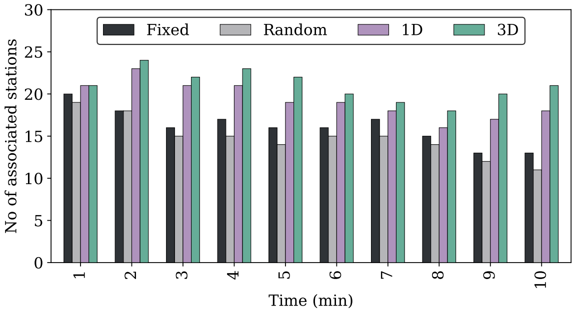


FIGURE 5. Number of associated stations (Single UAV).

The performance of the proposed scheme is evaluated to investigate the STAs association as shown in in Fig. 5.

Fig. 5 shows that the number of stations associated to a single GO. The STAs are initially placed randomly following a uniform distribution whereas the UAV is placed at (100, 100, 15). The STAs in the communication range connect to the GO whereas some of the STAs outside the coverage of UAV are not associated. The STAs in all cases are randomly moving which changes the network topology at different instants of time.

In the case of fixed GO, the STAs are frequently de-associated when they move far away from the GO, reducing the number of associated stations. At the same time, other distant STAs, initially not associated to the GO, may come closer and connect to the GO. The frequent movement of STAs is causing unpredictable association of STAs. A similar behavior can be observed in the case of randomly moving GO where both the GO and the STAs are moving.

On the other hand, the proposed scheme controls the movement of the UAV such that it periodically move the UAV to an optimal location where the distance to all STAs is minimized. As the objective is to minimize the distance to all STAs, the distance to some STAs initially closer may increase. However, the overall STAs association improves.

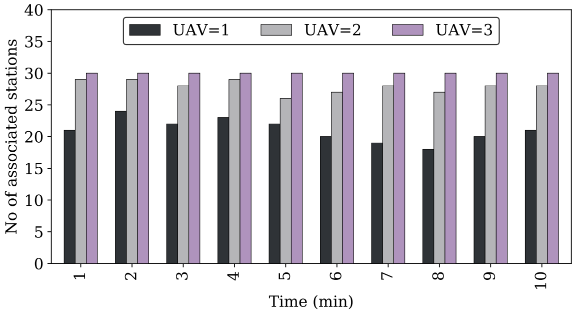
In the case of UAV movement over a straight path (1D), the proposed scheme can not place the UAV at the optimal location due to mobility constraint, however, it tends to move the UAV to a sub-optimal location to reduce distances to the STAs. It can be observed in Fig. 5, that the STAs association ratio using such the proposed scheme with restricted mobility, is still better than the fixed and randomly moving GO cases.

The analysis of the simulation results show that on average, the GO moving in 3D space can maintain 13% more connectivity than Fixed GO and 23% more than the randomly moving GO. In the case of GO moving in 1D, the values are reduced to 8% and 18% respectively.

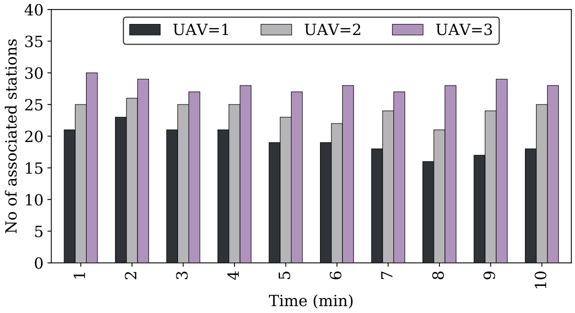
The stations association in the network in case of multiple UAVs is investigated by deploying different number of UAVs (1, 2 and 3) in the network. The aim is to further strengthen the claim of the proposed scheme by investigating the impact of using multiple UAVs.

The simulation results of STAs association with multiple number of UAVs using the proposed scheme in 3D and 1D mobility are reported in Fig. 6a and 6b respectively.

It can be easily observed in Fig. 6a and 6b that the increasing number of UAVs in the same network can significantly improve connectivity of network devices. The improvement in UAVs with 3D placement is expectedly greater than with 1D placement. The average association of STAs, using 3D movement is increased by 12% and 28% for increasing number of UAVs to 2 and 3. For 1D movement, the percentage



(a)



(b)

FIGURE 6. Number of associated stations (multiple UAVs). (a) STA association versus No. of UAVs (3D). (b) STA association versus No. of UAVs (1D).

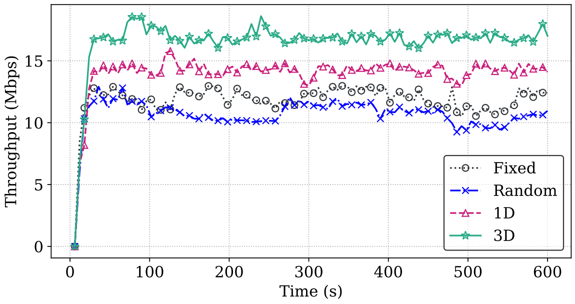


FIGURE 7. **Network throughput (Single UAV).**

improvement is reduced to 9% and 24% for 2 and 3 UAVs respectively. The presented results were expected, as increasing the number of UAVs can increase the chance of STAs to connect to one of the 2 (or 3) UAVs deployed in the network.

B. NETWORK THROUGHPUT

Network throughput is a widely used metric to evaluate the network performance. Increasing the received power or more specifically the received SNR directly increases the transmission throughput and consequently improve the application layer performance [58]. The UAV-aided network is simulated to evaluate the network throughput in Megabits per seconds (Mbps). Fig. 7 illustrates the total network throughput using the four distinct scenarios i.e. fixed UAV, randomly moving UAV, proposed scheme with 3D placement and proposed scheme with 1D placement. By inspecting Fig. 7, it can be observed for all the four cases that the throughput increases abruptly when the simulation starts in the first couple of seconds. The reason for this increase is that STAs in the coverage of UAV connect in this time and start receiving data.

In the case of fixed and randomly moving cases, when all the STAs are connected, the throughput does not increase further. There are slight variations in the instantaneous network throughput which indicates the connection status or the link quality of one or more STAs is changed. When STAs are disconnected, the throughput is decreased and vice versa. Similarly, one or more distant STAs with poor links quality can also vary the throughput.

In the case of Proposed scheme (3D and 1D), at time 10 seconds, the UAV has moved to the optimal location in the network which further increases the throughput. The rationale behind the high throughput in the proposed scheme is that by reducing the distance between the UAV and the randomly moving stations, higher SNR values can be achieved, which directly map with the selection of high MCS index, thus increasing higher data rates. Additionally, the selection of higher SNR depicts the quality of the wireless channel which reduces the number of retransmissions to further improve the throughput.

It can also be noticed in the graph, that the improvement in throughput is relatively less in the case of UAV moving along a straight path (1D) as compared to the 3D case. The reason is that in 1D case, the proposed scheme only ensure sub-optimal placement of the UAV. This causes an increase in the throughput relative to fixed and random use cases, but throughput is still less than the 3D case.

Another clear observation in Fig. 7 is the relatively less variations in the network throughput using the proposed scheme (3D and 1D). The reasons for the relatively more constant throughput using the proposed scheme is that STAs association as well as the link quality is maintained when the UAV is placed at the optimal location. The retransmissions are also reduced which further smooth the throughput.

The analysis of the results obtained show significance of proposed scheme over both 3D and 1D placement of GO. The throughput using the proposed scheme relative to fixed GO is increased by 35% and 15% for 3D and 1D deployments respectively. The throughput relative to randomly moving GO is increased by 54% and 31% using the proposed scheme with 3D and 1D movement of GO respectively.

We further investigated the impact of increasing the number of UAVs on the network throughput. We deployed different number of UAVs (1, 2 and 3) in the network and computed the network throughput with the same simulation parameters. The obtained results were analyzed that show that by increasing the number of UAVs to 2 and 3, the throughput is increased by 21% and 34% in 3D case, and 28% and 35% in 1D case. It is worthy to note that the throughput gain in 1D case is greater than 3D case. However it should not mislead the reader that the proposed scheme with 1D placement outperform 3D placement. Instead the reason for this contrasting behavior is that the gain is relative to single UAV case and the increasing number of UAVs with 3D placement does not connect more stations as compared to 1D placement. However, the actual throughput is still higher in 3D case for equal number of UAVs as depicted in Fig. 8a and 8b.

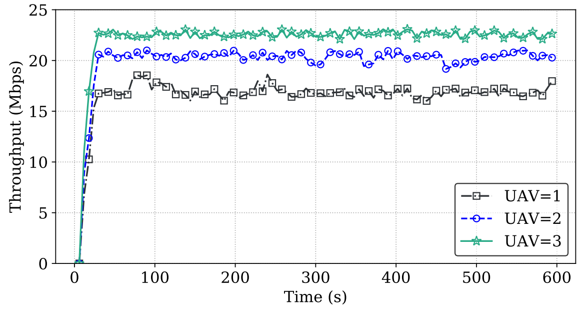
C. ENERGY EFFICIENCY

In Wi-Fi networks, energy efficiency can be achieved in several ways: firstly, by reducing the transmit power of the radio transmitter at the sending station; secondly, by using higher data rates at constant transmit power; and lastly by reducing the number of retransmissions and packet loss. Wi-Fi Direct offers additional algorithms known as OppPS and NoA to further save energy [5], [59], [60].

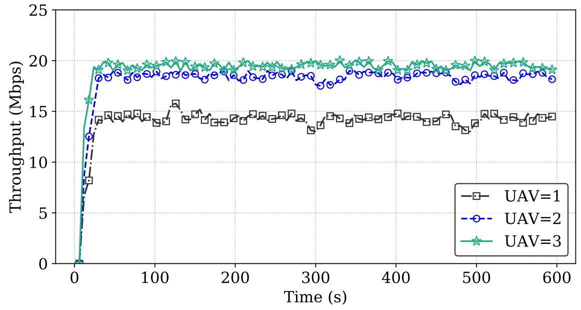
The proposed scheme in Section III constantly reduces the sum of distances between the GO and the STAs to achieve higher signal to noise ratios (SNR). With higher SNR, higher transmission rates can be achieved and the retransmissions of frames are significantly reduced. Ultimately, the energy consumed to transmit the user data can be reduced.

To evaluate the energy efficiency of the proposed scheme, we used the metric called "*energy consumed per 1 megabit of user data*" measured in Joules. The proposed metric precisely calculate the energy consumed in the transmission of the actual user data. A similar metric "energy consumed per frame" is used in [61].

The energy performance of the proposed scheme is evaluated and compared against the fixed and randomly



(a)



(b)

FIGURE 8. **Throughput versus No. of UAVs. (a) Network throughput versus No. of UAVs (3D). (b) Network throughput versus No. of UAVs (1D).**

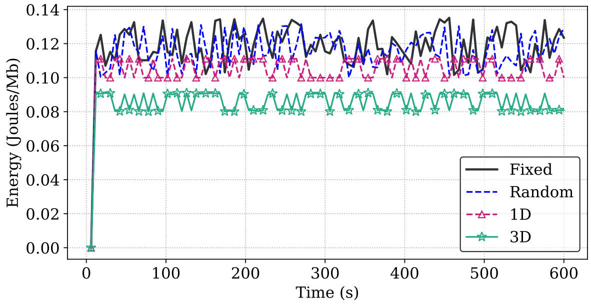
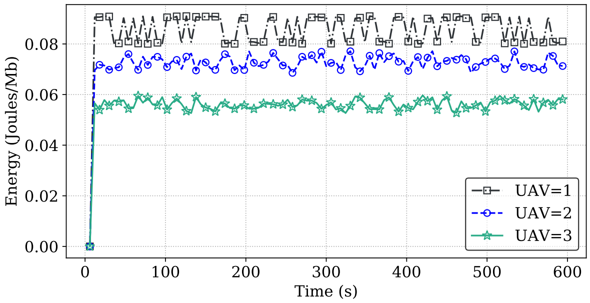
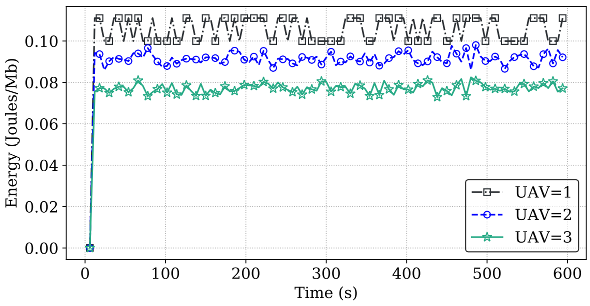


FIGURE 9. **Energy Efficiency of the Proposed Scheme.**

moving GO. The results are shown in Fig. 9. The energy consumption increases abruptly in the first few simulation seconds despite the fact that more control frames are communicated in the STAs association phase. However, the cumulative size of the control frames is less and the impact is negligible in terms of the proposed metric. When all the STAs in coverage associate with the GO, the energy consumption does not vary abruptly, however variations can be observed throughout the simulation duration. The variations for fixed and randomly moving GOs are higher as compared to that of the proposed scheme. To the best of our understanding, the higher variations in the fixed and random cases are caused by more frequent changes in data rates and higher number of re-transmissions caused by low links quality. In contrast, relatively less variations in the energy consumption are observed when the proposed scheme is used. We believe that the Variations can be further reduced if the STAs connected to the GO have similar quality of connections to the GO.



(a)



(b)

FIGURE 10. **Energy Efficiency versus Number of UAVs. (a) Energy efficiency with 3D placement of UAVs. (b) Energy efficiency with 1D placement of UAVs.**

It can be logically concluded that the proposed scheme is more efficient in saving energy than fixed GO as well as randomly moving GO. Furthermore, the energy efficiency is more evident in the case of 3D placement of P2P GO, whereas little improvement is achieved for the GO restricted to move along a straight path.

The detailed analysis of the obtained results show that the energy consumption using the proposed scheme as compared to the fixed GO, is reduced by 30% and 14% for 3D and 1D deployments respectively. Furthermore, the energy consumption relative to randomly moving GO is reduced by 28% and 12% using the proposed scheme with 3D and 1D movement of GO respectively.

The impact of different number of UAVs in the network is also studied. The energy consumption of the network in case of multiple UAVs is investigated by deploying different number of UAVs (1, 2 and 3) in the network. The results are plotted in Fig. 10a and 10b. A clear observation is that the variations in the energy consumption are reduced with increasing number of UAVs. This strengthen our explanation stated earlier that the possible cause of these variations in the higher variations in fixed and random UAV placement are frequently varying data rates and re-transmissions in the network. With increasing number of UAVs, the impact of both these parameters is reduced.

The analysis of the results obtained show that by increasing the number of UAVs to 2 and 3, the energy consumption of the network is reduced by 14% and 33% in 3D case, and 10% and 27% in 1D case. Our understanding is that the energy consumption of the network is highly impacted by the

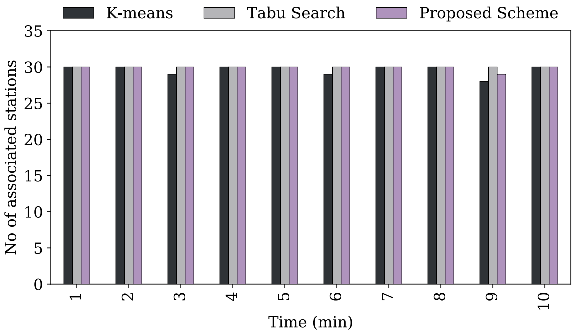


FIGURE 11. Comparison of STAs association.

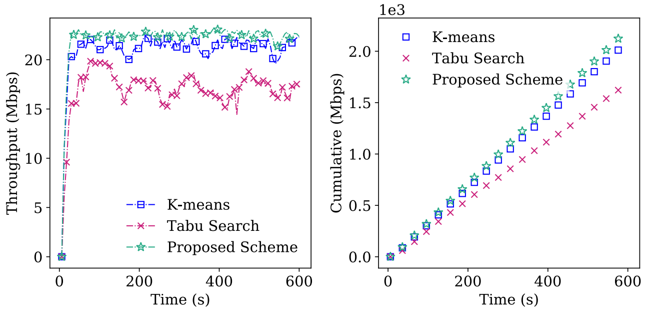


FIGURE 12. Comparison of network throughput.

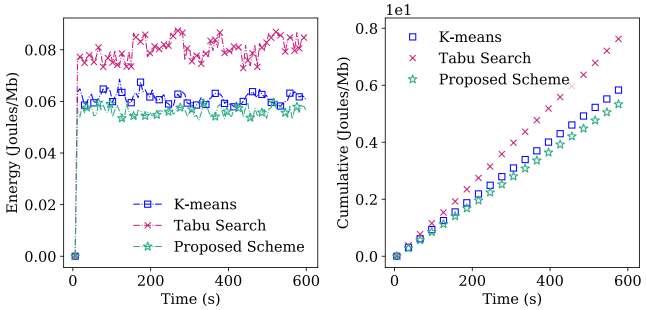


FIGURE 13. Comparison of energy efficiency.

distance between the UAV and clients, which reduces more when we placed three (3) UAVs in the network

D. COMPARING RESULTS WITH PREVIOUS WORKS

To further support the benefit of the proposed scheme, we performed simulation based comparison of our proposed scheme with two similar solution proposed in [53] and [29].

In [53], authors proposed to use a constrained K-means algorithm proposed in [62] for UAV placement and then assign devices to the UAVs. The K-means based algorithm divide the set of network devices into small clusters and optimally place the UAVs at the centers of each cluster. The authors argued that by placing the UAV at the center of the cluster, the sum of squared distances between UAVs and its assigned devices is minimized which will reduce the total energy consumption.

In [29], authors proposed a solution to place UAVs such that the total network throughput is maximized. The authors proposed an algorithm which is based on tabu-search to position UAV such that all associated STAs are within the transmission range of the UAV. To ensue that no STA loose the coverage, the UAV is restricted to move only in a fixed circular region called "containing region" of the UAV. The authors further restrict the movement of the UAV to grid of points inside the containing region called as "candidate UAV positions". To search for the optimal UAV position (i.e. grid point) inside the containing region, the authors used tabu search method [63]. The algorithm starts with a random initial solution and iteratively improves it by changing its position to a new grid point inside the containing region. A number of positions are evaluated and the best is chosen to place UAV. To avoid the previously searched non-optimal grid points, the algorithm maintains a list of previously visited positions.

We simulated the above two algorithms in NS-3 using the aforementioned system model in Section IV to compare the performance of our proposed scheme. For fair comparison, we used the same set of parameters (e.g. number and positions of STAs, mobility model of STAs, transmit power, propagation model, application type, and packet size parameters etc.). Fig. 11, 12 and 13 illustrate the performance comparison of the proposed scheme against the two algorithms.

In Fig. 11, the three schemes are evaluated to maintain STAs association. It can be observed that all the three schemes maintain connectivity of the STAs throughout the simulation, however, [29] outperform (i.e. maintains 100% connectivity of its associated STAs). It is because the algorithm in [29] is designed to restrict the movement of UAVs to the containing circle so that all the associated STAs remain in the coverage. Furthermore the proposed scheme outperform [53] at some instants in the simulation due to the constrained distance used in the algorithm (Eq. 3).

In Fig. 12, the three schemes are compared for throughput gain of the overall network. Both instantaneous (left) and cumulative throughput (right) values are plotted. The figure (left) shows that the proposed scheme outperform [53] and [29]. One possible reason for this improved performance of the proposed scheme is that it inherently considers the distant STAs in calculating the optimal location of the UAV. This minimize the distance fairly to all STAs, which results in improved quality of all the links. Similar to the proposed scheme. the algorithm in [53] using K-means, also moves the UAV to the center of the cluster periodically, thus achieves almost equal throughput gain. On the contrary, [29] uses tabu search to move the UAV in a grid and takes relatively longer time to find the optimal location, which degrades the performance. Furthermore, as the STAs are constantly moving around, the algorithm [29] rarely achieves optimum performance. The impact of STAs mobility over the throughput performance is also highlighted by the authors in [29]. The analysis of the average throughput gain of the three schemes show that the proposed scheme achieves 5% and 31% more throughput gain as compared to [53] and [29] respectively.

A comparison of energy efficiency of the three scheme is then presented in Fig. 13. The Tabu search based scheme [29] show poor performance in terms of energy efficiency. It was expected because the UAV in this scheme search all the grid points including several non-optimal grid points before it reaches the optimal location. In such non-optimal locations, the achievable data rates of the UAV is dropped and the number of retransmissions increases in the network which consume extra energy to transmit the same data several times. In contrast to this, the proposed scheme as well as the algorithm in [53] constantly move the UAV only to the optimal location (without searching through the non-optimal space) when the STAs change their positions. The analysis of results show that the proposed scheme achieves the maximum energy efficiency. The average energy consumption of the proposed scheme is 9% less than [53] and 29% less than [29].

Although, the proposed scheme provides a simpler solution to UAV-aided communication in Wi-Fi networks. However some challenges in terms of practical implementation are worthy to discuss. In order to optimally place UAV, the UAV requires the current location of devices. The location information i.e. GPS coordinates of the client devices can be acquired at the application layer which will require user agreement. Alternatively, location estimation algorithms such as RSSI and Angle-of-Arrival (AoA) based location estimation can be applied. Another challenge is the communication between the UAV and the controller. For instance, using only Wi-Fi interfaces, the UAV might leave out of the communication range of the controller. However, this problem can be addressed if the UAV and the controller are equipped with a cellular interface. The dual interfaces can leave a negative impact on the battery life of the UAV. Alternatively, highly directional antennas can be used to enable nearly LOS communication between the UAV and controller at large distances.

VI. CONCLUSION AND FUTURE WORK

In this paper, we proposed the use of UAVs in Wi-Fi Direct networks. In UAV-aided Wi-Fi Direct network, the P2P GO or the so called Soft-AP is installed over a UAV. The UAV is then optimally placed in the network to minimize the distance between the UAV and the ground Wi-Fi stations. We used simpler algorithms i.e. Weinszfeld and K-median to place a single or multiple UAVs respectively. Simulations performed in NS-3 reported significant improvements in maintaining clients associations up to 23%, while simultaneously increasing average network throughput by 54% and reducing energy consumption by 30% relative to the case of fixed or randomly moving GO.

We also discussed the case which consider the UAV placement in restricted environment. Assuming the UAV can move only along a straight path, the proposed algorithm still improve the network performance. Simulation reported a maximum improvement of 18% in client association, 31% in throughput and 14% in energy consumption relative to the fixed or randomly moving GO.

The reported results using the proposed scheme are compared in Section V-D with other similar works in the state-of-the-art. The proposed scheme reportedly brings significant improvements in the overall network performance. In view of the above discussion, future works to extend the proposed scheme shall address new challenges such as trajectory optimization and coordination among UAVs to avoid UAV collision, transmit power tuning for interference reduction. An interesting idea is to jointly optimize the "absence period" in NoA power saving scheme in Wi-Fi Direct and trajectory of the UAV to reduce packet loss while simultaneously saving energy of the UAV.

ACKNOWLEDGMENT

The statements made herein are solely the responsibility of the authors.

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