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# Connecting Disjoint Nodes Through a UAV-Based Wireless Network for Bridging Communication Using IEEE 802.11 Protocols

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**Abstract**

Cooperative aerial wireless networks composed of small unmanned aerial vehicles (UAVs) are easy and fast to deploy and provide on the fly communication facilities in situations where part of the communication infrastructure is destroyed and the survivors need to be rescued on emergency basis. In this article, we worked on such a cooperative aerial UAV-based wireless network to connect the two participating stations. The proposed method provides on the fly communication facilities to connect the two ground stations through a wireless access point (AP) mounted on a UAV using the IEEE 802.11a/b/g/n. We conducted our experiments both indoor and outdoor to investigate the performance of IEEE 802.11 protocol stack including a/b/g/n. We envisioned two different cases: line of sight (LoS) and non-line of sight (NLoS). In LoS, we consider three different scenarios with respect to UAV altitude and performed the experiments at different altitudes to measure the performance and applicability of the proposed system in catastrophic situations and healthcare applications. Similarly, for NLoS, we performed a single set of experiments in an indoor environment. Based on our observations from the experiments, 802.11n at 2.4 GHz outperforms the other IEEE protocols in terms of data rate followed by 802.11n at 5 GHz band. We also concluded that 802.11n is the more suitable protocol that can be practiced in disastrous situations such as rescue operations and healthcare applications.

**Keywords:** UAV-based wireless network, Bridging communication, Cooperative aerial wireless networks, IEEE 802.11 standards, Ground stations, 2.4 and 5 GHz band, Disaster management

## 1 Introduction

The use of unmanned aerial vehicles (UAVs) as wireless communication platforms for facilitating communication on the fly has gained significant importance recently [1–4]. Vehicles that provide such facilities are vital in terrible situations in order to help the rescue teams on emergency basis to reduce the casualties and avoid further destruction in the affected area. The earthquake in 2005 hit the north part of Pakistan and Pakistani administered Kashmir and perished more than 80,000 people, while more than four million were left homeless. Similarly, the 2010 flood in Pakistan affected almost twenty million people and destroyed almost the entire communication infrastructure in all parts of the country.

Providing timely rescue services in such disasters may help to reduce casualties and may save the life of many people.

Cooperative wireless networks composed of small UAVs are cost-effective and easy to deploy and can facilitate communication on the go through self-managed ad hoc Wi-Fi networks to help the rescue teams in tragic events [5]. Such networks can also be deployed in border surveillance and patrolling [6, 7], wildfire monitoring [8, 9], and extending the coverage of ad hoc networks by using the UAV as a relay [10–12], with many other applications listed in [13, 14]. On top of that, unmanned aerial base stations (UABSs) are used in natural disasters for public safety communication to save lives, property, and national infrastructure [15].

Similarly, some other application areas with latest trends are discussed in [16–18]. For example, UAVs in a 5G/Internet of Things (IoT)-enabled platforms are used for multimedia and video streaming purposes in industry-oriented applications [16]. Moreover, drones are also used in IoT-based electronic health system to showcase its significance in healthcare industry with a special concentration on the use of small UAVs which can benefit IoT-based healthcare industry and applications [19–23]. Apart from the UAV application areas, security issues and challenges in IoT-based healthcare applications and environments are explored in order to protect such platforms from unauthorised access [18, 22]. Finally, latest research problems and challenges with respect to UAV applications in terms of wireless networks are highlighted in [24, 25] in order to update the research community with the latest trends and issues in the aforementioned areas.

The main contribution of this paper is to extend the work of [26] and to measure the capabilities of IEEE 802.11 protocol stack (a/b/g/n). In [26], we only investigate the performance of IEEE 802.11n in a UAV-based network with a fixed distance of approximately 10 meters between the AP mounted on UAV and the antenna fixed on a USB adapter. The experiments were performed in an outdoor environment and different performance metrics were calculated. The main contribution of this paper is listed below:

- In this paper, we particularly consider a network where a single UAV will bridge communication between two ground stations through an AP mounted on a UAV using 802.11 a/b/g over 2.4 and 802.11n at both 2.4 and 5 GHz band.
- We consider two cases with respect to LoS and NLoS communication.
- In LoS communication, we analyse three different scenarios with respect to UAV height from the ground stations: in scenario 1, we calculate the data rate, signal strength, and SNR between UAV and ground stations at 10 meter height.
- In scenario 2, we calculate the same characteristics for the communication links between UAV and ground stations at a height of 15 m, while in scenario 3, we revise the same experiment at a height of 20 m to analyse the same performance metrics.
- The reason for such low altitudes is to provide the best communication facilities to the ground users as we are considering our scenarios for disaster management situations and more specifically for search and rescue operations and providing first-aid equipment and facilities on immediate basis in order to help the survivors and rescue team members. Also, the limited flight time of the UAV (8 to 10 min maximum) restrict the UAV to be flown at higher altitudes.
- Similarly, in case of NLoS communication, we consider a single scenario to check the performance of IEEE802.11 protocol stack.

- We conduct our experiments in both indoor and outdoor environments with a UAV, an air-lifted AP mounted on the UAV, and two ground stations.
- The ground stations are here working as a client and server, where the client send data of size 10 MB to the server through a communication link provided by the IEEE 802.11 protocol stack.

The rest of this paper is organised as follows: Section 2 describes the related work. Section 3 presents the experimental setup including the hardware and software components used in the experiments. Section 4 discusses the results and discussion, while Section 5 draws the conclusion and discusses future work.

## 2 Related work

In [27], the authors proposed an aerial wireless network based on drones to cover a large amount of area through their wireless system. Two different modes were envisioned: infrastructure mode and ad hoc operational mode. A Galileo board was configured to work as an AP and intermediate hop in both infrastructure and ad hoc operational mode respectively. The board was also equipped with a wireless AC 7620 card to provide support for connections up to 867 Mbps by using 802.11 protocol standards (a/b/g/n/ac). The authors mainly concentrated on providing a theoretical overview of the UAV-coverage area in an outdoor environment and to experimentally check the performance evaluation of the configured board both in lab as well as in real aerial deployment in order to study both the infrastructure mode and ad hoc operational mode of the IEEE 802.11. Energy consumption of the Galileo board with respect to different WiFi modes was also part of the study. Moreover, Performance evaluation of the entire system was studied in terms of coverage range, transmission rates, and energy efficiency [27].

Similarly, a performance evaluation of radio links between a UAV having a wireless radio and an AP on ground through field experiments were analysed in [28]. Field experiments were carried out by using a 802.11a wireless interface fixed on both the UAV and AP along with two directional antennas. A series of experiments was performed with various antenna setups to evaluate the effect of altitude and yaw of the UAV on different performance metrics. Path loss exponent for air-to-ground links was estimated using the received signal strength (RSS) values in both open field and campus environment scenarios. User Datagram Protocol (UDP) throughput of air-to-ground links along with aerial view of the given area were also measured using the UAV onboard cameras in the presence of high capacity links in downward direction. The authors concluded their experiments with respect to different antenna orientations and summarised how poor the results could be in terms of throughput and RSS if the right antenna orientation is not deployed on the UAV [28]. This work was further studied in a three-dimension space and positioning with the extension of sample antenna to 802.11 devices in the context of aerial nodes in [29]. Communication issues in 3D space were handled with a proposed solution based on an 802.11 system with multiple antennas fixed on small-scale quadrocopters. Path loss and fading features particularly in terms of Nakagami fading using RSS samples of the radio channel between UAV and ground station were also analysed through real-time experiments at 5 GHz. The authors addressed the network performance issues with respect to throughput and number of re-transmissions and concluded that a throughput of 12 Mbps could be achieved at distances in the order of 300 m [29].

Moreover, the work in [29] was further extended by introducing the concept of two-hop networks, where multiple UAVs were used to measure the performance of the proposed network in terms of throughput and link quality [30]. Three different scenarios were studied from a system architecture perspective: (i) standard one-hop communication from UAV to ground station, (ii) two-hop communication between UAV and ground station through another UAV having an AP, and (iii) mesh networking through 802.11s extension with two UAVs and a ground station. Through experimental results, the authors claimed that stable throughput could be achieved in the second case where all traffic goes through a UAV having the AP and should be preferred to two-hop communication in a scenario with low jitter [30]. A similar study was carried out to measure the performance of 802.11a wireless links between UAV and ground stations with various antenna orientations in [31]. The authors addressed the issues of performance degradation/upgradation of wireless links with respect to antenna types (omni/directional), position, orientation, and ground effects such as interference because of reflected signals. A series of field experiments was performed, and it was concluded that horizontal dipole antennas with a perpendicular direction to the UAV flight path produce the highest throughput [31].

In [32], four different issues in multipoint-to-point UAV communication with IEEE 80211n/ac were investigated. Throughput results for 802.11ac were shown in a UAV setting, while it was demonstrated that 802.11a could have much higher throughput over longer ranges. Further, the fairness in a multi-sender aerial network was analysed and, by using two mobile UAVs that were sending data to a single receiver, was also tested in a real-world coverage scenario. The aim of the entire study was to address the above issues and to develop and propose a system consisting of multiple UAVs, where the ground nodes/clients and the UAVs can have the capability of joining the network in an ad hoc manner. High throughput 802.11 wireless LAN technologies were implemented, and a series of experiments were performed in indoor and outdoor environment to verify the applicability and performance of the proposed multi-device, multi-sender network. The authors claimed that high throughput could be achieved in both infrastructure and mesh modes in terms of 802.11n, while high data rates and improved throughput could be achieved by using 802.11ac compared to 802.11n in an indoor environment. However, in outdoor experiments, very low RSS and transmit data were recorded in terms of IEEE 802.11ac [32].

Furthermore, in [33] the authors addressed the issues of wireless communication between UAVs equipped with cameras in search and rescue missions. An experimental study was conducted in a real testbed based on 802.11n and XBee-PRO 802.15.4 to check the quality of aerial UAV-to-UAV links in terms of mutual distance and speed under varying context parameters. The main purpose of this study was to introduce a hybrid network-based system architecture for bulk data transfer and to study the effect of different metrics on link quality and networking performance by conducting real-time experiments in an outdoor environment. It was summarised that the calculated throughput of 802.11n is far from the theoretical maximum and also varies drastically even at a constant distance between UAVs. The work of [33] was further extended in [34], where the proposed system architecture based on Wireless Local Area Network (WLAN) 802.11n and XBee-PRO 802.15.4 hybrid network for bulk data transfer was extensively explored in order to summarise the implications of embedded hardware restrictions. An analytical model was also presented to estimate the expected time for large-sized image data transfer in aerial transmission. The authors concluded that expected quality of communication could only be guaranteed if the UAV's antenna position is perfect. The authors also indicated that there is a need for some new features in 802.11 in order to assure the high speed and reliable communication between UAVs [34].

Similarly in [35], a quadrotor UAV-based communication relay system was proposed to address the issues of beyond-line-of-sight (BLoS) communication and short-range communication restrictions. The communication relay system was developed and tested to verify the radio communication relayed from one quadrotor to another. The main hardware platform consisted of a ground control system (GCS) and two UAVs named as 'Mom', and 'Son', that were mounted with a Pixhawk flight controller and a Raspberry Pi 2 Model B microprocessor. The communication was basically relayed from the Son UAV through the Mom UAV to the GCS. A software platform was also developed to facilitate the communication between the two UAVs and GCS. A series of experiments were performed in order to check the data transmission rate and reliable communication performance in both indoor and outdoor environments, respectively [35]. The use of extra hardware may decrease the UAV flight time and could affect the entire mission. In [36], the authors addressed the issue of inter-UAV communication by developing a specified evaluation methodology. This evaluation methodology along with a tool developed to automate the process was tested in a controlled testbed environment to verify the applicability of the proposed approach. The methodology consisted of two main elements, a testing tool and a data analysing tool: the test tool automates the communication performance tests and controls the environment, while the data analytics tool analyses the data and generates the proper graphs based on certain scripts. The tool was named the Dronning tool and was developed to simplify and automate performance tests. The tool can run on Raspberry Pi devices along with standard PC, and can connect different application instances through sockets over IEEE 802.11 based ad hoc network. The methodology was evaluated over a 2.4 GHz band using 802.11g wireless interface by performing real tests. The authors addressed only the issue of UAV-to-UAV communication, while the communication between UAV and ground nodes was not considered which may prevent the use of the tool in real-time applications.

Furthermore, in [37], the authors performed real-time experiments to exemplify air-to-ground wireless channels between UAV and ground users over a range of frequencies including 900 MHz and 1800 MHz (cellular), and 5 GHz (WiFi) with respect to LoS and NLoS scenarios. The authors also investigated the viability of using drone-based beamforming technology through IEEE 802.11-like signalling. Based on this beamforming technology, the authors concluded that the throughput can be improved up to 73.6% and 120.1% in both LoS and NLoS scenarios, respectively. In addition to this, the emerging 5G communication technologies that are discussed in [38–40] can be utilised in the context of UAV communication and specifically in situations where ultra-high-reliable and ultra low-latency communication is required. The authors explored the key building blocks of 5G communication in the context of vehicular communication and machine-to-machine (M2M) communication. Also, how 5G can address the issues with the existing infrastructures and how the performance can be improved by using 5G technology within the aforementioned domains were discussed [41].

Finally, some work has also been done to address the issue of minimising the number of drones and maximising the coverage while monitoring a specific environment [42].

Also, routing protocols for wireless multimedia sensor networks and IoT rule in different fields with respect to technological aspects are discussed in [43, 44]. To conclude, a number of shortcomings of the solutions discussed earlier in the literature has pointed out. In some cases, the potential solutions only provide simulation-based results that may not be applicable in real-time situations, while in some other cases, the throughput/date-rate claimed may not be practicable in real-time scenarios and critical infrastructure development. A short summary of the related work including key contribution, research gap, and similarities/differences with our work is listed in Table 1.

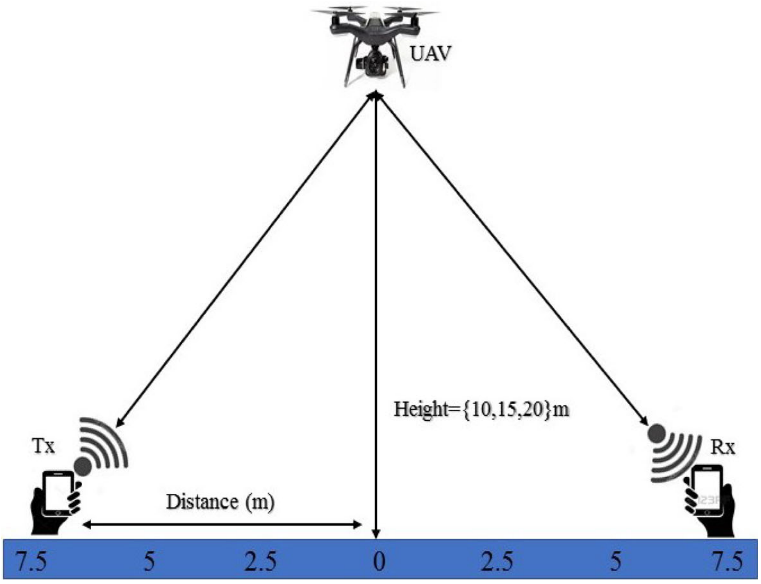
## 3 Experimental setup

In this section, we consider a UAV-based wireless network that employs 802.11a/b/g at 2.4 GHz and 802.11n at 2.4 and 5 GHz to analyse typical performance metrics, namely data rate, signal strength, and SNR for the communication links between UAV and the ground station, as illustrated in Fig. 1. Experimentation is carried out in an outdoor environment with a single UAV acting as an AP for communication bridge between two ground stations operating as client and server, respectively. The work is based on a mathematical model presented in [45] and is an extension of the research described in [26]. A glossary of mathematical notation used in this paper is provided in Table 2.

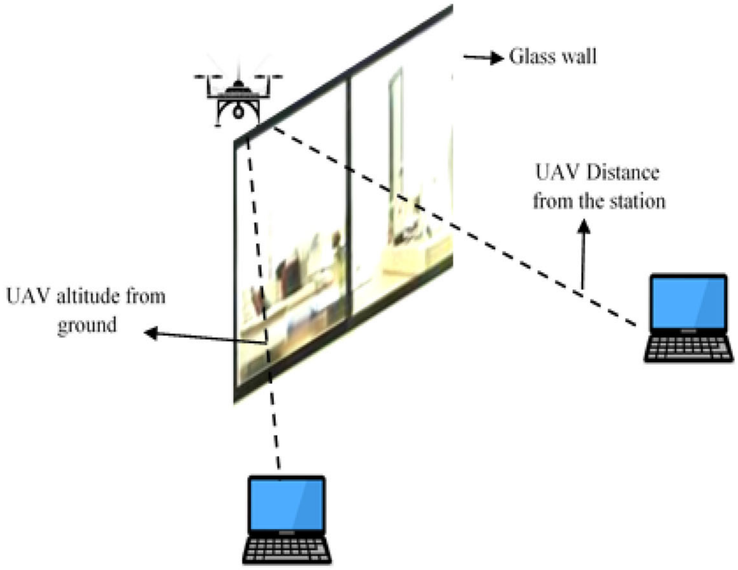
In UAV LoS communication, the UAV will always be direct communication with available ground stations. In such a situation, the electromagnetic waves that propagate between the UAV and participating nodes can be expressed mathematically as:

**Table 1** Summary of related work

| Reference papers | Key contribution | Research gaps | Our work |
|---|---|---|---|
| [27] | To extend the coverage of wireless systems | The authors only considered the free-space or LoS communication scenario | In our work, we considered both LoS and NLoS communication scenarios |
| [28, 29] | Characteristics of wireless links were analysed in both 2D and 3D space through field experiments using UAVs having a wireless radio and an AP | The authors only experimented 802.11a with two antenna orientations. Also, the system performs well only if the right antenna orientation is deployed on UAV | In our work, we experimented all the IEEE 802.11 standards in both LoS and NLoS scenarios. Also, we did not consider antenna orientation in our work, which means that the system is free of any orientation constraints |
| [30–32] | The performance of UAV-network in terms of throughput and link quality was measured in a two-hop network | The authors only measured the performance of 802.11a/ac and 802.11s. the authors claimed that the system only performs better if the horizontal dipole antenna is in a perpendicular direction to the UAV flight | In our work, we performed the same set of experiments but with an extension of 802.11b/g and n. Also, in our work, we considered both direct (LoS) and indirect (NLoS) communication scenarios in order to validate our proposed work |
| [33, 34] | Challenges of wireless communication between UAVs equipped with cameras to deliver high-resolution images to rescuers in search and rescue operations were investigated | The authors only tested 802.11n and also concluded that the throughput calculated during the experiments is far from the theoretical maximum. The authors also observed that the throughput varies drastically even at a constant distance between UAVs | In our work, we experimented all the possible 802.11 standards (a/b/g/n) and also claimed a throughput that is enough for both audio and video streaming in real-time communication during a disastrous situation |



(a) LoS Scenario



(b) NLoS Scenario

**Fig. 1** Experimental setup for both LoS and NLoS scenarios

$$P_r = \frac{P_t G_t(\theta_t, \phi_t) G_r(\theta_r, \phi_r)\lambda^2}{(4\pi d)^2} \tag{1}$$

where $P_t$ and $G_t$ are the power and gain of the transmitted antenna along with the elevation angle $\theta_t$ and azimuth angle $\phi_t$, respectively. $\lambda$ is the wavelength and $d$ is the distance between the UAV and available ground stations. Considering $\lambda = c/f$, Eq. (2) will become:

$$P_r = P_t G_t(\theta_t, \phi_t) G_r(\theta_r, \phi_r)\left(\frac{c}{4\pi df}\right)^2 \tag{2}$$

**Table 2** Mathematical terms and symbols

| Symbol | Description | Symbol | Description |
|---|---|---|---|
| $P_r$ | Received power | $P_t$ | Transmitted power |
| $G_t$ | Transmitted gain | $G_r$ | Received gain |
| $\theta$ | Elevation angle | $\phi$ | Azimuth angle |
| $\lambda$ | Wavelength of transmitted signal | $c$ | Speed of light (constant) |
| $T_x$ | Transmitter | $R_x$ | Receiver |
| $l$ | Total distance b/w ground stations | $a$ | Altitude of UAV |
| $\|h\|$ | Fading b/w UAV and ground stations | $P$ | Deterministic function |
| $P_1$ | Power b/w Node1 and UAV | $\sqrt{P_1}$ | Channel coefficient and power |
| $x$ | Signal transmitted (unit power) | $x_1$ | Signal transmitted b/w Node 1 and UAV |
| $n$ | Noise | $\|h_1\|$ | Fading b/w node 1 and UAV |
| $P_1(\|h_1\|)$ | Probability density function | $E_i$ | Exponential integral function |
| $C$ | Instant capacity | $\overline{C_1}$ | Average capacity |

We can also calculate the distance between the UAV and appropriate ground stations transmitter ($T_x$) and receiver ($R_x$) from Fig. 1 as follows.

$$d_1 = \sqrt{b^2 + a^2} \tag{3}$$

$$d_2 = \sqrt{(l-b)^2 + a^2} \tag{4}$$

where $l$ is the distance between two ground stations, $a$ is the height of the UAV, and $b$ is the distance in fraction from each ground station to the midway point. In a real-life deployment, signal power may depend on many factors including environmental, e.g. wind, with corresponding fading. The Rayleigh distribution is often used in such cases of signal variation with fading. To compute such fading, we assume that $|h|$ represents fading between the UAV and ground stations and can be described as follows:

$$|h|^2 \sim \frac{1}{\sigma_\ell^2} \exp\left(-\frac{|h|^2}{\sigma_\ell^2}\right) \tag{5}$$

For a full digital signal, we must also figure out the SNR between UAV and ground stations using the following equation.

$$SNR = \frac{|\sqrt{P_1}|^2\ |x_1|^2}{|n|^2} \quad \text{where} \quad n \sim N\left(0, \sigma_n^2\right) \tag{6}$$

In bandwidth restricted channels, we only consider instant and average capacity of the fading channel that can be computed from using the following equations.

$$C_1 = \log(1 + SNR_1) = \log\left(1 + \frac{P_1|h_1|^2}{(x^2 + a^2)\sigma_n^2}\right) \tag{7}$$

$$\overline{C_1} = \int_0^\infty C_1 p_1(|h_1|^2)\ d|h_1|^2 \tag{8}$$

where $p_1(|h_1|^2)$ is the probability density function (PDF) and can be used in the case of a fading channel. Putting the value of $C_1$ in Eq. (8) will result the next equation as follows:

$$\overline{C_1} = \int_0^\infty \log\left(1 + \frac{P_1|h_1|^2}{(x^2 + a^2)\sigma_n^2}\right) \frac{1}{\sigma_\ell^2} \exp\left(-\frac{|h_1|^2}{\sigma_\ell^2}\right)\ d|h_1|^2 \tag{9}$$

In the equation above, only $|h_1|^2$ is a variable, while the remainder are considered to be deterministic during the integration, as described in [45], leading to the simplified final equation given below.

$$\overline{C_1} = \mathrm{Ei}\left(-\frac{(x^2+a^2)\sigma_n^2}{P_1\sigma_\ell^2}\right)\exp\left(\frac{(x^2+a^2)\sigma_n^2}{P_1\sigma_\ell^2}\right) \tag{10}$$

From Eq. (10), the UAV position can easily be computed through variable $x$ and $a$, where $x$ is the transmitted signal and $a$ is the altitude/distance between a UAV and the ground stations. Real-time experiments were carried out based on the above mathematical model using the IEEE 802.11 protocols in order to validate the use of the above model in real-life situations.

### 3.1 Overview

Our testbed consists of two ground stations, i.e. a client machine and a server machine, and both of these machines are connected to each other through an AP that is mounted on a UAV. Both the machines are $\approx 15$ m away from each other. Iperf version 2.0.5 is used on both machines to receive and transfer the traffic flows within the machines through the AP. All the experiments are repeated 10 times for each network configuration transferring a transmission control protocol (TCP) iperf measurement of 10MB (Megabytes). The experiments are performed at 10, 15, and 20 m of UAV altitude from the ground stations using the IEEE 802.11 protocol stack including a/b/g/n at 2.4 GHz and 5 GHz(n) band in an outdoor environment for LoS scenario, while at a 5 m height with the same setup in an indoor environment for NLoS scenario.

### 3.2 Hardware setup

Our testbed consists of two different machines having the same specifications. The machine we used in our experiments are Apple machines equipped with Intel Core i5 processor with dual independent cores on a single silicon chip, 3 MB shared level 3 cache, 8 GB of onboard SDRAM, 256 GB Flash Storage, integrated intel Iris graphics, and having the latest Macintosh operating system X EI Capitan version 10.11.6. Connectivity of the system includes 802.11ac WiFi that supports all the IEEE 802.11 standards, Bluetooth 4.0, and with some USB 3.0 and Thunderbolt 2.0 ports. The rest of the hardware components of our testbed are discussed in the following section.

#### *3.2.1 Solo 3DR*

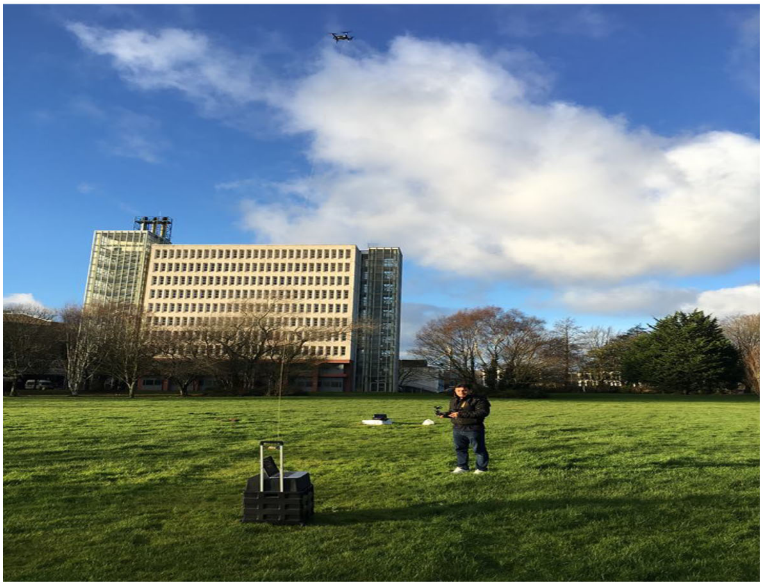
The main hardware part of the experiments is the small quadrocopter drone from Solo 3DR that holds the AP which connects the two ground stations to bridge communication. Solo is powered by two 1 GHz computers out of which one is running on copter and the other one is installed on controller, and both computers control the entire functionality of the UAV such as navigation, altitude, and inflight communication to exchange data between UAV and the UAV-controller. Figure 2 provide a full picture of different components of Solo 3DR. Solo is also powered by four motors along with four propellers that helps the UAV in inflight activities. With its powerful dedicated WiFi signal carried by the 3DR link, it provides connectivity between UAV and solo App to exchange real-time data and videos between UAV, controller, and other ground stations [46]. Flight time is 25 min, and with payload it is $\dashrightarrow$ 8–10 min, range is almost half a mile, maximum speed during flight is almost 55 mph (miles/hour) while in ascent it is 10 m/s if the UAV is in stabilise mode, and 5 m/s if it is in fly mode. The maximum altitude the UAV can fly in compliance with the civil aviation authority UK and federal aviation administration UK

& USA is 400 ft, but the user can adjust it to 122 m [47]. Another part of the solo 3DR is the UAV-controller which controls the UAV movement during flight and shows the inflight telemetry including GPS signal, height, battery power, and the position where the UAV will be landed back. Two antennas are also fitted on the controller to manage the communication over the radio link [48].

#### *3.2.2 The wireless AP*

The wireless AP is basically a portable router that helps to connect the two ground stations to facilitate communication through IEEE 802.11a/b/g over 2.4 and 802.11n over

(a) Hardware Setup



(b) Real Snapshot

**Fig. 2** Solo quadrocopter with its controller and AP along with a real snapshot of the testbed environment

2.4 and 5 GHz band. The AC750 portable WiFi router from D-Link provide the bridging facility in our experiments and is mounted on the UAV as shown in Fig. 2. The device is fully equipped with latest technology that provides speed up to 750 Mbps over 2.4 and 5 GHz band, and supports all the IEEE 802.11 protocols [49]. Its built-in rechargeable battery facilitates the UAV using its own battery for maximum time during the flight, while its low weight makes it easy to mount on the accessory bay part of the UAV.

### 3.3 Software setup (IPerf)

Iperf is a well-known tool that can create TCP and UDP data streams and can measure the maximum bandwidth and throughput of a network. The software is coded in C and is freely available to everyone. Iperf can be used to measure the end-to-end network performance between the two users. This open-source software is compatible with different operating systems including Windows, MAC OS, Linux, and Unix [50]. In our experiments, we used Iperf to send the TCP data streams of 10 MB from the client machine over the communication link provided by IEEE 802.11 standards to the server machine. The same tool is used on the server side to receive the data streams and to evaluate the data for different metrics of interest such as data rate, SNR, and signal strength. Based on the available data, different results are generated in terms of graphs that will be discussed in detail in the upcoming sections.

## 4 Results and discussion

This section will provide a detail about the results obtained based on the experimental parameters listed in Table 3. The results mentioned here are obtained from the experiments performed in an indoor and outdoor environment. The results are generated in terms of graphs for different metrics such as data rate, signal strength, and SNR at 10, 15, and 20 m of UAV altitude and at a distance of $\approx$15 m between the participating ground stations in an outdoor environment for LoS scenario, while at a 5 m height with the same distance between the stations in an indoor environment for NLoS scenario. To provide a detail overview of the metrics, 10 quantities have been summarised as a standard boxplot (minimum whisker, 25th percentile, median, 75th percentile, maximum whisker). For each set of 10 measurements, where the offset to the right of the boxplot (purple lines) presents the mean value with a whisker showing the 95th percentile and 99th percentile, respectively. The remaining details for each metric are given in the following subsections.

**Table 3** Experimental parameters for our testbed

| Experimental parameters | Value |
|---|---|
| No. of nodes (notebooks) | 2 |
| No. of UAVs | 1 |
| Band | 2.4/5 GHz |
| IEEE protocols | 802.11a/b/g/n |
| Channel width | 20 MHz |
| UAV altitude | 5 m, 10 m, 15 m, 20 m |
| UAV maximum speed | 15 m/s |
| UAV payload (AP weight) | 155 g |
| External interference (wind power) | 8–20 mph |

### 4.1 Line-of-sight (LoS) scenario

In LoS scenario, we performed three set of experiments with respect to UAV altitude in an outdoor environment to investigate the performance of our proposed network. The results for different metrics are generated in the form of graphs which will be explained in the following sections.

#### *4.1.1 Data rate*

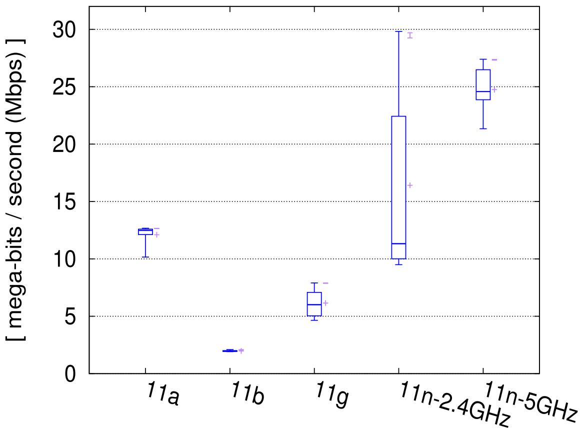
Data rate can be defined as the rate at which the data is transferred from one ground station to another ground station through an air-lifted AP. Figure 3 illustrates the data rate of 802.11a/b/g/n at 2.4 GHz and 802.11n at 5 GHz band using a 20 MHz channel at 10 m (Fig. 3a), 15 m (Fig. 3b), and 20 m (Fig. 3c), respectively, for LoS scenario. The data rate captured at all UAV altitudes using 802.11a/b/g at 2.4 GHz band is quite low and is not practicable in real-time scenarios during any rescue operation. The data rate in all these three cases at 11a/b/g ranges from a minimum of 2 Mbps and goes to a maximum of 13 Mbps as shown in Fig. 3. Instead, the data rate captured at 10, 15, and 20 m using 802.11n at both 2.4 and 5 GHz band is quite impressive and ranges from a minimum of 5 Mbps to a maximum of 30 Mbps. The data rate at 10 m UAV altitude is pretty good, but once the UAV starts moving up, the data rate starts decreasing and reaches as low as 5 Mbps as visible from Fig. 3c. 802.11n at 2.4 GHz claims the highest data rate in all three scenarios followed by 802.11n at 5 GHz band. The data rate or throughput we gained in our experiments is much better than the throughput claimed by the authors in [31]. The average throughput the authors claimed in [31] in both infrastructure mode and ad hoc mode is ∼3–5 Mbps, while in our case, the average data rate/throughput is ∼ 5–20 Mbps in all three scenarios, which means that our proposed system is more suited for real-time applications than the one proposed in [31] for LoS communication.

#### *4.1.2 Signal-to-noise ratio*

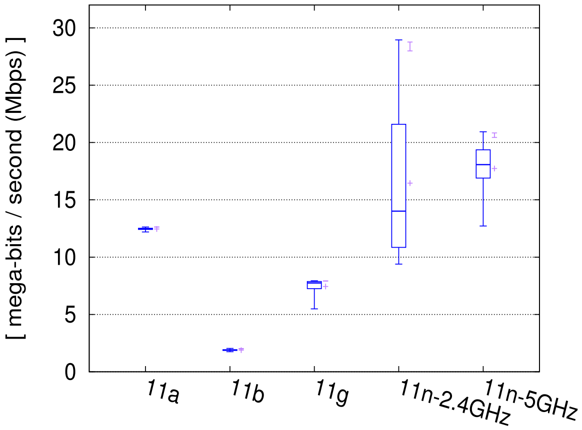
SNR can be defined as the ratio of the signal power to the noise power interrupting the signal. Figure 4 shows the SNR of both client and server stations at 10, 15, and 20 m for 802.11a/b/g at 2.4 GHz and for 802.11n at both 2.4 and 5 GHz. SNR of 802.11a ranges from ∼– 98 to ∼– 96 dBm at both client and server side in all three cases as shown in Fig. 4. Figure **a**, **c**, and **e** represent The SNR at client machine, while **b**, **d**, and **f** represents the SNR at the server side, respectively. Similarly, for 802.11b, the SNR ranges from ∼– 101 to – 91 dBm, while for 11g, it ranges from ∼– 98 to ∼-91 dBm. Moreover, for 11n at 2.4 GHz, the SNR is quite high at both 10 and 15 m altitude on both client and server machines, but at 20 m, the SNR is quite low and ranges from – 98 to ∼– 87 dBm on both ground stations, while the SNR for 802.11n at 5 GHz remains almost the same in all three cases for both client and server. In terms of SNR, 11n at 2.4 GHz (20 m) outperforms the others followed by 11g at 15 m and 11b at 10 m in terms of LoS communication. Based on the facts shown in Fig. 4, we concluded that 802.11b remains constant in terms of SNR and does not varies a lot. The main reason for such a high SNR is the interference because of high wind in our outdoor testbed as mentioned in Table 3.

#### *4.1.3 Signal strength*

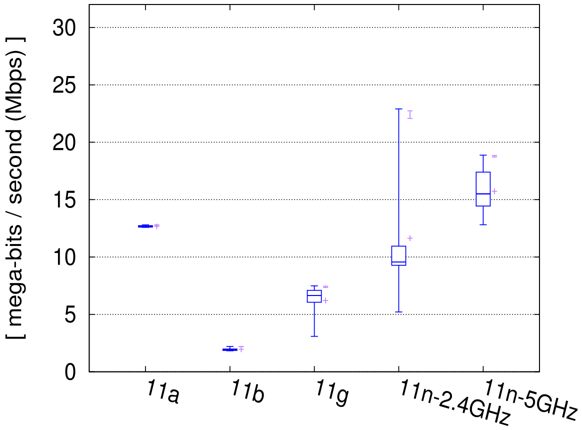
Signal strength is a phenomenon which depends on how well the AP is listing to both client and server machines during the communication between UAV and ground stations. Figure 5 shows the signal strength for both clients **a**, **c**, and **e** and servers **b**, **d**,



(a) Data rate (Mbps) @ 10 m



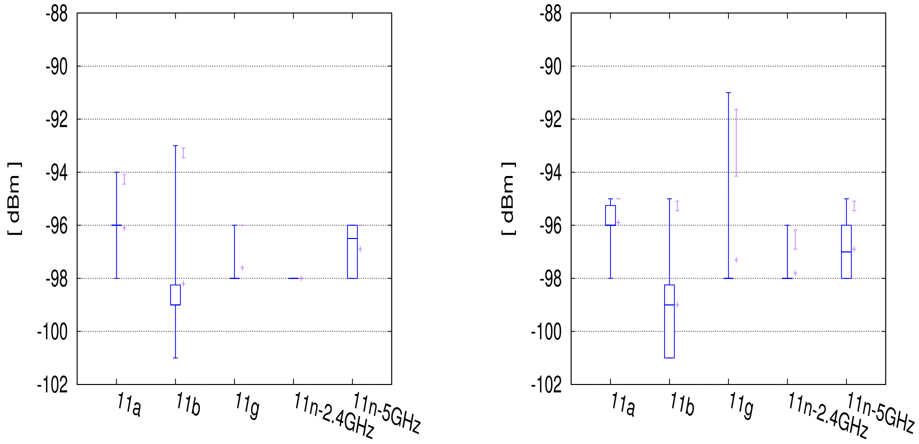
(b) Data rate (Mbps) @ 15 m



(c) Data rate (Mbps) @ 20 m

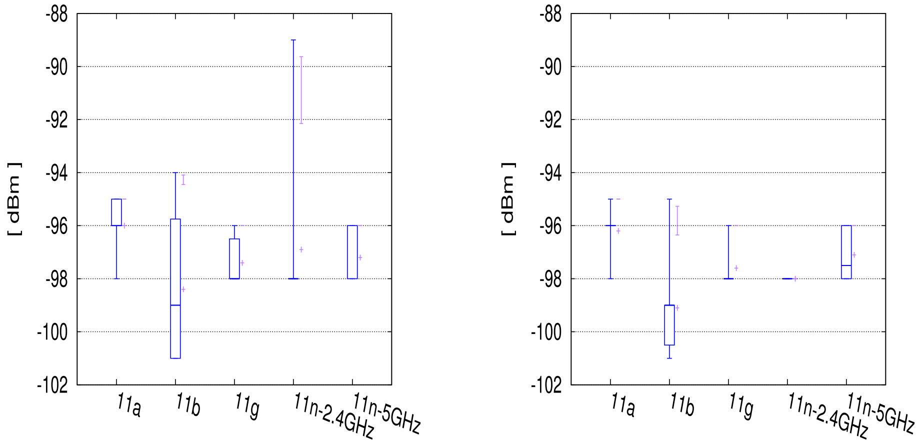
**Fig. 3** Data rate of 802.11 Protocols @ 10-, 15,- and 20-m altitude

and **f** machines at 10, 15, and 20 m altitude using 802.11a/b/g at 2.4 GHz and 802.11n at both 2.4 and 5 GHz band. Signal strength of 802.11a at 10 m ranges from − 60 to − 54 dBm, while at 15 and 20 m, the signal strength remains the same and is rounded



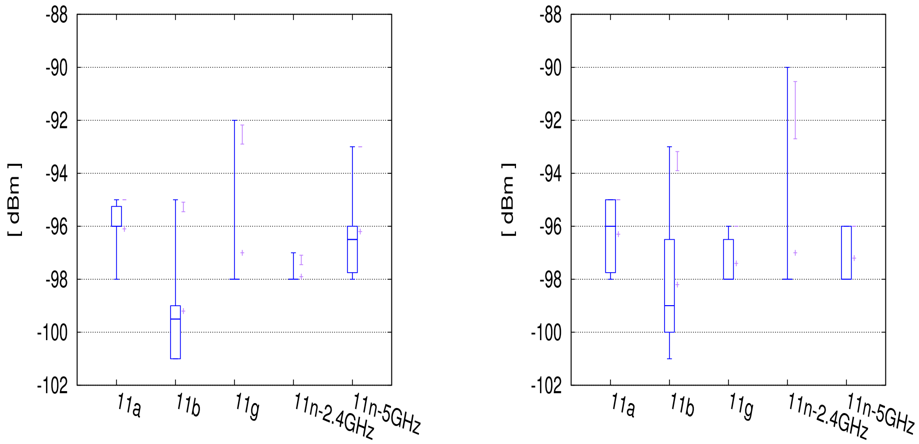
(a) SNR (dBm) @ 10 m (Client)

(b) SNR (dBm) @ 15 m (Client)



(c) SNR (dBm) @ 20 m (Client)

(d) SNR (dBm) @ 10 m (Server)



(e) SNR (dBm) @ 15 m (Server)

(f) SNR (dBm) @ 20 m (Server)

**Fig. 4** SNR of 802.11 standards @ 10, 15, and 20 m for both client and server

to ∼– 59 dBm at both client and server sides. Similarly, for 11b, it ranges from – 60 to ∼– 51 dBm in all three cases, while for 11g, it varies a lot and ranges from ∼– 70 to ∼– 59 dBm as shown in Fig. 5. Moreover, for 11n at 2.4 GHz, the signal strength varies slightly and ranges from ∼– 59 to ∼– 53 dBm in all three scenarios, while in terms of 802.11n at 5 GHz, it ranges from ∼– 74 to – 60 dBm at all 10, 15, and 20 m UAV altitude. In terms of signal strength, 11b performs slightly better than the other IEEE standards followed by 802.11a at both client and server sides and are more suited for LoS communication.

### 4.2 Non-line-of-sight (NLoS) scenario

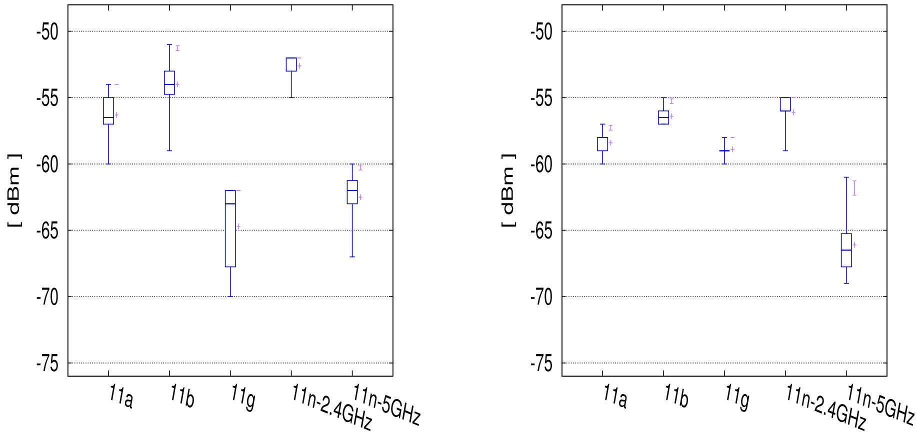
In this section, we will explain the results we obtained from our indoor experiments to check the feasibility of the proposed system in situations where the UAV is not in a direct sight/communication with the ground stations. We performed a single set of experiment that are conducted in a way that the AP mounted on a UAV is at 5 m height from the ground communicating with the ground stations having a glass wall in the middle as shown in Fig. 1b. We obtained the results in terms of graphs with respect to data rate, signal strength, and SNR that are detailed in the succeeding section.

#### *4.2.1 Data rate, signal strength, and SNR (NLoS)*

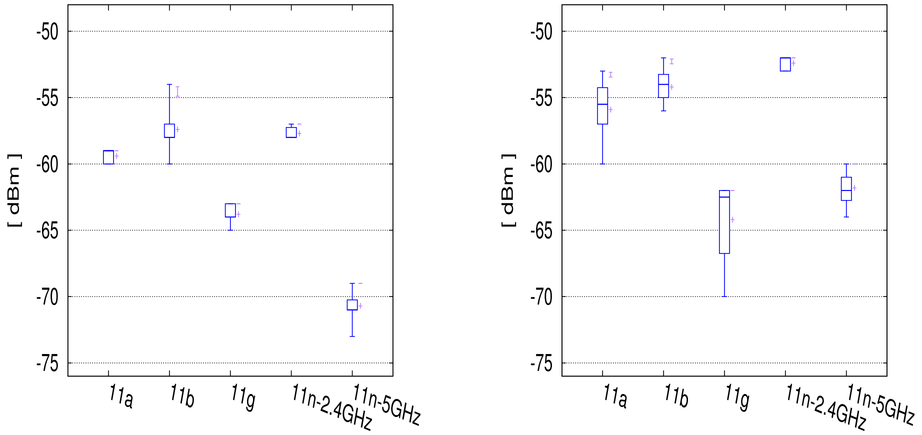
Figure 6a shows the data rate of 802.11a/b/g/n at 2.4 GHz and 802.11n at 5 GHz band having a 20 MHz channel at 5 m height in an indoor environment for NLoS scenario. The data rate captured using 802.11a/b/g/n at 2.4 GHz is very low (1 Mbps to a maximum of 10 Mbps) and is not applicable in real-time situations in terms of disaster management. But the data rate captured at 802.11n at 5 GHz is quite impressive (up to 20 Mbps) and can be operable in real-time NLoS scenarios. Similarly, Fig. 6b, and c shows the SNR for both client and server using 802.11a/b/g/n at both 2.4 and 5 GHz band for NLoS scenario. In all cases, the SNR ranges from ∼– 99 to ∼–83 dBm at both client and server sides. The reason for such a high SNR is mainly the shadowing and refraction of signal in NLoS communication. Moreover, Fig. 6d, and e shows the signal strength for both client and server respectively using the same protocol stack. On both sides, i.e. client and server side, the signal strength ranges from – 65 to ∼– 56 dBm, which is quite good in the case of NLoS communication.

## 5 Conclusion and future work

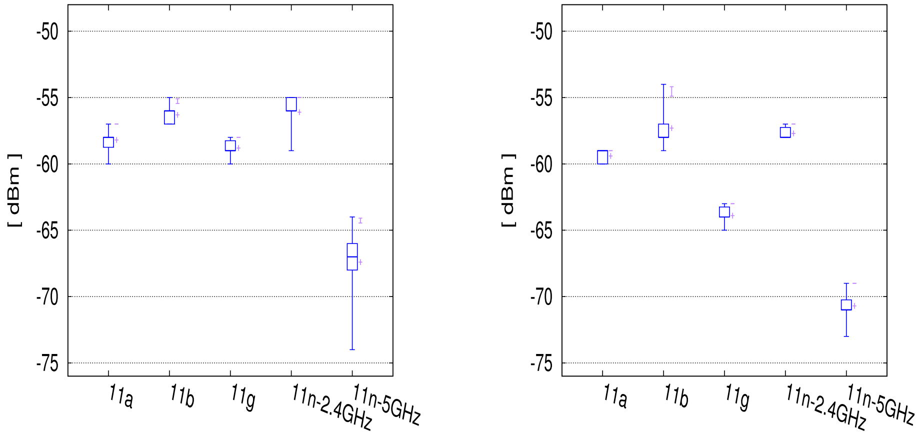
In this paper, we have tested IEEE 802.11a/b/g at 2.4 GHz and IEEE 802.11n at both 2.4 and 5 GHz bands using a 20 MHz channel in both indoor (NLoS) and outdoor (LoS) environment to check the performance of communication links between UAV and ground stations connected through an air-lifted AP on a UAV in terms of data rate, SNR, and signal strength for both scenarios. In our testbed, we find that IEEE 802.11n at 2.4 GHz outperforms the other IEEE 802.11 standards in terms of data rate reaching to a maximum of 30 Mbps followed by IEEE 802.11n at 5 GHz in the case of LoS, while for NLoS scenario, 802.11n at 5 GHz performs much better than the other protocols. Similarly, based on the SNR, IEEE 802.11b performs slightly better than the others followed by 802.11n at 2.4 GHz (for LoS scenario), while 802.11n at both 2.4 and 5 GHz performs well as compared to others in the case of NLoS. Moreover, in terms of signal strength, again 802.11b and 802.11n at both 2.4 and 5 GHz are slightly better than the other IEEE standards for both LoS and NLoS scenarios respectively. Based on the facts and figures, we concluded that IEEE 802.11n at both 2.4 and 5 GHz is practicable in real-time applications in the context of disaster management and healthcare applications for both scenarios.



(a) SS (dBm) @ 10 m (Client) (b) SS (dBm) @ 15 m (Client)



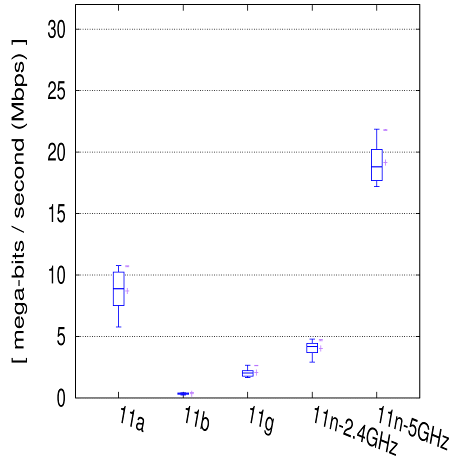
(c) SS (dBm) @ 20 m (Client) (d) SS (dBm) @ 10 m (Server)



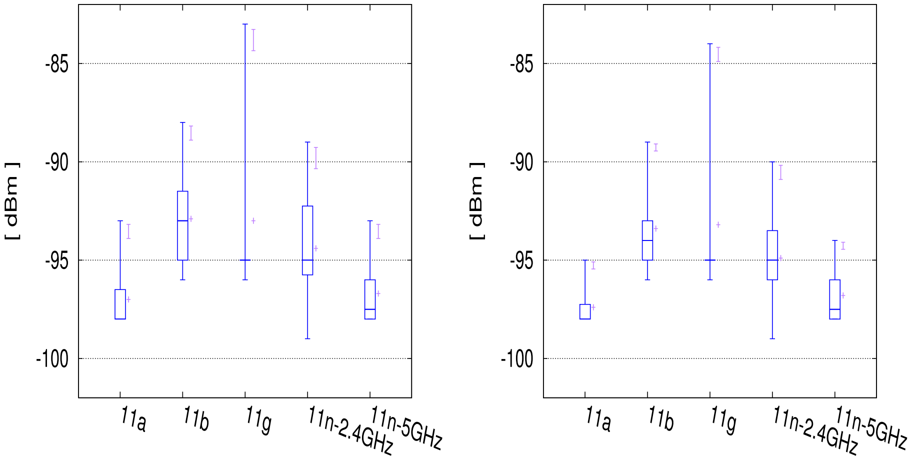
(e) SS (dBm) @ 15 m (Server) (f) SS (dBm) @ 20 m (Server)

**Fig. 5** Signal strength (SS) of 802.11 standards @ 10, 15, and 20 m for both client and server

As stated in the introduction, we restrict our experiments up to 20 m height only because of the limited flight time of the UAV. Also, the UAV can search only for a short period of time (2 to 3 min), while providing the communication facility for the rest of

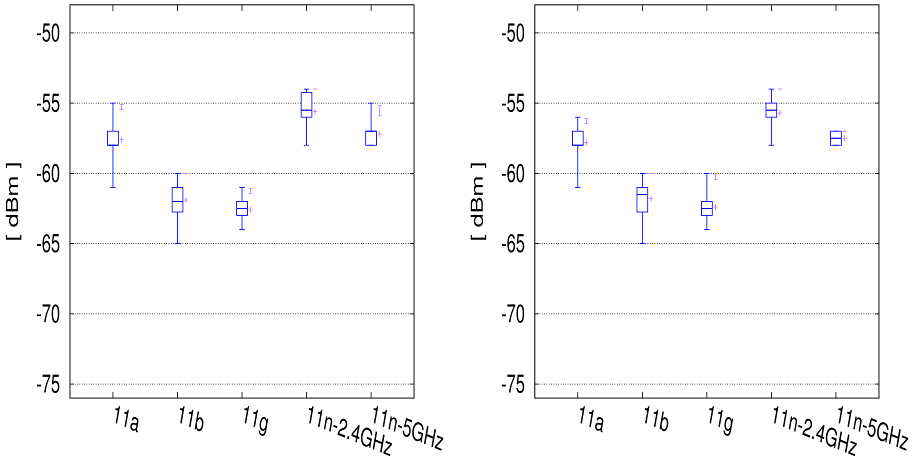


(a) NLoS Data Rate



(b) NLoS SNR (dBm) (Client)

(c) NLoS SNR (dBm)(Server)



(d) NLoS SS (dBm) (Client)

(e) NLoS SS (dBm) (Server)

**Fig. 6** Data rate, SNR, and signal strength (SS) of 802.11 standards for NLoS scenario the time. In future, we are planning to extend our experiments in terms of more UAV-altitudes, up to the maximum height the UAV can fly. We are also planning to use multiple moving nodes instead of just two static nodes in order to perform some more realistic experiments. We also intend to implement a frontier-based search algorithm to search the target area in a rescue operation along with an optimisation algorithm to improve the position of the UAV and to provide the best possible communication facilities to the participating ground stations. Moreover, we are planning to integrate the emerging 5G communication technology with UAV communication in critical infrastructure development.

### Abbreviations

UAV: Unmanned aerial vehicle; UABS: Unmanned aerial base station; IoT: Internet-of-Things; GA: Genetic algorithm; BAHN: Broadband and UAV-assisted heterogeneous network; BLoS: Beyond-line-of-sight; GCS: Ground control system; AP: Access point; LoS: Line-of-sight; NLoS: Non-line-of-sight; M2M: Machine-to-machine; SNR: Signal-to-noise ratio; RSS: Received signal strength; UDP: User Datagram Protocol; WLAN: Wireless local area network; TCP: Transmission control protocol; GPS: Global Positioning System

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### Authors' contributions

H.U. and M.A. conceived, designed, and performed the experiments; H.U. wrote the paper. S.M, P.N., G.P, and C.L. reviewed the paper. The authors read and approved the final manuscript.

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### Availability of data and materials

Data sharing is not applicable to this article as no datasets were generated or analysed during the current study.

### Competing interest

The authors declare that they have no competing interests.

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## Publisher's Note