A Survey of Radio Propagation Channel Modelling for Low Altitude Flying Base Stations

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A B S T R A C T

The increased utilization of unmanned aerial vehicles (UAVs) in the commercial market and military on account of their agility, nonpiloted and easy manoeuvering leads their applications in the telecommunication sector as well. It is expected that UAVs will play a vital role in 5G and Beyond 5G (B5G) networks as flying base stations (BSs) and/or relays. Recently, they are also proposed to assist the existing terrestrial communication infrastructure in forthcoming 5G/B5G to provide improved wireless network coverage particularly to the areas difficult to reach, the scenarios demanding high data rate and low latency on emergency needs, transceiving sensors data from field to the ground servers and providing wireless network coverage in a disaster where existing terrestrial communication infrastructure gets partially/severely damaged. However, it is of an utmost challenge to model the radio propagation channel from a UAV (low altitude platforms) to existing terrestrial BSs, the receiver on ground and with other flying UAVs in a network. This paper provides a survey of both measurement and simulation based radio propagation channel modelling investigations for a low altitude UAV enabled wireless network. Furthermore, the potential open research gaps and use cases are highlighted which will be key to define the role of UAVs in future wireless networks for various applications.

1 Introduction

The use of unmanned aerial vehicles (UAVs) or commonly known as drones, is progressing tremendously in our everyday life. In UK and US, small UAVs with weight less than 20 kg in permitted areas (e.g. a specific distance away from aerodrome boundary and flying without being into conflict with people or properties) can be flown on an altitude less than 400 feet (i.e. 122 m) without any license [1,2]. Here, the altitude is considered from the surface of the earth whether the operational area belongs to hilly, undulating or flat surface. Now a days, UAVs are in use in various applications like transportation of goods or first aid, inspection of crops in farming, surveillance by government agencies, filming movies, live coverage of concerts and sports, remote sensing, search and rescue and many more on account of their small size, cost-effective, agility, nonpiloted and low altitude flying ability [3]. According to recent research [4], the market value of UAVs will tend to grow up to $12.6 billion by 2025.

Apart from aforementioned applications of small UAVs, they were proposed to assist in providing improved wireless network coverage by manoeuvring as low altitude platforms (LAPs: from tens to few hundreds of meter) [5–12]. They can be deployed as flying base stations (BSs) or relays to improve wireless network coverage [13]. Particularly, in the scenarios demanding high data rate on emergency needs and in the areas where signals get severely deteriorated due to various obstacles [14], [15].

In case of natural disasters, already existing terrestrial communication infrastructures are prone to get severely damaged (e.g. Indonesia tsunami (2004), Gulf Coast Katrina hurricane (2005), Haiti Earthquake (2010) [16] and Japan Earthquake (2011) [17]). It is noticed that the number of natural disasters tends to increase in every decade [18]. Generally, the major issue faced with severely damaged terrestrial communication infrastructures in the result of large scale disasters is that the enduring BSs get congested and due to this quality of service gets compromised [19]. The first 72 hours after a disaster are of vital importance for the first responders to accomplish effective search and rescue missions [14]. Therefore, such unexpected scenarios demand the provision of wireless network coverage on an emergency basis for strategical disasters management [20]. Authors in [21], analysed the performance of several algorithms to be used in UAV assisted networks for visual based searching of a victim with time to find the victim as an optimization parameter.

The existing terrestrial communication infrastructure support systems (e.g. deployment of the

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cell on wheels (COW) and cell on light trunks (COLT)) has several shortcomings to meet the need of wireless network coverage for disaster management [22]. For example, time taken to physically arrive in the affected areas and network congestion are the basic shortcomings in COW and COLT. Furthermore, fifth-generation (5G) and beyond 5G (B5G) are expected to have improved resilience in wireless network coverage in case of emergencies or unavailability of existing terrestrial communication infrastructure [23]. How non-terrestrial networks (e.g. drone assisted) will assist to improve resilience in future wireless networks coverage, is an important dimension to explore.

One possible solution might be satellite-based communication systems however, they have their own limitations [24]. For example, the geostationary satellites have a large distance from the surface of the earth and face large delays. Whereas the non-geostationary satellites are complex, costly to launch, and they can only be launched in the limited number of orbits due to which available communication links are expensive. Another possible solution could be high altitude platforms (HAPs: on an altitude of 20 – 50 km) [25,26], however, they have own limitations [27,28]. For example, cost, hardware complexity, time taking deployment and configuration, and limited data rate are the major issues. HAPs may be useful when the wireless network coverage needs to be provided on a very large coverage area for longer endurance. Facebook and Google are currently working on a project for HAP to provide internet access [29]. However, in the scenarios of emergencies for being quickly deployable, HAPs are not an adequate solution to support terrestrial communication infrastructures. On the other hand, LAPs do not have such kind of issues. For example, they can be ready to deploy, easily reconfigurable, adaptive altitude, cost-effectiveness, and more chances of having short distance line-of-sight (LOS) communication links with the receiver for providing high capacity and low latency [9,30]. UAVs enabled flying BSs and relays are considered to assist terrestrial communication infrastructure for improved wireless network coverage [31–35]. GSMA (Groupe Spéciale Mobile Association) encouraged the use of UAVs in disaster management for surveillance to assist the first responders and flying BSs or relays to make the partially damaged terrestrial mobile networks functional [36]. The integration of UAVs with existing terrestrial communication infrastructures can enhance capacity and coverage with energy efficiency and reliability in future wireless networks, particularly for the scenarios of emergencies or hard to reach areas for broadcasted signals [12]. In [15], researchers highlighted how UAVs connected with terrestrial BS can assist to provide wide area coverage, secure identification and authorization, and interoperability among globally evolving wireless network coverage. Furthermore, the communication link from flying BS to a receiver can have another advantage of controlled mobility of UAV. For example, in the need of high data rate, if LOS link is established with the receiver, the motion of UAV can be switched to the only hover for maintaining the LOS link for improved communication between flying BS and the receiver.

One of the major challenges in designing UAVs enabled wireless network coverage is the modelling of the radio propagation channel (RPC) [9,12,27,37]. The better understanding of the RPC will be helpful to model the fading (large scale and small scale) effects caused by the environment and design the reliable wireless communication systems. The radio propagation in flying BSs will significantly differ from existing terrestrial communication infrastructures. The basic constraints behind these differences consist of communication link distance variation, ground reflections, multipath fading effects, antenna orientation, interference and jamming, the effect of electronics equipment of UAV and vibrations of the UAV [8]. Fig. 1 shows the possible effects (to count few) on the signal propagation from a UAV to a receiver.

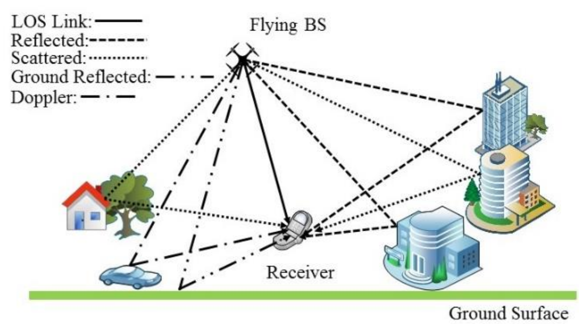

Fig. 1. An illustration of signal propagation from a UAV to the receiver on the ground

The 5G is expected to be launched in various parts of the world in 2020 and its spectrums will occupy majorly in three bands: low band (below 1 GHz), mid band (1 – 6 GHz), and high band (6 – 100 GHz) [38]. Mid band and high band in most parts of Europe (including the UK) will be auctioned around frequencies of 3.5 GHz and 26 GHz respectively [38]. The mid band around 3.5 GHz could be useful in search and rescue operations on account of being able to penetrate into a vast variety of materials [39] (e.g. walls, doors, building, and beneath the ground to get images of buried objects) along with required wireless communication services. Therefore, modelling of the RPC in the mid band can contribute significantly in the research of UAVs enabled assistance to the terrestrial

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communication infrastructure for its improved wireless network coverage. On the other hand, it is also important to model the RPC in spectrums already being used in the existing cellular networks (from 800 MHz to 2600 MHz) [40].

3rd Generation Partnership Project (3GPP) started focusing to handle required data rate, latency, altitude and speed limitations, interference mitigation, evaluation scenarios and channel modelling in low altitude UAV based communication systems [41,42]. Furthermore, International Telecommunication Union (ITU) emphasized the use of UAVs as a relay for transmitting wireless sensor networks (WSNs) information from affected areas to computer servers for assistance in disaster management [43].

This paper provides a detailed survey (section 2) of the RPC quantification and modelling that includes both measurement based and simulation based investigations for UAV enabled future wireless networks. Section 0 highlight open research problems. The future research directions are provided in section 4 along with proposed use cases which are expected to be important for UAV enabled networks and required further investigation for radio propagation channel modelling. Finally, the paper is concluded in section 5.

2 Literature Review

This section provides a comprehensive literature review of the RPC modelling for UAV enabled wireless networks along with the considered use cases and the limitations. Several survey papers have been published in the literature on the research of UAVs enabled wireless network coverage to summarize the use cases, challenges, resources management, and future perspectives [8,12,16,34,44–51]. In this review paper, our focus is to summarize the on-going research work relating to the radio propagation channel modelling for low altitude UAV based wireless networks. This review will summarize the platforms (i.e. hardware and software) and relating parameters for channel modelling, modelling approaches (i.e. measurements or simulation), scenarios, key findings and limitations. These limitations are key to define the proposed use cases and relating research gaps, as discussed in section 4, to improve network coverage for disaster management and upcoming market of 5G and B5G.

This section is explicitly divided into two sub-sections based on the type of modelling approach: 1) measurement and 2) simulation based channel modelling. In order to remain consistent, few terminologies need to be defined first. The downlink from a UAV to a receiver and terrestrial BS are respectively referred to as air-to-ground (A2G) and air-to-BS (A2B), as shown in Fig. 2. While the uplink from the receiver and terrestrial BS to UAV are referred to as ground-to-air (G2A) and BS-to-air (B2A), respectively. The distance from a UAV to the receiver and ground level refers as link-distance and altitude and the acute angle between link-distance and horizontal distance is refer to an elevation angle. The distance from ground level to the receiver is referred to as receiver height. Fig. 3 shows the graphical representation of these distances and the elevation angle.

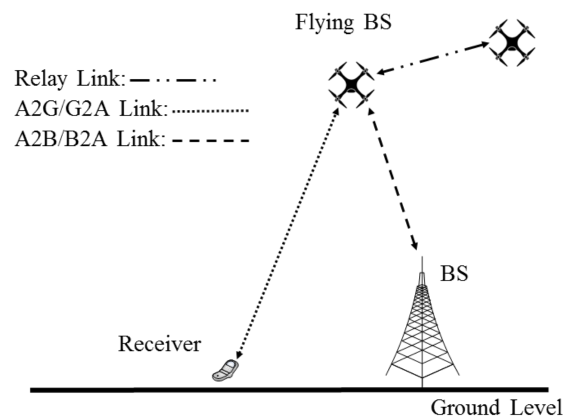

Fig. 2. Types of channel links in the UAV based wireless network

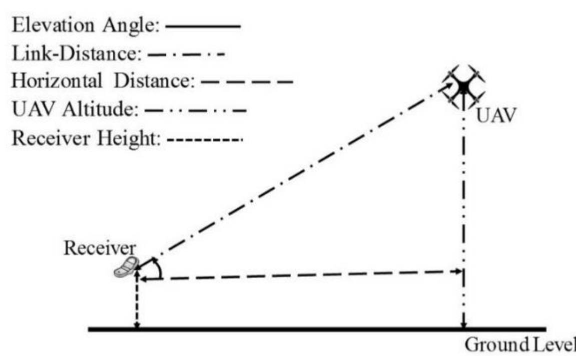

Fig. 3. Types of distances and elevation angle in UAV based wireless network

2.1 Measurement Based Channel Modelling

Radio waves when propagate undergo several types of losses and environmental effects (e.g. large scale and small scale fading) depending upon the type of environment, distance travelled and transmitted frequency [52]. Mainly, two methods were used to investigate the RPC modelling by measuring: (1) channel impulse response (CIR) by an appropriate channel sounding equipment [52–56] and using CIRs to compute both large scale fading (e.g. path loss and shadowing) and/or small scale fading parameters (e.g. delay spread) and (2) received power, which can only

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provide large scale fading parameters. Each measurement based attempt in the literature to model the RPC is classified into one of the four categories: A2G, G2A, A2B and B2A, and will be discussed in following sub-sections.

2.1.1 A2G Channel Modelling

Received power and throughput were measured in [57] for the open area on altitude 20 – 120 m in the frequency spectrum of 2.4 GHz and large scale fading analysis was provided. Measurement campaign with CIR based large and small scale fading analysis however, limited to an open area and very low altitude (16 m) was performed in [58]. In [59], only path loss and throughput were measured in open area scenarios within cellular (900 MHz and 1800 MHz) and Wi-Fi (5 GHz) bands for a maximum altitude of 30 m. In the continuation of this research [60], while UAV was hovering and flying in a circular path with 6 m/s speed, bit error rate (BER) and throughput were measured. A measurement campaign in the open area was done for large scale and small scale A2G channel modelling in frequency bands around 1.8 GHz and 5.7 GHz for LOS communication link with an altitude of 30 m [61]. However, the RPC modelling needs to be further investigated for the partially and fully obstructed channel because channel models in LOS distinctly differ from that of non-LOS (NLOS) [62]. An A2G channel modelling in the open area by investigating both large and small scale parameters within 3.4 – 3.8 GHz frequencies was done in [63]. Another measurement campaign limited to open area and 40 m altitude in 1.2 GHz band for A2G channel modelling was done in [64]. The results showed less multipath propagation for higher altitudes. A measurement based effort was done for channel modelling within altitude ranges from 50 – 950 m, horizontal distance up to 70 km and frequency bands around 785 MHz and 2160 MHz in LOS communication scenarios [65]. This measurement campaign for channel modelling was limited to only large scale fading and it was not a small UAV based, rather an aerial ship-based communication. The channel characteristics may differ when a small UAV is flown under altitude of 122 m. In [66], UAV to vehicle LOS channel was analysed in terms of packet delivery ratio in the frequency band of 5 GHz on two fix altitudes i.e. 40 m and 100 m. Packet delivery ratio was observed greater for higher altitude.

2.1.2 G2A Channel Modelling

Comprehensive measurement campaigns [67–69] for large scale and small scale channel modelling from a tower to piloted aircraft up to 20 km altitude within frequency bands 0.968 GHz and 5.06 GHz were studied in open area, over the mountainous and surface of the sea. Significant variations in small scale fading parameters for larger link-distances were observed which possibly depicted the reflections from the water surface. Yet, G2A channel modelling for relatively low altitudes for smaller UAVs lacks and required further investigation.

2.1.3 B2A Chanel modelling

B2A channel was investigated in terms of measured received power and adjacent cell interference in 2 GHz band on altitudes 50 m and 150 m [70]. The results were compared with the study of channel modelling from BS to a moving receiver (in a car) and B2A communication link was overall found to be better. In [71], a comprehensive measurement campaign in LOS scenarios was carried for B2A channel modelling on different altitudes and link-distances in 2.5 GHz band. Overall, the results described that with larger altitudes and link-distances the fluctuations in the large and small scale parameters are significant. The work was a significant contribution for modelling of B2A channel, however, further adequate use cases for disaster management are needed to be studied e.g. including the effect of disaster debris on earth in various environments or weather conditions.

2.1.4 A2B channel modelling

The channel between a UAV and mobile network in the open area was modelled using large scale parameters and signal to interference and noise ratio (SINR) in 800 MHz band [72].

In this sub-section 2.1, measurement based channel modelling attempts in different scenarios are useful as an initiative, however, more comprehensive investigations are further required particularly for relatively higher altitudes [42,73], in 5G mid/high band in obstructed LOS and NLOS use cases and with mobility factors (e.g. either receiver is moving slowly or in a vehicle). In addition, channel modelling in the use cases with a flying UAV and continuously transmitting while ground receiver static/moving is important to be discussed. Authors in [74,75], modelled vehicle-to-vehicle channel for moving scatterers by considering Doppler effects in dynamic scenarios and such channel models can provide a base for dynamic scenarios (UAV, scatterers and/or receiver are in motion) in UAV enabled networks.

Table 1 summarizes the RPC channel models which have been used for measurement based channel modelling. The Log-distance path loss model has been widely used for scenarios relating LOS and open area. Apart from already used models as given in Table 1, further channel modelling approaches can be adopted for different scenarios [55].

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Table 1. Summary of the RPC Models used in Surveyed papers

Channel Model	(Reference / Link Type)	Adopted Scenarios
Log-distance Path Loss Model (with/without modification)	([57] / A2G), ([58] / A2G), ([59] / A2G), ([60] / A2G), ([61] / A2G), ([67–69] / G2A), ([71] / B2A), ([72] / A2B)	Open area, LOS
Modified COST – 2100 model	([65] / A2G)	Airship (altitude from 50 – 950 m) communication with a vehicle.
Two-ray model (validation with actual results)	([67,69] / G2A)	LOS over water and in urban environment.

2.2 Simulation Based Channel Modelling

Simulation based investigations of the RPC models were mostly done in the mid band and high band of 5G spectrum. The following section comprehensively describes the published literature related to RPC modelling for three channel links: A2G, G2A and B2A. To best of authors' knowledge, none of the publication was found relating the use cases for A2B.

2.2.1 A2G Channel Modelling

The probability of availability of LOS link and elevation angle dependent large scale fading were studied in 2 – 6 GHz band for an altitude of 22 km [76]. In [77], the RPC from an aircraft to the receiver on the ground was modelled as a function of altitude and the horizontal distance. The model was based on a strong assumption that all multipath components (MPCs) were within the elliptical planar region. A ray-tracing simulation based A2G channel was modelled in hilly areas within frequencies from 200 MHz to 5 GHz in [78]. The presented results contained elevation angle dependent large scale and small fading analysis as well as probabilities of LOS, obstructed LOS and NLOS links. Another elevation angle dependent path loss for altitude up to 200 m was modelled in various LOS scenarios by using Wireless InSite Simulator [27]. In 2.4 GHz band, only large scale fading was modelled based on elevation angle for altitudes 100 – 2000 m by using Wireless InSite Simulator in LOS and NLOS scenarios [79]. In [80], UAV assisted A2G channel in the cellular network was investigated in terms of probability of SINR greater than a certain threshold and dependence of UAV altitude and path loss exponent on the area spectral efficiency. Researchers in [81] and [82], modelled three-dimensional geometry-based (cylindrical and ellipsoidal respectively) A2G multiple-input multiple-output (MIMO) channels.

2.2.2 G2A channel modelling

In [83], a simulation based analysis of communication link for rescue vehicles (in terms of probability of received SNR greater than a threshold) against the UAV altitude up to 1000 m was performed for different transmit powers, number of vehicles and the coverage area.

2.2.3 B2A Chanel modelling

A simulation based study was carried out for unwanted interferences coming from adjacent BSs to UAV along with taking into account the coverage probability of a terrestrial BS and several UAV altitudes [84]. The result described that lowering the heights of terrestrial BSs, limiting the UAV altitude and down tilting the terrestrial BS antennas can be beneficial for optimized coverage towards both UAV and receivers.

In above all referred simulation based RPC investigations, the research attempts are mostly limited to LOS communication with several assumptions. Therefore, further simulation based campaigns are required for use cases in shopping malls, high-rise buildings and relating disasters. Furthermore, NYUSIM simulator can be useful to investigate simulations based RPC in various frequency bands [85].

The summary of channel modelling investigations including both measurement based and simulation based is provided in Table 2 and Table 3. This summary includes parameters of investigations, scenarios, type of link and highlight their key findings. Following list of abbreviation is used in both Table 2 and Table 3.

Abbreviation	**Description**
COMM	Communication
Tx	Transmitter
Rx	Receiver
Freq	Frequency
DDP	Distance Dependent Path loss
PED	Path loss-Elevation angle-Dependent
PLE	Path Loss Exponent
PDP	Power Delay Profile
RMS-DS	Root Mean Square-Delay Spread
RKF	Rician-LOS K-Factor
DSSS-CCS	Direct Sequence Spread Spectrum Correlator Channel Sounder
RSS	Received Signal Strength
PDF	Probability Density Function

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Table 2. Summary of measurement based channel modelling and relating parameters

Ref	Freq MHz	Applications	Scenario	Type	Main Findings	Studies Parameters	Distance (m); Tx height (m); Rx height(m); v (m/s)	Sounding method and/or equipment
[57]	2400	Military, search, tracking, surveillance	Open area, campus building in LOS Com	A2G	PLE = 2.6 and 2.5	RSS, throughput	0:500; 0:20:120; 2; N/A;	Atheros 802.11 wireless cards
[58]	3100 – 5300	Environmental sensing system, 3G, 4G, 5G networks,	In open area LOS COMM	A2G	PLE = 2.60 – 3.03; Shadow standard deviation = 2.79 – 5.30	CIR (PDP, DDP, RMS-DS, mean excess delay, coherence BW)	5.6 – 16.5; 4:4:16; 1.5, 0.07; 20	Time Domain P-410 kit in bi-static mode
[59]	900, 1800 and 5000	Search, rescue,	LOS and NLOS in SISO and beamforming (2x1)	A2G	LOS and NLOS throughput vary 2.22 – 30.59 Mbps.	DDP and throughput	10:10:100; 10,20,30; 1; N/A	Spectrum Analyzer, USRP
[60]	900, 1800 and 5000	Search, rescue, Disaster, military	LOS in SISO and beamforming (2x1), UAV hovering and encircling	A2G	PLE = 0.07 – 1.99. Shadow standard deviation 1.30 – 6.12.	DDP, BER and throughput	10:10:100; 1; 10,20,30; 1,3,6	Spectrum Analyzer, USRP
[61]	1817 and 5760	Wildlife Monitoring, search and rescue	In LOS COMM, UAV moving and hovering	A2G	PLE = 0.74,2.29; Shadow fading = 1.23 dB, 2.15 dB	CIR (PDP, DDP, RMS-DS, RKF)	210; (20, 30) and (0 – 50); N/A; N/A	USRP
[63]	3400 - 3800	Disaster management, Cellular BS, Relay	In LOS COMM, moving on low altitudes	A2G	Modelled delay parameters with Rician, Weibull and Lognormal distributions.	CIR (PDP, RMS-DS, mean Depay Spread)	-10:10; 5,10,15; ≈1.3; 0.5	Time domain PulsON 210 kit
[64]	1200	Surveillance, transportation, disasters	Open area	A2G	RMS-DS = 294.78 – 286. 20 ns.	CIR (PDP, RSS, RMS-DS)	50; 4,10,40; 1.5; 0.5;	Pulse based channel sounder
[65]	785 and 2160	Emergency based COMM	In LOS COMM from aerial ship (of size 35 m) while receiver on vehicle	A2G	COST 2100 PL model parameters.	DDP, PDF of shadow fading throughput	0:70000; 50, 250, 450, 715and 950; Rx on vehicle; 14 (speed of vehicle);	Frequency-sweeping based channel sounding
[66]	5000	Emergency based COMM, for safety purposes	In LOS COMM from UAV to car on inclined road	A2G	Modified Gaussian fitting with finding goodness of fit.	Packet delivery ratio	0:3000; 40,100; Rx on vehicle;	Raspberry Pi, Smartphone, GRCBox
[67]	960 – 977 and 5000 – 5150	Rescue, surveillance, cargo	Piloted aircraft in LOS COMM over water	G2A	Exponential distribution on time domain parameters.	CIR (PDP, DDP, RMS-DS, RKF)	2500, 4-20, 800, 90	DSSS-CCS
[68]	968 and 5060	Rescue, surveillance, cargo	Piloted aircraft in LOS COMM in hills and mountains	G2A	PLE = 1.0 – 1.8;	CIR (PDP, DDP, RMS-DS, RKF)	2500; 20; 1158, 2728, 3900; 75 – 95	DSSS-CCS
[69]	968 and 5060	Rescue, surveillance, cargo	Piloted aircraft in LOS COMM in sub-urban and urban	G2A	Two ray modelling parameters.	CIR (PDP, DDP, RMS-DS, RKF)	542; 20; 1.07, 1.69, 20.31; 77	DSSS-CCS
[70]	2000	UAV enabled wireless comm	Tx on UAV and Rx on moving car	B2A	More adjacent cell interference is experienced in the air than at ground.	RSS, Interference	N/A; 50,150; N/A; UAV (5), car (5.5)	Smart Phone App. "TEMS Pocket 16.3"
[71]	2585	Monitoring, search and rescue, farming, transportation, disaster management	LOS comm in the presence of trees	B2A	Deviations in large scale fading increases with increase in altitude or distance.	CIR (PDP, RSS, RMS-DS, RKF, CDF, shadowing)	100:100:500; 15,30,50,75,100; 20; 5.6, 2.5;	USRP

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[72]	800	Monitoring, search and rescue,	From BS to UAV LOS COMM	A2B	PLE reduces with increase of UAV altitude in LOS COMM.	Altitude dependent PL exponent	N/A; N/S; 15, 30, 60, 120; 4	TSMA scanner

Table 3. Summary of simulation based channel modelling and relating parameters

Ref	Freq MHz	Applications	Scenario	Type	Main Findings	Studies Parameters	Distance (m); Tx height (m); Rx height(m); v (m/s)	Sounding method and/or equipment
[76]	2000 - 6000	Cellular BS, Disasters	LOS and NLOS with multipath propagation	A2G	Found ITU R-1410 model parameters.	Elevation angle dependent probability of LOS, shadowing	211,000; 22,000; N/A; N/A;	N/A (simulation based)
[77]	N/A	Cellular BS, Simulations based	Assumes, all MPCs lie in an elliptical plane	A2G	Defined geometry-based channel model and found Direction of Arrival.	CIR (path loss, delay resolution, DOA of MPC)	N/A; N/A; N/A; N/A;	Derived mathematical relations
[78]	200 – 5000	Public safety, disasters recovery, military in the field	LOS, OLOS, NLOS COMM in hilly areas	A2G	Eliminated PLE dependence and found mean PL parameters.	PED, CIR (PDP), Probability (of LOS, OLOS, NLOS)	N/A; 100; 15; N/A;	N/A (ray tracing simulations)
[27]	700, 2000 and 5800	Cellular BS, disaster recovery,	LOS COMM in several suburban and urban use cases	A2G	Proposed a statistical RPC model for LAPs.	PED	N/A 200; 1.5; N/A	N/A (Wireless InSite Simulator)
[79]	2442	Rescue, surveillance, weather detection, monitoring wildlife	LOS and NLOS COMM in multipath propagation for high altitudes	A2G	PLE is modelled based on Tx height.	PED, shadowing, probability of LOS	N/A; 100:100:2000 N/A; N/A;	N/A (Wireless InSite Simulator)
[80]	N/A	Cellular BS, disaster recovery,	LOS and NLOS COMM	A2G	Found the effect of PLE and the number of UAVs on coverage performance.	Probability of SNIR, area spectral efficiency	N/A; N/A; N/A; N/A;	N/A
[81]	N/A	UAV assisted A2G MIMO COMM	Assumes, all MPCs have identical propagation delays coming from the same ellipsoid	A2G	Defined 3D cylinder based UAV MIMO channel model.	spatial cross-correlation functions, Doppler power spectrum density, PDPs	N/A; N/A; N/A; N/A;	N/A
[82]	N/A	UAV assisted A2G MIMO COMM	All MPCs experience similar delays from UAV to receiver.	A2G	Defined 3D ellipsoid channel model.	spatial cross-correlation functions, Doppler power spectrum density, PDPs	N/A; N/A; N/A; N/A;	N/A
[83]	2000, 5800, 5900	Rescue vehicles for disaster management	LOS COMM	G2A	Studied connectivity among UAV and vehicles as a function of UAV altitude.	Probability of SNR greater than a threshold	N/A; 0:1000; Vehicle height; N/A;	Derived mathematical relations
[84]	N/A	Comm from fixed BS to aerial and ground Rx	LOS and NLOS comm	B2A	Limiting UAV altitude, lowering terrestrial BS height and tilt angle improves COMM performance.	Coverage probability (UAV altitude, BS height, BS antenna tilt)	N/A; 0:120; 0:50; N/A;	N/A (modified Nakagami-m fading model)

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3 Open Research Problems

It is evident from the Table *2*2 and 3, the research work relating the RPC modelling for low altitude UAV enabled networks is still in an early stage. In addition, RPC modelling is mainly limited to the use cases in open areas with LOS communication links, very low altitudes, and provide very limited large scale and small scale fading analysis. Only a few of the measurements were comprehensively carried out (by modelling both large scale and small scale fading) however, they were limited to the use cases of open area and LOS links. It is important to perform further comprehensive RPC studies (measurements and simulation) for NLOS, relatively higher UAV altitudes, antenna orientation and polarization, characterization of shadowing due to UAV body and the use cases where UAV would be continuously flying while transmitting/receiving as well. In future wireless networks, UAV enabled wireless network coverage might be required in NLOS communication scenarios as well. Practically, there might be more chances of occurrence of scenarios having both the LOS and NLOS links due to the unexpected appearance of obstacles during UAV flights as a BS. For future perspective, UAVs will not only be used as a flying BS or relay. Instead, they will remain connected with everything [47,86] i.e. Internet of Things (IoT), which for example may need to establish a communication link with indoor and outdoor electronic devices. This ultimately urges to investigate the RPC between a flying UAV and receiver(s) in various scenarios of indoor as well as outdoor e.g. receiver inside a building obstructed with of different materials and objects (e.g. wall and windows).

4 Future Directions

In addition to RPC modelling in UAV enabled wireless network, several other challenges need to be fulfilled to leverage the full benefits of flying BSs and relays in future wireless networks. This section particularly proposes the use cases inspired by the recommendations of standardization bodies for outdoor channel modelling [41–43,87–89] and limitation of the previous work (as discussed in section 2 and 3). In addition, this section discusses the challenges in UAV based 3D wireless networks, cellular connected UAVs and highlight the issues like UAV detection and battery power constraints.

4.1 Proposed Use Cases

Table 4 provides a summary of use cases which either have been investigated or still need to be investigated with some modification (if applicable). For better understanding, a colour scheme is used in Table 4. Four colours are used for four current statuses of summarized research from the literature: green (for the scenarios already done); yellow (for the scenarios need to be investigated with modifications e.g. in term of different altitudes); blue (for the scenarios yet to be investigated); and white (for the scenarios that are possibly not applicable).

Table 4 describes the scenarios in terms of various kind of UAV and receiver placement (receiver on ground/in vehicle and UAV moving or hovering) in different use cases e.g. open area, LOS, OLOS and NLOS for residential areas, industrial sites, high rise buildings, hilly area and in caves and tunnels. All these proposed scenarios tend to be significant for UAV enabled wireless network coverage not only for consumer and commercial market but also for emergency needs and disaster management.

Table 4. Use Cases for UAV based Channel Modelling with Research Gaps

SR: Static Receiver, **RiV:** Receiver in Vehicle, **RoG:** Receiver on Ground, **AD:** Already Done, **Md:** needs to be done with Modification, **RI:** required Investigation, **NA:** Not Applicable, **OLOS**: Obstructed LOS.

Sr. No	**Use cases**	**UAV and receiver placement**				
		UAV Hovering		**Only UAV moving**	**Both UAV and receiver moving**	
		SR	**RiV**	**SR**	**RoG**	**RiV**
1	Open Area	AD	RI	Md	RI	RI
2	OLOS and NLOS in vegetation, Halls, Residential Areas, High rise Buildings	Md	RI	Md	RI	RI
3	LOS, OLOS, and NLOS in natural disasters	RI	RI	RI	RI	RI
4	LOS, OLOS and NLOS in Industrial catastrophes	RI	RI	RI	RI	RI
5	Caves and tunnels LOS, OLOS and NLOS	RI	RI	RI	RI	RI
6	LOS, OLOS and NLOS in While receiver on various floors of buildings	RI	NA	RI	RI	NA

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Measurement campaigns can be initiated from the simplest use cases of open area to more focused and related use cases on several link-distances and the mid-band for 5G (preferably around 3.5 GHz) and the effects of natural disasters. These use cases should not be considered the only and hardly finalized, they can be adopted according to the latest recommendations or directions by standardization bodies or other stakeholders e.g. ITU, 3GPP, and GSMA.

4.2 UAV Based Heterogeneous 3D Wireless Networks

UAVs will be deployed as flying BS or relay for wireless coverage in 3D (three dimensional) future wireless networks [90,91]. Where they might be simultaneously connected with other flying BSs, terrestrial BSs, ground users, drones as user equipment and HAPs for backhaul. This kind of deployment of UAVs imparts the need for modelling the RPC among various kind of communication links. HAPs or satellites can play a vital role in establishing a link for backhaul. Researchers in [92], proposed a theoretical model to study 3D A2G propagation channel in terms of angle and time of arrival however required validation for measurements. Considering the 3GPP 3D channel model for terrestrial communication (i.e. LTE based), they can provide an initiative for a UAV enabled 3D channel models [93,94]. Furthermore, the placement of UAV BS for effective energy utilization with maximum coverage [95] while also taking into account the overall network delay [96], interference management from adjacent cells [97,98], dynamic spectrum access for UAV enabled networks [99], and 3D positing control [100] are vital research areas for UAV enabled network and required further investigation.

4.3 Cellular Connected UAVs

In the radio propagation channel modelling, it is intended that UAV will remain connected with a ground user as a BS or user equipment. Several other challenges exist for UAVs as flying BS. For example, estimating the number of UAV assisted BSs to provide wireless network coverage to a certain/uncertain number of ground users in a particular geographical area. Moreover, interested readers may refer to [62,84,101–104], for a detailed study of challenges expected to be faced in cellular connected UAVs for example the command and control of UAVs, defining combined network architecture for flying BSs and terrestrial BSs, high data rate requirements, inter and intra cell interference mitigation, identification of a flying user equipment, determining optimal altitude of a UAV flying BS, an effective antenna pointing towards a ground user or terrestrial BS, enhanced mobility and effective handover with low latency. In addition, weather effects on the UAV enabled network, particularly in millimetre band, will be important to investigate like on-going research in 5G and B5G terrestrial networks [105].

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4.4 Other Challenges

Other challenges in UAV enabled future wireless networks include e.g. detection and jamming of unauthorized UAVs [106–108], command and control of inter-connected UAVs [109,110], and battery or power constraint of the UAVs [111,112].

5 CONCLUSION

In addition to the continuously increasing utilization of UAVs in the consumer and commercial market, they are also now proposing to assist the existing terrestrial communication infrastructure for improved wireless network coverage. Particularly, the forthcoming 5G/B5G technologies are expected to provide improved wireless network coverage in the scenarios demanding high capacity and low latency on emergency needs, temporary coverage in hard to reach areas, IoT and for disasters management. It is expected that UAV enabled network will play an important role in future wireless networks to improve coverage and to provide on demand connectivity.

In this paper, a comprehensive survey of channel modelling for UAV enabled network has been presented for both measurement and simulation based approaches. In addition, potential open research problems are highlighted and proposed key use cases which will be vital for a functional low altitude UAV enable wireless networks particularly with the focus on the radio propagation channel modelling.

Declaration of competing interest
None

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