CAPITAL UNIVERSITY OF SCIENCE AND TECHNOLOGY, ISLAMABAD

# Multiray Channel Modeling for the Communication Networks of Flying Things

by

Fawad Ahmad

A thesis submitted in partial fulfillment for the degree of Master of Science

in the

Faculty of Engineering
Department of Electrical Engineering

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*I dedicate this thesis to my family for their affectionate love and support*

## CERTIFICATE OF APPROVAL

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**(Fawad Ahmad)**

# *Abstract*

During the last few years, the use of Unmanned Aerial Vehicles (UAVs) has increased impressively in various civil, military, and commercial applications. They have proved themselves capable of performing and completing a wide range of industrial applications and hence have become a versatile and powerful industrial tool. To have a good insight of an effective communication between base station and aerial vehicle a reliable multipath channel model is required. This research work presents a critical review of the existing G2A and A2A channel models and concludes that most of the research studies have assumed only Line of Sight (LoS) signal component for channel modeling which may not be a realistic approach when multiple air vehicles are flying together. The study proposes that in a network of flying things, the surrounding air vehicles may act as scatterers and may form a multipath environment due to reflections from the surface of proximate vehicles. For this purpose, a closed-form expression for the path difference of the reflected ray with the LoS ray in multipath fading environment is developed for Ground-to-Air (G2A) and Air-to-Air (A2A) communication links. This path difference is further utilized to calculate the received power at the intended air vehicle as a result of the combination of the LoS and diffused components reflected from the surrounding air vehicles. Simulations are performed in MATLAB®by utilizing the reflective properties of drone's surface and multi-ray channel model that estimate the received power at the intended air vehicle in a network of flying things. The proposed multi ray channel model is also utilized for channel characterization and performance analysis of G2A and A2A communication links. Moreover, the impact of various factors including altitude, number of aerial vehicles, separation distance is analyzed on the received power at intended air vehicle. Finally, the simulation results are validated with the measured data.

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# Abbreviations

| | |
|---|---|
| **AAoD** | Azimuth Angle of Departure |
| **AFL** | Average Fade Length |
| **AoA** | Azimuth Angle of Arrival |
| **AUE** | Aerial User Equipment |
| **A2A** | Air-to-Air |
| **A2AT-R** | Air-to-air Two Ray |
| **A2G** | Air-to-Ground |
| **CFs** | Correction Factors |
| **dB** | Decibels |
| **EAoD** | Elevation Angle of Departure |
| **EoA** | Elevation Angle of Arrival |
| **FTDD** | Finite-Difference Time-Domain |
| **FVs** | Flying Vehicles |
| **GBSM** | Geometry-based Stochastic Models |
| **GS** | Ground Station |
| **G2A** | Ground-to-Air |
| **HAP** | High-Altitude Platforms |
| **IoTs** | Internet-of-things |
| **LCR** | Level Crossing Rate |
| **LEDs** | Light Emitting Diodes |
| **LoS** | Line of Sight |
| **LTE** | Long-Term Evolution |
| **MANET** | Mobile Ad-hoc Network |

| | |
|---|---|
| **MIMO** | Multiple Input Multiple Output |
| **MOM** | Method of Moments |
| **M2M** | Mobile-to-Mobile |
| **NGBSM** | Non Geometrical stochastic models |
| **NLoS** | Non-line of sight |
| **PDF** | Probability Density Function |
| **PL** | Path Loss |
| **PLE** | Path Loss Exponents |
| **RADAR** | Radio Detection and Ranging |
| **RCS** | Radar Cross Section |
| **Rma** | Rural Macro Cell |
| **RSSI** | Received Signal Strength Indicator |
| **RT** | Ray-Tracing |
| **SISO** | Single Input Single Output |
| **SRC** | Spatial Reflection Coefficient |
| **UAS** | Unmanned Artifact System |
| **UAVs** | Unmanned Aerial Vehicles |
| **Uma** | Urban Macro Cell |
| **VANET** | Vehicular ad-hoc Networks |
| **V2V** | Vehicle-to-Vehicle |
| **WSN** | Wireless Sensor Networks |
| **3G** | Third-Generation |
| **3GPP** | 3rd Generation Partnership Project |
| **4G** | Fourth-Generation |
| **5G** | Fifth-Generation |
| **6G** | Sixth-generation |

# Symbols

| | |
|---|---|
| $A_0$ | Intended Air Vehicle |
| $A_k$ | Scattering Air Vehicles |
| $\theta_0$ | Elevation Angle of Intended Air Vehicle |
| $\phi_0$ | Azimuth Angle of Intended Air Vehicle |
| $\theta_k$ | Elevation Angle of Scattering Air Vehicles |
| $\phi_k$ | Azimuth Angle of Scattering Air Vehicles |
| $r_0$ | Shortest Aerial Distance between Intended Air Vehicle and Base Station |
| $r_k$ | Distance between Base Station & Scattering Air Vehicles |
| $x'_k$ | Distance between Scattering Air Vehicles and Intended Air Vehicle |
| $x''_k$ | Distance between Base station and Intended Air Vehicle Via Scattering Air Vehicles |
| $\Delta x_k$ | Path Difference |
| $T_k$ | Time Delay |
| c | Speed of light |
| $P_r$ | Received Power |
| $\Gamma$ | Reflection Coefficient |
| $P_t$ | Transmit Power |
| $G_t$ | Transmitting Antenna Gain |
| $G_r$ | Receiving Antenna Gain |
| $A_e$ | Antenna Aperture |
| $P_d$ | Received Power Density |

# Chapter 1

# Introduction

## 1.1 Overview

During the last few years, the use of Unmanned Aerial Vehicles (UAVs) has increased impressively in various civil, military, and commercial applications. Initially, the UAV or flying vehicles (FVs) were supposed to be used only for military purposes to combat enemy activities from a remote station. Due to the advancements in electronics and mobile technology, the size and cost of UAVs have been optimized tremendously, which further enhanced their demand. The use of FVs opened up new opportunities in industries and helped to provide efficiencies in many industrial sectors like oil & gas, seaports, mining, and many other extensive industrial facilities. They have proved themselves capable of performing and completing a wide range of industrial applications and hence became a versatile and powerful industrial tool. They have also been introduced in various new commercial, security, entertainment, medical, and telecommunication-related applications. The rising demand for flying vehicles has further sparked many new companies to invest and research in assembling well-featured flying vehicles at reasonable market prices. As the number of flying vehicles increases, there is an imminent requirement to safely integrate commercial flying vehicles into the country's airspace regulations. According to the sixth generation (6G) standards, electronic devices would be inter-connected with each other and would form a network, generally termed as internet-of-things (IoT). In order to establish a wireless network among the electronic devices, a reasonably good and stable internet would be required. In areas where the internet facility is not available, or it is not feasible to install the wireless network structure, the flying vehicles are suggested to be used effectively for internet coverage. In cases when a collaborative work of flying vehicles is required for a specific application, then these vehicles may establish a wireless network to perform their task efficiently. Although flying vehicles are being used in numerous fields; however, there are still many countries that have not permitted and legalized their commercial use due to security concerns. In sixth-generation (6G) communication or beyond, electronic devices would be inter-connected with each other, which require seamless internet coverage for all devices to form a wireless communication network. The demand for flying vehicles is expected to accelerate more when proper country-wise rules and regulations are made, and flying vehicles are allowed to operate commercially. Recently, in the 2018 Olympics, 1218 intel's drones, named shooting stars, were used to perform Olympics fireworks, whereas, in Tokyo 2020 Olympics games, 1824 drones were flown with super bright Light Emitting Diodes (LEDs) to form the Olympics emblem in the sky [1]. In cases, when multiple drones are used in a network, a reliable communication link is required to control and operate their operations. The communication performance of air vehicles may get affected due to multipath interference caused as a result of reflections from the surrounding vehicles. In order to analyze the communication performance of the network, the multipath channel environment of flying vehicles is required to be investigated and analyzed.

## 1.2 Networks of Flying Things

FANET is basically the integration of multiple flying vehicles, generally known as Unmanned Aerial Vehicles (UAVs) or drones, under the same network as illustrated in Fig. 1.1. It is basically a combination of Mobile Ad-hoc Network

(MANET) and Unmanned Artifact System (UAS). The communication and operational services of the network are supported through the Internet of Things (IoT). FANET can be utilized for several applications of detection and management such as fire detection, environmental monitoring, surveillance, tracking etc. It can be used to collect the desired information from several flying vehicles and send them towards the base station through wireless links. The base station can further analyze and process the received information for a better and more vigilant decision beforehand [2]. Due to the ubiquitous usability and cost-effectiveness of air vehicles, FANET is being supported to expand a variety of applications and services. For example, the FANETs can support IoT applications by enhancing the network coverage and decreasing the cost of the IoT network by collecting the essential data, gathering information from various resources/points, and dispatching the data in infrastructure-less regions [3]. FANET has gained exceptional attention and demand due to its flexibility and reduced acquisition costs; however, legislation may curtail its operations in critical environments. Despite their well-supported usability, there are still some cases where the free-operability of flying vehicles may raise security issues, such as airports (where accidental strike may pose a threat to jets/planes), prisons (transportation of illegal goods to prisoners), and no-fly zones (confidential areas). In order to perform a bigger task over abandoned areas, the FANET can be used to enhance the communication coverage. Despite many advantages, FANET also suffers from some challenges such as connectivity, battery recharge, storage, computing capacity, transmission delay, interference management, collaboration, and cooperation. The low density or the high speed of air vehicles may cause link fluctuation or connectivity issues in FANET, which may decrease the performance of the network due to bit error rate, latency, and jitter. Since, air vehicles are equipped with a limited battery resource; therefore, their limited capacity of batteries may reduce the flight time [4]. The limited data storage and computing capacity of air vehicles is the one major challenge of FANET, because the protocol which offloads the sensed data towards base station requires high data saving and computing capacity. A multi-hop communication mode is adopted when a stable communication link is not available;

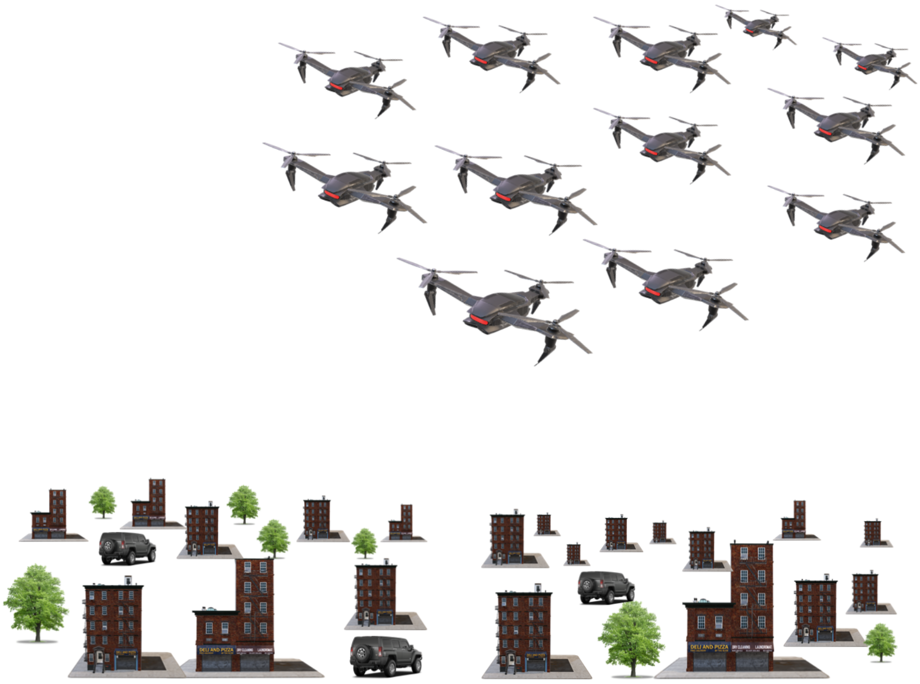

FIGURE 1.1: Network of flying things

however, this may result in an increased propagation time delay [5]. The FANET with multiple air vehicles generates a multipath environment as a result of reflections from vehicles surfaces. The limited capacity of wireless communication mode, along with the continuously changing topologies, make interference management more difficult. In order to complete a specific task, a trusted collaboration and cooperation between air vehicles is necessary, which is the one major challenge of FANET [6].

### 1.2.1 Air-to-Air Communication Channel

In recent years, Air-to-air (A2A) communication has gained much attention from academia and research due to its immense potential in the air telecommunication and air vehicles industry. Since, the use of aerial vehicles is rapidly growing day-by-day; therefore, there is an immense requirement of improving the efficiency of air vehicles from the production to the services end. With the advancements of chip technology, the cost of air vehicles or drones has been reduced tremendously, which made them viable to be used in various applications. In order to perform the control operations and other data services of air vehicles, the vehicles are required to be connected with a ground station, satellite station, or both. Although, connection with satellite provides global coverage; however, it is considered infeasible due to its longer route delay. Since, air vehicles or drones are normally operated in environments crowded with drones, airplanes, jets, and high-rise buildings; therefore, seamless instant control operations would be required to perform the operations, which can only be guaranteed through seamless connection with the base station. In cases, when an air vehicle is connected with the base station through a multi-hop connection, then the wireless connection with neighboring drones/vehicles should also be reasonable to perform instant control operations. The working principles of air-to-air (A2A) communication systems are similar to the existing mobile-to-mobile (M2M) or vehicle-to-vehicle (V2V) communications except with a difference of highly moving aerial base station and air vehicles. In A2A communications, the aerial base station is connected with the ground base station and works as a relying station to transmit and receive data from a base station to air vehicles and from air vehicles to the base station as shown in Fig. 1.2. Moreover, for a large number of air vehicles in a network, an optimized trajectory must be guaranteed to avoid collision. Since, the vehicles are interconnected with each other through a wireless link; therefore, a stable connection is mandatory to avoid an expected collision, to assign various application tasks, and to coordinate the related control operations. In case, the connection between the ground station and the air vehicles is not stable, these operations may suffer and may not guarantee an autonomous movement. As multiple air vehicles or drones are incorporated in FANET, the vehicles may become a source of reflections towards the intended air vehicle or drone. In such a case, the reflections may create fluctuations and degrade the signal quality, which may further lead to multipath fading. Moreover, the micro-mobility of air vehicles may get affected due to wind conditions, weather, link quality. As discussed earlier that it is not necessary to provide a direct dedicated link to each air vehicle; therefore, the network has to cater the effects of a multipath environment and has to guarantee a reliable communication environment to serve the purpose. Since, air vehicles or drones normally move

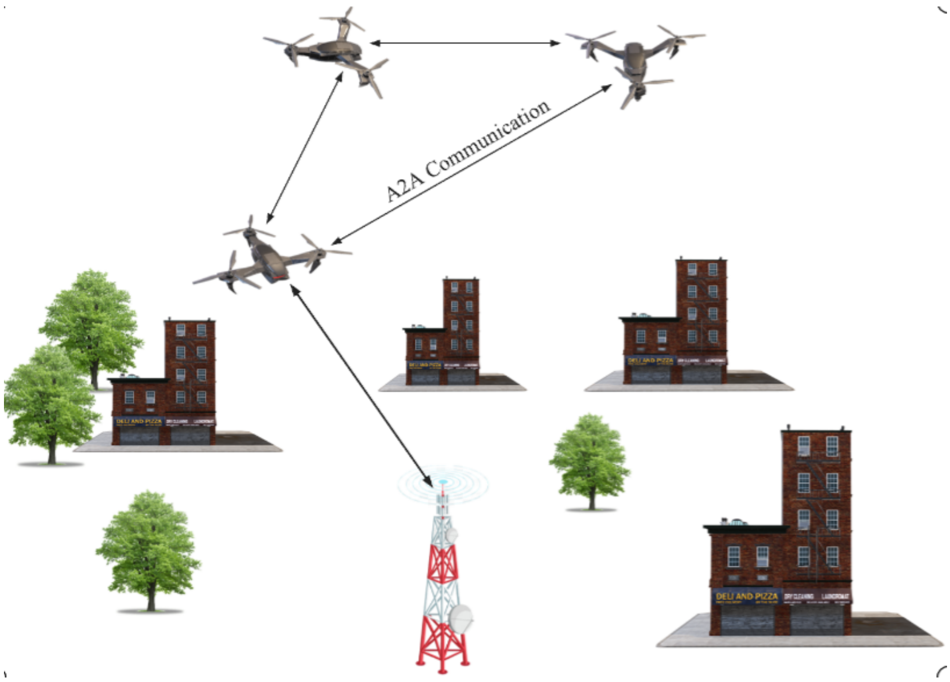


FIGURE 1.2: Air-to-air communication

with high mobility; therefore, a larger Doppler effect is expected in the FANET A2A communication channel. In order to analyze the FANET A2A communication channel environment, a rigorous study is required to judge the behavior or Doppler effect and time-variations of multipath environment considering the altitude of air vehicles.

### 1.2.2 Ground-to-Air and Air-to-Ground Communication

In Ground-to-air communications (G2A), the ground stations are considered to be located at ground and serve the air vehicles by transmitting radio waves upwards towards the sky, whereas in the air-to-ground (A2G), the base stations are considered to be flying in the air and serves the ground vehicles by transmitting downwards towards the earth, as shown in Fig. 1.3. In G2A communication, the air vehicles, some of them, are connected with the ground terminal and relay the data towards other neighboring air vehicles and vice versa. The advancement in wireless communication technology has optimized the network coverage for large areas, which explored many more opportunities of operating air vehicles remotely. The advancements in mobile technology have made it necessary to stay connected with

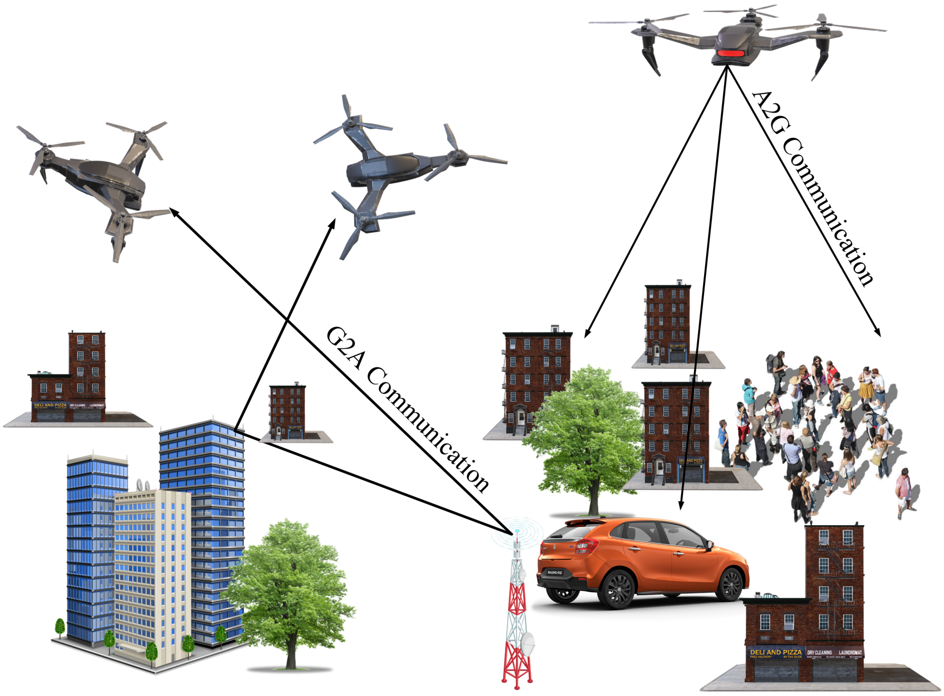


FIGURE 1.3: Ground-to-air and Air-to-ground communication

the people living much far from each other. With the passage of time, the mobile phone and wireless technology have been improved tremendously. The low-cost smart phones have further increased the demand for internet and communication services. In areas, where the network coverage is not accessible, these air vehicles can be used to provide internet and communication services. The initial concept of G2A/A2G communication service was only meant to provide communication services to military air vehicles or commercial airplanes only. The high usability of air vehicles and their effectiveness to perform different tasks have forced the researcher and industry to develop a reliable network. When multiple drones or air vehicles fly together then it is required to provide them a seamless coverage. Initially, satellite-based communication was considered as a best choice due to its global coverage; however, the end-to-end delay, cost inefficiency, and lower data rates made it as a secondary option. To encounter all these issues, researchers and development organizations focused to developed ground-to-air (G2A) and air-to-ground (A2G) communication systems as a solution that is more efficient and reliable as compared to satellite technology. A2G/G2A communication systems have become very popular for their advantages of assisting in different fields, especially in situations where two-way communications are required. A2G/G2A communication systems have the advantage of lower cost and rapid deployment. Hence, these systems are considered as the best possible alternatives to satellite-based communication systems. These systems can also be utilized as a relay to connect ground base stations and satellites which has the advantage of providing cellular coverage to a large area and are also robust to any natural disaster such as heavy floods and earthquakes that can damage the terrestrial network infrastructure completely. G2A communication channels are used to provide communication services to high-altitude platforms (HAP). HAP can fly and stay in the air for a long time at height ranging from 17 to 30 km. A radio signal may influenced by environmental conditions when transmitted from transmitter to receiver in a wireless channel. Unlike conventional ground communication channels, characteristics of G2A channels are different. The Characterization of radio channel helps in analyzing the channel performance in various terms including signal coverage and channel capacity in UAV-based communication. Accuracy of G2A channel models are crucial in scenarios where UAVs are used in various applications including coverage and IoT communications. Various factors such as UAV altitude, channel environment and elevation angle may influence G2A/A2G channel.

## 1.3 Radar

Radar (Radio Detection and Ranging) systems utilize electromagnetic radio waves to detect the presence of reflecting bodies, including aerial vehicles and ground objects etc. In this particular operation, the signals are transmitted as short pulses into airspace, which might be received as reflected echo signals, back to radar after reflecting by the aerial vehicle. The reflected echo signals identify the existence of the aerial vehicle. Moreover, It also helps to determine the location of an aerial vehicle or target by comparing the transmitted and received signals. The radar system has the ability to properly continue its particular operation for both short and long-range distances in any weather condition, including rain,

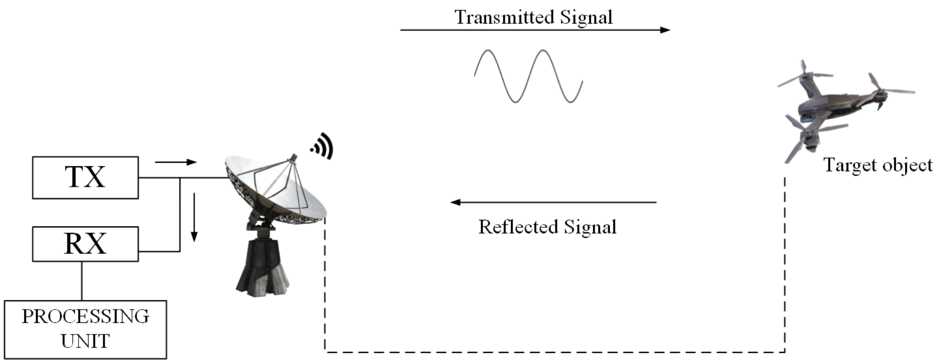


FIGURE 1.4: Working principle of radar and its fundamental components

snowfall, fog, and even in darkness. The basic principle and components of radar are illustrated in Fig. 1.4

The transmitting antenna of radar illuminates the intended target by incident radio waves, the waves are diffracted or scattered in all directions, and the receiving antenna receives a portion of the scattered signal back. In order to identify the target presence and its location, the received signal is sent to the processing unit of radar. The range of an object can be defined by the measurement of the total time that a transmitted signal takes from traveling a radar to the target and then back to the radar. These can be used for the detection of targets, including aerial vehicles, ground vehicles, ships, gunfire, etc. Furthermore, with the advancement of technology, these days, modern radars are more advanced and smarter, it may be utilized to cover a wide range of applications, including tracking of satellites, air boundary surveillance, military purposes, aerial vehicles anti-collision systems, missile defense system, terrestrial and road traffic control system and meteorology.

### 1.3.1 Radar Cross Section

Radar Cross Section (RCS) estimates the intensity of scattered or reflected waves returned back to the direction of the radar receiving antenna when a target is illuminated by radiating EM signal energy. It is a measure that shows the exposure of a target to the radar. RCS can be categorized as either monostatic or bistatic RCS. If the location of both transmitter and receiver are identical, it can be termed as monostatic RCS. However, if the transmitter is located at one place

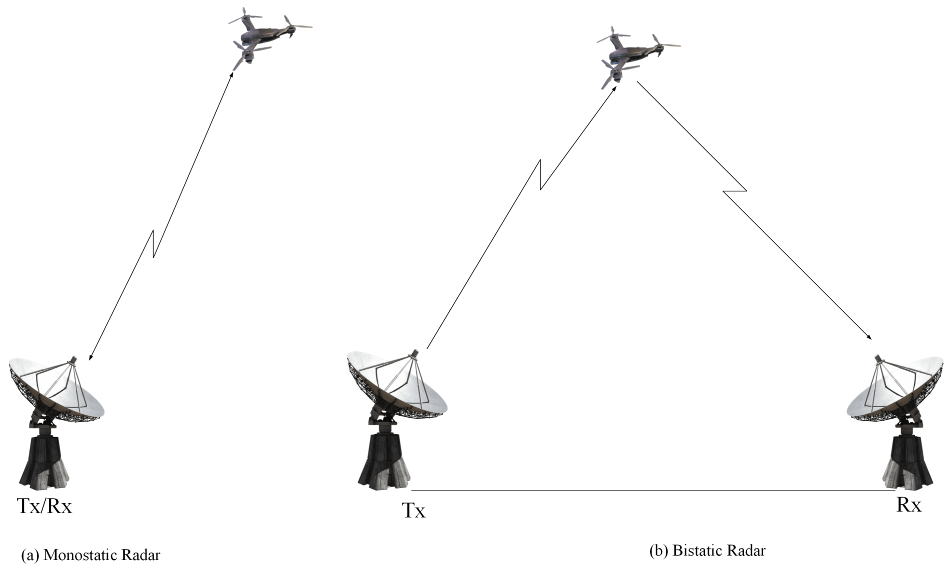


FIGURE 1.5: Bisttic and monostatic radars

and the reflected signal is received back at a different location to the receiver, it is interpreted as Bistatic RCS. Fig. 1.5 shows the typical geometry of both scenarios. In terms of scattering methodology, the working principle of both scenarios are similar, but the addition of bistatic angle in BRCS makes that scenario very different and more complex than monostatic RCS.

The visibility of the target object to radar can be affected by many factors, including target size, incident angle, geometry and orientation of target, incident wave polarization, manufacturing material and frequency and wavelength, etc. Large size targets have strong reflection capability as compared to small size targets that may change the behavior of RCS. It is examined that incident angles give direction to the reflected waves that are received on the radar receiver antenna; hence hitting the same target with different incident angles will vary the value of measured RCS. To obtain a good measurement of RCS, the orientation of the target object is considered to be in the best fitting view of radar. The measured RCS value for a target is different if viewed from the side as compared to the front. Moreover, for security purposes in many types of military equipment, complex geometry is designed to avoid the prediction and measurement of RCS by reflecting the incident waves to some other direction instead of a radar's receiver. The strength of the reflected signal is also dependent on the reflective surface material. Metals and aluminum are capable of generating stronger signals than materials like fiberglass and plastics. The RCS results obtained for two different materials, such as metal and wood, must be different.

### 1.3.2 Reflection Coefficient

In electromagnetic wave theory, reflection is considered an important phenomenon to understand the basic principles of waves. Reflection occurs when a wave encounters any reflective surface which has a large dimension as compared to the wavelength of the transmitted wave. In practical environments, many scattering surfaces like trees, buildings, or any other surface that exists between the transmitter and receiver may reflect the radio waves after absorbing a very small portion of energy in them. When a radio wave is reflected from a scatter, the scatterer absorbs a small amount of its energy hence making the intensity of the reflected wave lesser than the incident wave. The ratio of the amplitude of reflected wave from a scattering surface and incident wave is termed as the reflection coefficient of the surface. The reflected wave plays an important role in the radar detection mechanism, and the reflection coefficient can be viewed as the transfer function of the reflected process. This relation can be characterized by the Fresnel equation that depends on polarization, medium, and incidence angle. The characteristics of a medium can be defined by studying different wave parameters, including permittivity, permeability, angular frequency, and conductivity. Generally, the change in amplitude and phase is possibly expected at the reflection point, which makes the coefficient complex. The relation between incident electric field $E_i$ and reflected electric field $E_r$ intensities can be described in terms of complex reflection coefficients as follows

$$E_r = \Gamma E_i \tag{1.1}$$

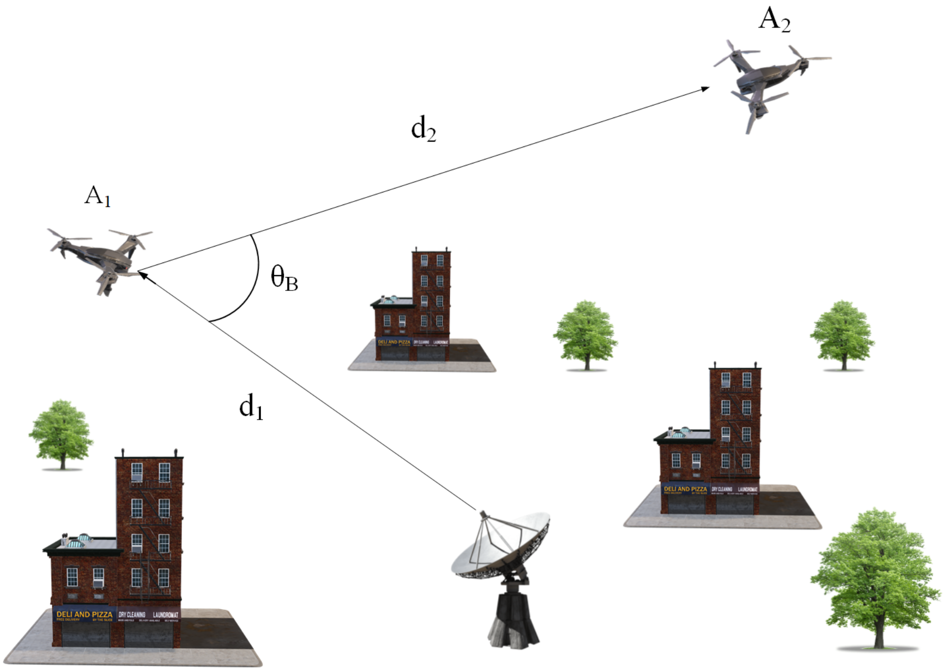


FIGURE 1.6: Signal reflection from aerial vehicle $A_1$ to aerial vehicle $A_2$ in bistatic radar

### 1.3.3 Relationship of Spatial Reflection Coefficient and RCS

Since Reflection Coefficient and Radar Cross Section measurements depend on reflected waves, they are interdependent and affected by the characteristics of reflected radio signals; therefore, it is easily possible to develop a relationship between these two terms. The measured value of both RCS and SRC depends on many factors such as frequency, angle of incidence, angle of observation, material properties, and polarization. In order to relate RCS and SRC with each other, we have considered two aerial vehicles making a bistatic geometry of signal reflection from one aerial vehicle towards another vehicle present in a nearby area, as shown in Fig. 1.6. The radar transmitting antenna impugns radio waves on the aerial vehicle ($A_1$) located at radial distance $d_1$ from the radar. The reflective surface of $A_1$ reflects the signal towards the aerial vehicle ($A_2$) present at distance $d_2$. The received power density at $d_1$ can be written as

$$P_d = \frac{P_t G_t}{4\pi d_1^2} \tag{1.2}$$

Where $P_t$ and $G_t$ represent the transmitted power and gain of the radar transmitting antenna, respectively. Similarly, by considering the principle of bistatic radar cross-section for aerial vehicle $A_2$ located at distance $d_2$ from the aerial vehicle $A_1$, the total reflected power received at vehicle $A_2$ can be given as

$$(P_r)_{ref} = \frac{P_t G_t A_e \Gamma^2(\phi_i, \theta_i, \phi, \theta)}{(4\pi)^2 {d_1}^2 {d_2}^2} \tag{1.3}$$

Whereas $A_e$ is known as the effective aperture. The total reflected power received at $A_1$ can be represented in terms of the reflection coefficient as follow:

$$(P_r)_{ref} = \frac{P_t G_t A_e \Gamma^2(\phi_i, \theta_i, \phi, \theta)}{4\pi (d_1 + d_2)^2} \tag{1.4}$$

In order to formulate a relationship between the RCS and SRC, both expressions given in equations Eq (1.3) and Eq (1.4) are compared.The final look of the relationship between the magnitude of spatial reflection coefficient (SRC) and RCS, resulting by solving both expressions, can be written as

$$|\Gamma(\phi_i, \theta_i, \phi, \theta)| = \frac{(d_1 + d_2)}{d_1 d_2} \sqrt{\frac{\sigma_B(\phi_i, \theta_i, \phi, \theta)}{4\pi}} \tag{1.5}$$

where as $\sigma_B$ represents the bistatic angle between the two aerial vehicles.

## 1.4 Ground Mobile Networks

Ground mobile networks includes vehicle-to-vehicle communication, mobile-to-mobile Communication and Cellular communication network which are briefly discussed as follow

### 1.4.1 Vehicle-to-Vehicle (V2V) Communication

Vehicles-to-vehicle (V2V) communication network is basically a short-range communication between vehicles and roadside units, acting as communicating nodes,

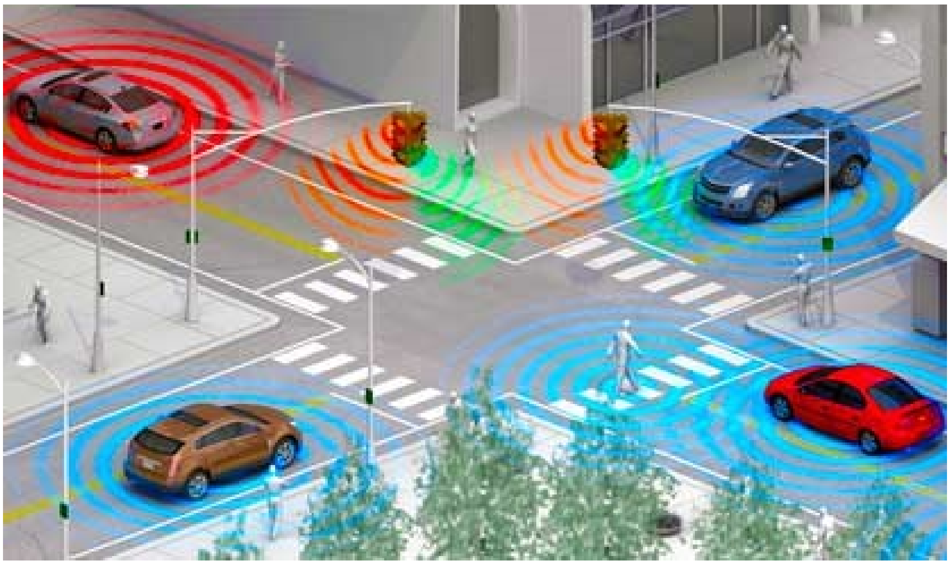

FIGURE 1.7: Vehicle-to-vehicle communication

to exchange traffic information for their safety and the safety of other vehicles connected with the network. The V2V network has been proved effective in avoiding accidents and traffic congestions. Moreover, the connected vehicles can share their information such as current speed, braking, location and directions, and congestion, which could be required by other vehicles or the network administrator to circulate any possible instruction. Vehicle-to-vehicle communication enables the bi-directional communication of cars with the road system, road users, and any other entities that interact with them, including traffic signals, parking meters, roadside cameras, pedestrian, lane markers, and other devices, as shown in Fig. 1.7. This communication is mainly used to avoid possible collision of a car with any other car, pedestrian, or any other thing coming in its way. In case of such an emergency, either the driver will receive a warning message or the car will take precautionary action itself, according to the developed technology such as braking, etc. Vehicular communication is considered a key element in traffic management and providing road safety by reducing accidents and traffic jamming

### 1.4.2 Mobile-to-Mobile Communication

A wireless communication system can be termed as Mobile-to-mobile communication (M2M) when both the transmitter and receiver are in motion acting as mobile

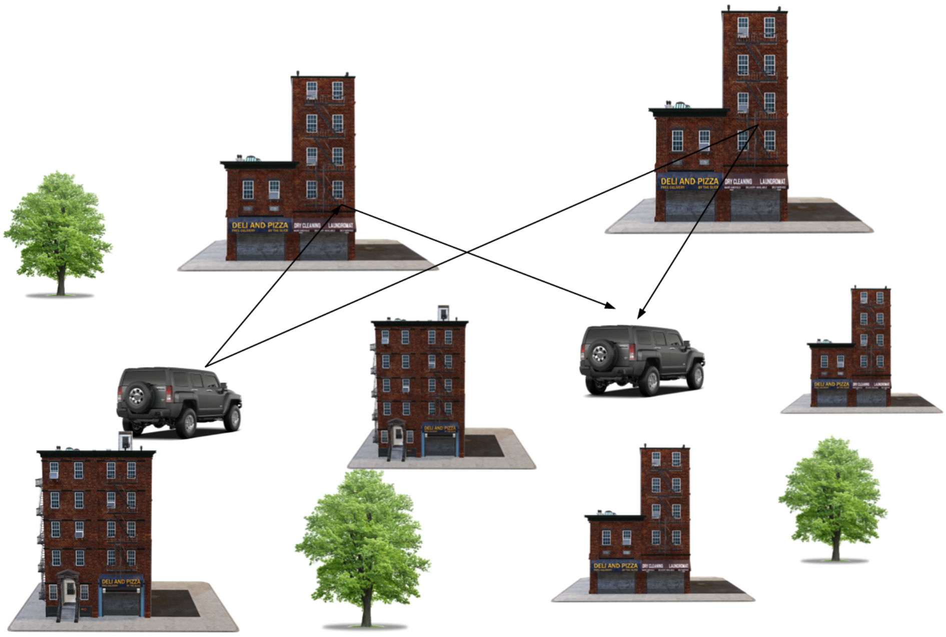


FIGURE 1.8: Scattering environment in Mobile-to-Mobile communication

stations, capable of communicating with each other without any intermediary fix source. Both mobile stations are equipped with low-elevated antennas, so they do not need another fixed source for their communication. M2M communication environments are usually surrounded by many local scatters which can cause the generation of numerous multipath signals. The scenario of the M2M communication system is shown in Fig. 1.8. The movement of both mobile stations at the same time results in an enhanced Doppler shift. In M2M communication systems, the sum of individual Doppler shifts of both mobile stations is considered to obtain the total Doppler shift. The enhanced Doppler shift in M2M communication as compared to cellular systems results in faster fading with more rapid fluctuations in signal power. M2M communication systems play an important role in a wide range of applications in wireless networks including wireless sensor networks (WSN), mobile ad hoc networks (MANET), and vehicular ad-hoc networks (VANET).

### 1.4.3 Cellular Networks

A cellular network is basically a cell-based communication network in which the link between the transmitter and receiver is wireless. The land area is distributed in cells in which a fixed base station equipped with a transceiver is placed. Each base station is capable of providing network coverage with the transmission of voice, data, and other types of content. In order to accommodate a large number, sharing of the same frequency cannot be used again throughout the system. Reuse of the same frequency causes interference and degrades the signal quality. In order to avoid interference, the concept of cellular networks was introduced, which is based on the idea to divide the total services area into many small sub-areas known as a cell. The signal coverage is provided to all cells with the help of many low-power transmitters instead of a single high-power transmitter. Hence, the basic concept of a cellular network was developed to efficiently utilize the frequency spectrum by reusing a different set of frequencies from neighboring cells. The total number of radio channels available in the system is divided among cells in such a way that all adjacent cells have different radio channels. The distant cells can reuse the same frequency. A cellular communication system allows multiple cells to access the same wireless radio channel at distant distances without occurring any interference, increasing the user capacity without affecting the quality of service. The cellular network provides radio coverage over a wide geographic area by enabling guaranteed quality of service with minimum interference level.

Cellular networks provide a number of desirable features such as more capacity than a single large transceiver, less power utilization of mobile devices as compared to a single transmitter or satellite, and a large coverage area than a single transmitter.

The first-generation cellular communications systems were used to provide only voice facilities to mobile users with analog modulation. With the enhancement of technology, second-generation cellular systems were introduced and considered as the optimal choice for voice conservation with an additional facility of providing data services to mobile users. With the high use of mobile phones, HD streaming, etc., third-generation (3G) and (4G) cellular systems were deployed for high data and user capacity.

Recently, fifth-generation (5G) cellular communication systems will move a step forward in supporting IoT devices and critical autonomous systems such as UAVs that will play an important role in digital transformation.

## 1.5 Multipath Channel Modelling

In a wireless communication system, the existing medium between the transmitter and receiver is called a channel. The characteristics of the radio wave, propagating from the transmitting antenna to the receiving antenna, change due to many factors, including the T-R distance, the speeds of the transmitter and receiver, the path of the signal, and the environment. The channel consists of many components that can affect the transmitted signal, resulting in numerous phenomena in the wireless communication channel. Among many other phenomena, multipath propagation is considered very important and drastically changes the signal performance. It occurs when a transmitted signal reaches the receiver through two or more paths. It results from reflections, diffractions, scattering or shadowing by surrounding reflective objects called scatterers. The direct radio wave between the transmitter and receiver, usually referred to as line-of-sight (LoS), is often affected by many obstacles such as trees, buildings, hills, and so on. As a result, many non-line-of-sight (NLoS) paths are created, also referred to as multipath. Many copies of the transmitted signal are received at the receiver from all directions with different time delays, resulting in a phase shift of the composite received signal. This phenomenon leads to constructive and destructive addition of the delayed signals, which may result in signal fading. The interference caused by the multipath environment is usually referred to as multipath interference or multipath distortion. The formation of a multipath environment where a radio wave propagate is shown as in Fig. 1.9.

The performance of a channel to transmit a reliable signal is possibly degraded in the presence of multipath propagation environment by path loss and interference. Moreover, the challenge of phase shift and delay in the received signal is also

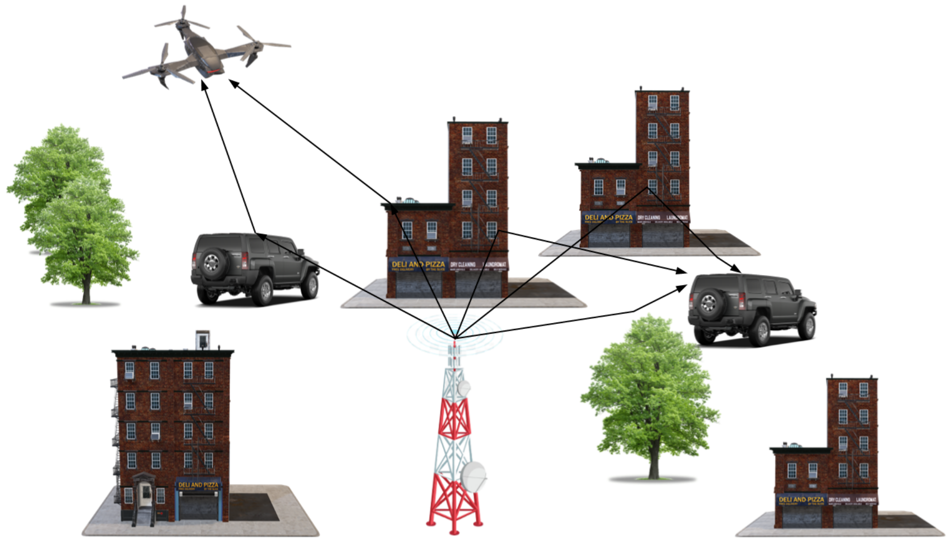

FIGURE 1.9: Multipath environment

possible. Considering these issues of channel propagation, it is necessary to model a multipath channel to examine a channel behavior and predict the received signal. The multipath channel models can be used to characterize different channel parameters such as Doppler shift, received power, angle of arrival, and departure. Factors that cause multipath phenomenons are briefly discussed as follows.

### 1.5.1 Reflection

Reflection occurs when an electromagnetic (EM) radio wave hits a reflective surface (as shown in Fig. 1.10) or objects that have very large dimensions compared to the wavelength of the transmitted wave. In practical propagation scenarios, many reflective surfaces like trees, buildings, walls, ground surfaces, or any other surface that exists between the transmitter and receiver may reflect the radio waves.
Reflection is considered as most important phenomenon in wireless communication as many obstacles are present in surrounding area that may reflect the signal and degrade the received power at receiver.

### 1.5.2 Diffraction

Diffraction can be termed as a phenomenon that occurs in a wireless communication channel when a propagating radio wave is disturbed by an obstacle having sharp irregular surfaces such as edges etc. The radio wave can propagate behind the obstacle with the available non-line of sight (NLoS) path through diffraction mechanism; however, the field strength is decreased after the obstruction.
In wireless communication channel, many obstacles are present in surround area having irregular shapes that can effect the signal quality at receiver side, hence, diffraction is considered an important factor that may degrade the received power.

### 1.5.3 Scattering

The phenomenon of scattering occurs when a wireless communication channel contains objects having small dimensions, as compared to the wavelength of transmitted radio waves. The impugned wave is spread out/scattered in all directions. The transmitted signal dissipates into multiple copies of the transmitted signal, which might cause a rapid fluctuation in its amplitude as well as in phase, In the worst-case scenario, the originally transmitted signal may lose completely. In practical situations, scattering may occur due to small objects such as smog, street signs and lights, tree foliage, and sandstorms.

## 1.6 Classification of Channel Models

Channel models are characterized in distinctive classifications on the basis of time, frequency, environments etc. Channel models are classified into three categories on the basis of modelling approaches. i.e, physical models, stochastic models and analytical models.
These models are briefly discussed as follow

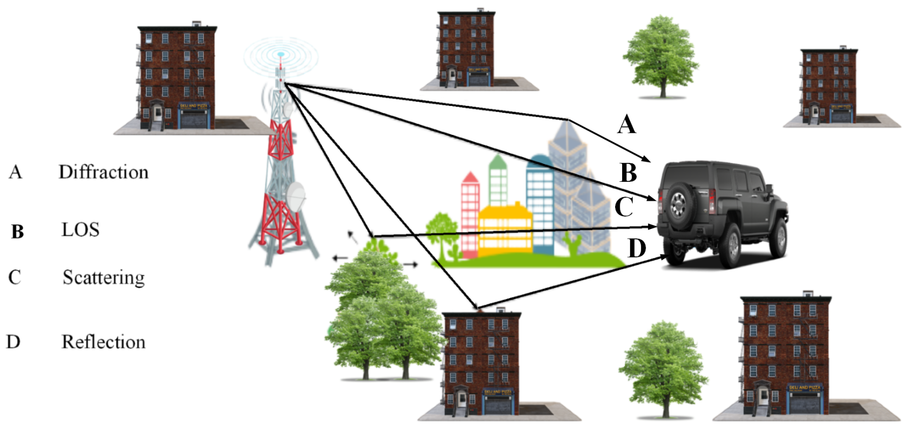


FIGURE 1.10: Various multipath phenomenons including reflection, diffraction and scattering

### 1.6.1 Physical Models

Physical models includes empirical models and deterministic models and which are discussed as follows

#### 1.6.1.1 Empirical Models

Empirical models, also known as statistical models, are based on different algorithms and mathematical expressions, formulated through a large number of field measurements and obtained data to determine the received signal strength. These models are easy to use for quick predictions, but the results are not very accurate. Empirical models are primarily used to estimate accurate path loss with rapid results for scenarios having similar characteristics to the measurement field. Moreover, some empirical models are also proposed to predict multipath and rain-fade. To use these model for different environments, further modifications are needed; for example, macro cells and indoor pico-cells can not use the same empirical model. Empirical path loss models are further subdivided into two categories, i.e., time dispersive and non-time dispersive. Examples of propagation models based on the empirical model are the log distance model, Okumura model, COST231, Anderson 2D, and Hata model.

#### 1.6.1.2 Deterministic Models

Deterministic models, also known as site-specific methods, are used to predict the propagation characteristics of radio channels at exact locations by using the basic laws and principles of electromagnetic wave propagation. For this purpose, complete details of a given site, usually a 3D map of the environment, are also required. These models increase the prediction accuracy and also reduce the number of required measurements. This approach requires very extensive calculations that can not be performed for many environments. Examples of deterministic models include Ray-Tracing (RT) method, log normal shadowing, the Finite-Difference Time-Domain method (FDTD) and the Method of Moments (MoM).

### 1.6.2 Stochastic Models

In stochastic models, a number of different random variables are used to model various types of environments. Stochastic models require less information about the propagation environment/site but the predicted results are not very accurate. Stochastic models characterize the impulse response of propagation channel by using the basic law of wave propagation. Random results are obtained each time for a particular parameter such as Tx, Rx and scatterer geometries. The impulse response is predefined in a stochastic way to model radio channel. however, the random channel modelling is performed in a specific manner. Stochastic models are considered more flexible and less complex in terms of computation as compared to deterministic models. It can be used to model both small scale fading and large scale fading. Stochastic models are further divided in geometry-based stochastic Models (GBSM) and non geometrical stochastic models (NGBSM).

### 1.6.3 Analytical Models

Analytical models include channel models that rely on assumptions and parameters to characterize the channel behavior. These models are commonly based on mathematical equations which are quite close to the behavior of radio wave propagation. Two ray model is one of the best examples of such models.

#### 1.6.3.1 Two Ray Model

Two ray model estimates the received power of a transmitted signal in a scenario where only a single reflected ray is considered from the ground surface. In the two-ray model, two signal components are received at the receiver side, i.e., the signal component that arrives the receiver directly from transmitter and the signal component reflected from the ground. The reflection exists only from the ground surface, since no buildings or other obstacles are considered. The signal component arriving directly to the receiver and the signal component reflected from the ground can be referred to as the LoS and NLoS components, respectively. Both components are shown in the figure 1.11. Both components are added together to calculate the received power. The reflected signal can lead to either constructive or destructive interference. The received power of a transmitted signal located at distance d from the transmitter can be expressed as,

$$P_r(d) = \frac{P_t G_t G_r h_t^2 h_r^2}{d^4 L} \tag{1.6}$$

$P_t$ in Eq (1.6) represents the transmitted power, d is the T-R separation, $G_t$ and $G_r$ are the respective gains of transmitter and receiver while $h_t$ and $h_r$ are the heights of transmitter and receiver, respectively. The above equation show that received power decreases rapidly as distance between the transmitter and receiver increases.

## 1.7 Signal Strength Estimation

Received signal estimation is the measurement of transmitted signal power at the receiver end after possible losses, attenuation, and fading, etc. over a certain

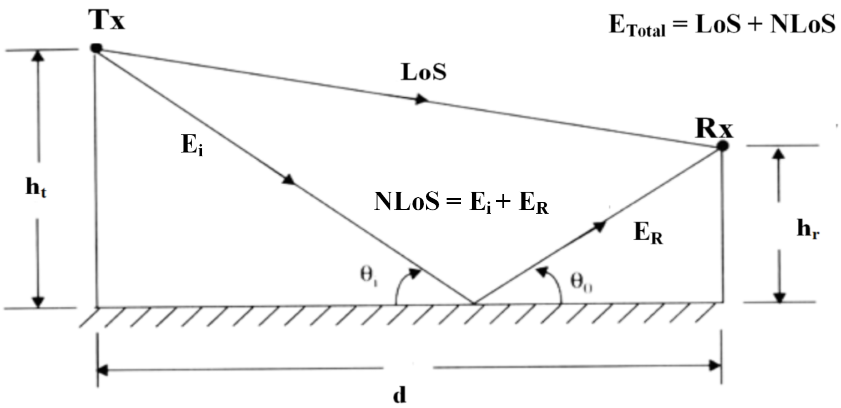


FIGURE 1.11: Direct and ground reflected signal components in two ray model

time period. It is usually represented by the received signal strength indicator (RSSI) and is measured in decibels (dB). RSSI depends on many factors including radio channel environment, interference, transmitted power, etc. The high value of RSSI shows a good quality signal on receiving side and vice versa. Communication systems need to maintain a certain value of RSSI to avoid interruption and link failure. The value of RSSI can be used to determine the separation distance between transmitter and receiver and can also help to identify/estimate the exact position and location.

## 1.8 Research Objectives

The prominent goal of this research work is to analyze the G2A and A2A multipath environments for various influencing factors that affect and degrade their performance. Generally, it is assumed that G2A and A2A communication link is usually comprised of line-of-sight (LoS) component only, however, in reality there also exist many non-line-of-sight (NLoS) components that are easily feasible due to the reflection of signals from nearby drones present in the surrounding area. In G2A communication systems these nearby drones may act as scatterers and may deteriorate the performance of radio channel propagation. This thesis explicates the objective of modelling the existence of multipath scenarios due to the presence of drone scatterers to characterize and analyze the path loss in a better way.

## 1.9 Thesis Organization

In Chapter 2, a comprehensive and detail review of existing work is presented with appropriate discussion and opinions wherever it is required. Various approaches used for multipath channel modeling and characterization in literature are studied to create gap of the research work. In Chapter 3, a multipath channel model is proposed for network of flying things and a closed-form expression of multi-ray channel model is derived to estimate the power of received signal at the intended air vehicle. In Chapter 4, the simulation results are presented to analyze the impact of various factors on the received power for two communication link scenarios i.e. G2A and A2G. Finally, Chapter 5 concludes the research work performed throughout in this thesis. Moreover, this chapter also gives a brief detail of possible future work.

# Chapter 2

# Literature Survey, Gap Analysis and Problem Formulation

In this chapter, a comprehensive survey of existing work is explored to create the research gap. In section 2.1, a detailed review of literature is presented with appropriate discussion wherever it is required. This section is explained in two sub sections which represent a detailed study of previous approaches used for multipath channel modeling and characterization. Research gap and problem formulation of this study is explained in section 2.2. The proposed research methodology is presented in section 2.3. Finally, section 2.4 presents the main contributions of this thesis.

## 2.1 Literature Review

Multipath phenomenon is considered as a major cause which may degrade the performance of communication link in every realistic radio communication scenario. In case of air to ground communication, the researchers have focused on characterizing multipath propagation phenomenon between aerial vehicles and ground BS for the improvement of link performance. In this regard, various studies have been carried out to study the impact of various propagation parameters in such links. In [7], a comprehensive study was presented, where analytical and empirical models were discussed in detail for A2G and A2A UAV communication. These models have been intensively reviewed for satellite links and terrestrial cellular networks in [8, 9]. Besides these models, some hybrid aeronautical channel models were also characterized in [10],[11]. Since, large number of channel models have been reported in the literature for G2A/A2G and A2A communication links, therefore for the purpose of ease, we categorize the literature on these models into two major groups i.e. analytical and simulation based studies and measurement based studies.

### 2.1.1 Analytical and Simulation-based Studies

The presence of multipath phenomenon in a wireless communication system may limit its performance if the multipath components are not handled properly. In order to characterize multipath channel environment, simulation-based approach is normally considered when practical experiments are not feasible. Ray tracing is useful to predict the radio channel propagation and can be used as alternative for measurements when proper 3D maps are available [12]. In [1-10], ray-tracing based simulation approaches were presented to investigate the characteristics of communication link between unmanned aerial vehicle (UAV) and base station. In literature, several analytical and simulation based models using various channel parameters were proposed which are discussed as follows.

In [13], the two ray model was modified in terms of elevation angle to formulate a closed-form expression for path loss predication in A2G communication channel. Impact of various parameters regarding path loss were also examined. The parameters used included UAV height, different propagation environments, and antenna polarization. Furthermore, the obtained results were compared with ray tracing simulation to validate the model.The authors considered the ground reflected signal in both vertical and horizontal polarization but only a single reflected signal was accommodated from the ground surface which is not a realistic approach as the ground surface and nearby obstacles may reflect a number of multipath signals towards the receiver.

In [14], a geometry based analytical multipath propagation model was proposed to investigate channel behavior in hilly territory. The proposed model was validated with ray tracing simulations. The authors also discussed the impact of height on the received power. The simulation results of proposed model was more accurate than ray tracing and two ray model. However, the authors assumed the path length of reflected components equal to the LoS component which make a pure LoS propagation environment and hence the effect of multipath signal were ignored. Another geometry based model was proposed in [15] considering mm waves but the authors only presented LoS probability and the received power of signal was not investigated. In [16], the authors characterized path loss in multipath environment using different altitudes and proposed a distance dependent path loss model for A2G communication links. In another study [17], Ray tracing were performed in various environments to characterize the performance of UAV but a close-form expression for received signal is not provided.

The impact of multipath components were investigated in [18] for scenario when several air-crafts are flying in air. The authors provided a close form expression for received power in G2A communication link. Moreover, the time delay for multipath components were also calculated but the model is only valid for air-crafts flying with same altitude. In [19], the authors proposed path loss model for a hilly and forested environments at Very High Frequency (VHF) bands of 182.25 MHz and 203.25 MHz. In order to study the impact of vegetation on path loss exponent, various scenarios were investigated. On the basis of their study, they proposed an elevation angle-based model considering the classified vegetation scenario. The results of proposed model were compared with the existing empirical models. In [20], ray tracing simulations were utilized to characterize the urban area of Xian city using 2.2 GHz frequency. The authors provided a close-in path loss model. Furthermore, path loss exponent (PLE) and shadow fading were also analyzed for altitude ranging from 50 m to 140 m but received power was not investigated

In [21], a height dependent model was proposed and extensive ray tracing simulations were performed by using mm wave in a campus scenario to analyse various channel parameters. The proposed model was claimed to be used for different propagating scenarios in A2G communication by adjusting its height.

In [12], the authors examined the possibility of accurate prediction of variations occurring in shadow fading with the help of ray tracing without field measurements at different heights. The ray tracing results proved that using proper 3D maps, ray tracing was useful to predict the radio channel propagation and can be used as alternative for measurements.

In [22], characteristics of narrow band and wide band channels were studied in urban area for multipath environment in air to ground UAV communication system. Ray tracing simulations were performed to estimate the received power and delay spread. The received power was calculated by limited number of reflected rays

In [23], a geometry-based non-stationary 3D channel model was proposed for mm wave to analyze different channel parameters such as distance, propagation angles, path loss, received power and to evaluate the communication performance in A2G radio communication channel at carrier frequency of 28 GHz. The authors considered a single UAV for analyzing the channel performance and the presence of other drones are possible in near by area which may degrade the system performance. In [24], the authors performed simulation for a small size UAV at lower altitudes to analyze path loss, multipath components, k factor and delay spread in a sub urban scenario at carrier frequency 4.2 GHz. The authors observed that multipath components decrease with increase in UAV height. In this study the authors ignored the scattering phenomenon

In [25], the impact of different propagation parameters such as UAV altitude, building heights, environment, and user distance etc. were investigated for several path-loss models, for this purpose, various path loss models based on 3D environments including both indoor and outdoor scenarios were considered and their performance were compared. Moreover, the authors performed simulations to understand and characterize UAV communication. The simulation results suggested Winner II model as best path loss model for urban area.

In [35], a hybrid channel model was provided for Tetra Hz frequency based on ray tracing simulation to characterize A2G radio channel. Different parameters including path loss, UAV altitude and excess delay were analyzed. Moreover, the authors considered different channel parameters including line-of-sight and ground-reflection path. In [26], free space model was developed for UAVs swarm. The authors also studied pathloss at various altitudes i.e., 10m to 50m for individual UAV in swarm at 400 MHz frequency. The propagation model combines a ray-tracing algorithm with the uniform theory of diffraction. The height of transmitting and receiving drones were kept same which is not practically possible as the positions of drones may vary. Moreover, the results of ray tracing simulations were also not validated with measured data. In [27], an altitude dependent empirical model was proposed for prediction of path loss in different scenarios having multipath components at mm wave frequencies. Ray tracing technique were used for data collection in different propagation environments including line-of-sight, reflections, and diffraction. The prediction results of proposed model were closer to ray tracing simulation results as compared to 3GPP model and the close-in model. In [28], a hybrid channel model is provided for Tetra Hz frequency based on ray tracing simulation to characterize A2G radio channel. Different parameters including path loss, UAV altitude and excess delay were analyzed. Moreover, the authors considered different channel parameters including line-of-sight, ground-reflection path, and stochastic ally generated multi-path in the proposed channel model. In [29], ray tracing simulation were used to characterize A2G channel propagation for UAV considering target frequencies of 28 GHz and 60 GHz in urban, suburban, rural and over sea scenarios. Received signal strength was investigated at different altitudes. In this study, no mathematical expression were derived for received signal power.

### 2.1.2 Measurement-based Studies

The performance of channel models proposed on the basis of analytical methods are often not accurate, as real time results of communication system over radio channels vary due to the assumed assumptions not based on real environment.

To improve the link performance using a particular channel model, field measurements are required for channel modeling. For this purpose, many measurement campaigns are conducted in different scenarios to understand the actual behavior of radio propagation in G2A and A2A communication systems.

In [30], the authors presented a detailed survey of available literature regarding air to ground channel modeling of UAV communication system based on measured campaigns. They provided small and large-scale fading channel models and discussed the limitations and future research direction of A2G propagation. They also evaluated some other parameters such as the elevation, propagation environment, channel statistics, link distance and path loss etc. In [31], the authors presented a channel propagation model for UAV communication system. Measurement campaigns were conducted in urban area at Tsinghua University to study different parameters of path loss model that are helpful in providing long time prediction but the channel impulse response was considered in LoS situations only. In [32], different propagation parameters including multi path components that effect channel impulse response were studied for three different scenarios i.e., rural, urban and industrial at low altitudes ranging from 0m to 40 m. A2G radio channel were characterized in [33],[34] at carrier frequency of 970 MHz and 5GHz in near urban and hilly areas but the authors didn't assessed the UAV altitudes in their studies. In [35], the authors provided an analysis of A2G channel which is based on various parameters including geometry, radius and height of drone. Furthermore, for the calculation of precise path loss, both LoS and NLoS conditions were considered and average loss were added to free space propagation in a realistic path loss model. The probability of having both LoS and NLoS links from the transmitter to receiver are also taken into the account for more precise path loss calculation. another study where the authors over-viewed the research work done til now about the use of drones as aerial user equipment (AUE) and Aerial Base Station (ABS) are provided in [36]. In [37], measurement campaigns are conducted in various scenarios including urban, sub-urban and rural areas for the characterization of large scale fading in air to ground communication channel. The received signal strength is measured at different altitudes ranging from 50 m

Table 2.1: Summary of some notable simulation-based studies

| References | Scenario | Frequency | Tx-Rx Separation | Simulated Parameter | Tx Power | Bandwidth | Limitation |
|---|---|---|---|---|---|---|---|
| Zhuang et al [14],2019 | Mountain Terrain | 2.4 GHz | 100 m | Path loss | - | - | Los condition only. Assumed path length of reflected and LoS components same |
| Minghui et al [15],2021 | Built up | 28 GHz | 0-1000 m | Los Probability | - | 500 MHz | Received power is not estimated. Only LoS link |
| Xingqin et al [17],2018 | Rural | 700 MHz | - | Path gain Los probability | - | 10 MHz | No close-in expression |
| Cheng-Xiang et al [23],2020 | Campus scenario | 28 GHz | - | Received power PDF | - | 500 MHz | Single UAV is considered |
| Xi Chu at al [24],2018 | Sub-Urban | 4.2 GHz 1.2 GHz | 0-100 m | Received power RMS Delay K factor | 15 dBm | 100 MHz | Scattering phenomenon is ignored |
| Eran et al [22],2017 | Urban | 2.4 GHz | - | Received power Delay spread | | - | Limited number of reflected ray. Only a single UAV is considered |
| Luoyan et al [20],2019 | Urban | 2.2 GHz | 5 km | Path loss | 40 dB | 20 MHz | Received power is not investigated |
| Wahab et al [29],2017 | Urban Sub-urban Rural Oversea | 28 GHz 60 GHz | 2 km | Received power RMS-DS | 30 dBm | - | No close in expression |
| Ranchagoda et al [13],2021 | Urban | 700 MHz | 1 km | Received power | 0 dBm | - | Only single reflected ray is considered |
| Yasir et al [18],2020 | urban | 2.4 GHz | - | Recieved Power | - | - | Not valid for multi-altitude G2A multipaths geometry |
| Eran et al [26],2019 | Urban | 2.4 GHz | 1 km | Path loss | - | - | Same Tx and Rx height |

to 950 m and horizontal distance up to 70 km at carrier frequencies of 785 and 2160 GHz. The authors did not considered the NLoS links and small-scale fading. Moreover the study covered only high altitudes flights. In [32], Measurement campaigns were conducted in rural areas to measure the elevation and azimuth arrival (EoA/AoA) of the multipath components (MPCs) at carrier frequency 3.5 GHz at different heights ranging from 50 m to 350 m and horizontal distance up to 300 m. The results of proposed model were compared with the standard 3GPP model for verification.

In [38], a height dependent model was proposed for estimating path loss in both LoS and NLoS scenarios at 1 GHZ and 4 GHz. Furthermore, different channel parameters including shadowing, small scale fading and large-scale fading were analyzed. The study was limited for low altitudes and high altitudes measurements were not investigated. Path loss was also calculated for same scenario i.e. Los and NLoS in [39] considering different frequency bands. The authors investigated the impact of frequency and height on path loss. However, the measurements were performed in environment which consists of trees and bushes only. In [40], different target frequencies such as 1 GHz, 4 GHz, 12 GHz, and 24 GHz were used to perform air-to-ground radio channel measurement. The important channel parameters were thoroughly examined using measurement data. In [41], a 3D MIMO channel was proposed for A2G UAV communication. For the non stationary mode of the proposed channel model, an algorithm known as a novel angular estimation algorithm was proposed to estimate different angular parameters including the elevation angle of departure (EAoD), the real-time azimuth angle of departure (AAoD), the elevation angle of arrival (EAoA), and the azimuth angle of arrival (AAoA). Moreover, different channel characteristics were also analyzed.

In [42], multipath channel for ground and above sea environment were analyzed at 5GHz frequency in terms of delay spread. The multipath components were also analyzed for frequency of 3.5 GHz at altitudes ranging from 50 m to 300 m but the received power was not investigated [43]

In [44], the authors described many measurement campaigns carried out in a suburban area at different lower altitudes with the help of a medium-sized UAV to investigate the effect of different parameters such as UAV height, distance and elevation angle, on A2G channel. Among these parameters height was found the most effective factor on channel characteristics. Path loss exponent was determined based on measurements performed at various altitudes. Furthermore, a height dependent model was also proposed. In [45], a channel model was proposed to describe the behavior of received signal strength by accounting the effects of shadowing and mobility to reduce the complexity of signal processing without impacting the channel performance. Empirical data obtained in measurement campaign was used to verify the model results. In [46], measurement campaigns were performed in multiple suburban areas to characterize radio channel by using small size drone over low altitudes in terms of path loss, shadow fading, Doppler spread, and RMS-delay. In [47], an analytical path loss model was provided for scenarios where the received power depends on the antenna gain of LoS component with no obstacle. The proposed model was based on the gain of antenna in the elevation plane. The effect of different parameters including path loss, RMS-DS, multipath components and k factors were examined for both LOS and NLoS scenarios through measurement campaigns performed in open field at 3.1 GHz to 4.8 GHz frequencies. The path loss measurements and ray tracing simulations results were compared to verify the proposed model.

Measurement campaigns were performed in various scenarios including grass, soil and rubber floor to characterize the path loss. The authors investigated the impact of ground reflection for different altitudes in all three scenarios. Moreover, the author also suggested that analytical model such as A2AT-R and modified log distance model may be deployed in A2A communication links to model path loss. In this research work only a single reflected ray was considered which is not the realistic approach to measure the received power in multipath environments. [48]. As discussed in early studies, different channel parameters including shadowing, small scale fading and large-scale fading were analyzed. Theses studies were limited for low altitudes and high altitudes measurements were not investigated. Path loss was also calculated for same scenario in many research work.

TABLE 2.2: Summary of some notable measurement-based studies

| Reverences | Scenario | Frequency | Bandwidth | Tx power | Tx Height | Rx Height | Measured Parameters | Limitations |
|---|---|---|---|---|---|---|---|---|
| Yang et al [31], 2018 | Urban | 2.4 GHz | 20 MHz | 15 dBm | 5-80 m | 1 m | Pathloss RMS delay spread | Channel impulse response is recorded in LoS situation only |
| Zhang et al [37],2019 | Rural Urban Suburban | 5060 MHz | 20MHz | 46 dBm | 50 to 950 m | - | Pathloss Data rate | Limited to High altitudes and large scale fading. Not for small UAV |
| Wang et al [43],2019 | RMa & LoS | 3.5Hz | 10 dBm | 30 to 300 m | 1.5m | - | Analyzed Multipath Components | Received Power is not Investigated |
| Matolak et al [33],2015 | Near-Urban | 970 MHz & 5GHz | 5 MHz | 10 Watts | 20 m | 1.4 m | Path loss RMS-DS | Altitude was not Assessed |
| Cui et al [38],2019 | Open field | 1 GHz 4 GHz | - | 30 dBm | 0-24 m | 25 m | Pathloss Correlation | Measurements are performed only for low altitudes |
| Sarun et al [48] 2021 | Rubber, Glass & Soil Floor | 2.4 GHz, 868 MHz | - | 20 dBm | 1 m | 1-10 m | Path loss | Single Reflected ray was Considered. |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Cui et al [40],2020 | Semi urban | 1,4, 12, 24 GHz | - | 30 dBm | 25 m | 0-24 m | Path loss | Low Altitude of Tx and Rx |
| Shi et al [39],2018 | Los Tree-based NLoS | 900 MHz,1800 MHz,5GHz | 20 MHz | - | 10 to 30 m | 1 m | Path loss | Enviroment only consist trees. No other obstacle like building etc . |
| Qiu et al [44],2017 | Open sub-urban | 2.4 GHz | - | 3 dB | 0 -100 m | 1.5 m | Received Power PathLoss Small Scale Fading | Limited to open area and low altitudes |
| Huang et al [46],2020 | Sub urban | 2.5 GHz | 15.36 MHz | 40 dBm | 15 m | 25-105 m | Received power, RMS-DS, K-factor | Number of MPCs were limited to fix value |

## 2.2 Gap Analysis and Problem Formulation

Since, G2A and A2A radio channels are primarily developed to provide dedicated coverage to the vehicles flying in the sky such as airplanes; therefore, for such scenarios, directional antennas are preferred to be used both for the transmission and reception of radio signals. In literature, various research studies have been performed to characterize the channel behavior; however, most of the research studies are based on the assumption of single ray from the ground stations i.e. line-of-sight (LoS) component, which may not be a realistic approach when multiple air vehicles are flying together. Table 2.1 provides a comparative literature survey of all analytical and simulation based models. It is evident from the table that almost all existing analytical models either depend on LoS links only or are deficient of analytical expressions that include multiple rays in their formulations. Table 2.2 gives a detail review of literature regarding measurement campaigns conducted for A2G and A2A communication. It is evident from the table that not a single measurement campaign is performed that incorporate multiple number of drones flying together. In other words, most of the research studies related to drones or air vehicles are performed through measurement campaigns considering a very less number of drones i.e., one or two drones. Network of flying vehicles is specifically built to accommodate multiple vehicles connected to a ground station dedicatedly or through a neighboring vehicle. In such scenario, the surrounding air vehicles may act as scatterers and may form a multipath environment due to reflections from the surface of proximate vehicles. Such phenomenon may induce multipath fading environment between air vehicles and base station.

However, to the best of our knowledge and study it is observed that closed-form expressions for G2A and A2A channel models have not been developed yet that take into account a multipath environment around the receiving air vehicle. Hence, it is necessary to develop a multi-ray channel model for network of flying things that provides a clear insight of the propagation environment and gives best prediction about the received power and the network performance.

## 2.3 Proposed Research Methodology

As discussed earlier in Section 2.2, network of flying things always consists of a number of flying vehicles connected with the same ground station. The vehicles around the intended air vehicle may act as scatterers and generate a multipath environment around the intended air vehicle. In order to accommodate multipath environment, a multi-ray channel model for a network of flying things is formulated. The proposed model is designed on the basis of geometrical positions of air vehicles and provides a closed form expression of the received power in multipath environment. The reflections through proximate air vehicles are handled for the estimation of reflected power by using Spatial Reflection Coefficient (SRC) obtained through a simulation software (EPOFACET). In order to obtain the SRC, a facet-based Parrot Anafi Thermal drone model in Stereo Lithography (.Stl) format is considered. Utilizing the facet-based model of drone along with reflective information of drone's surface in EPOFACET, the SRCs are computed at specific incident and observation angles. Utilizing the proposed multi-ray channel model along with the reflective properties of drones the intended research objectives are achieved. To validate the closed-form expression of the proposed multi-ray channel model of the network of flying things, the results are then compared with the measurement data [49].

## 2.4 Research/Thesis Contribution

The research contributions of this thesis are summarized as follows.

1. Existing work on network of flying things incorporating multipath environment is critically reviewed in detail as well as properly commented wherever it is required.
2. The existence of multipath environment in network of flying things is explored. Utilizing the reflective properties of drone's surface and multi-ray

channel model, the power of the signal received at the intended air vehicle is estimated.

3. A closed-form expression for the path difference of the reflected ray with the LoS ray in multipath fading environment is proposed in a network of flying things. This path difference is further utilized to calculate the received power at the intended air vehicle as a result of the combination of the LoS and diffused components reflected from the surrounding air vehicles. The model justifies its existence and provides an insight to realistically analyze the multipath environment in network of flying things. The model is applicable to analyze the performance of high data-rate communication link among the network of flying things.

4. The proposed multi ray model is utilized for channel characterization and performance analysis of G2A and A2A communication links. The simulation results are verified through the measured data.

# Chapter 3

# Proposed Multi Ray Channel Model

In this chapter, The existence of multipath environment in network of flying things is explored. In section 3.1, a multi-path channel model is developed. A cLoSed-form expression of a multi-ray channel model is derived in section 3.3 for ground-to-air (G2A) and air-to-air (A2A) communication links to estimate the received power at the intended air vehicle in a network of flying things.

## 3.1 System Model

Consider a ground-to-air communication scenario with multiple drones or air vehicles flying around the intended air vehicle, as illustrated in Fig. 3.1. The flying vehicles are assumed to fly independently with different altitudes. The intended air vehicle ($A_0$) is assumed to be connected with the ground station (GS). In order to avoid collision between air vehicles, the safe separation distance between air vehicles is kept at 10m. This means that every drone or flying vehicle is located 10m apart from other drones. Consider a model with K number of air vehicles. The notation $A_k$ represents the $k$th air vehicle, where k=1,2, 3. . . , K. The shortest three-dimensional distance between the ground station (GS) and the intended air

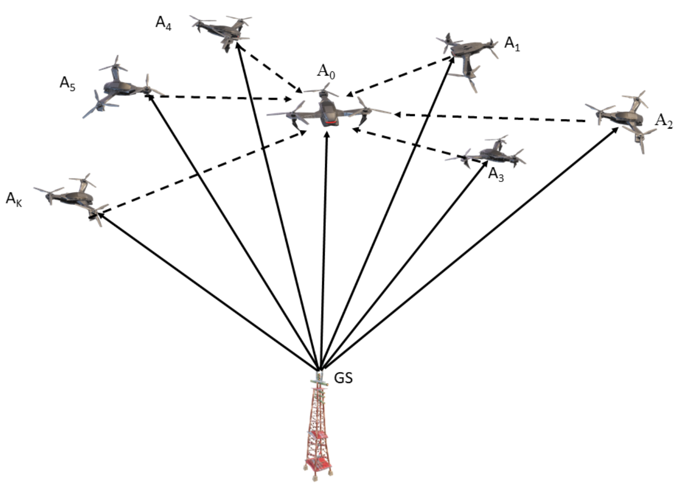


FIGURE 3.1: Ground-to-air communication link

vehicle is denoted by

$$r = \sqrt{(x - x_0)^2 + (y - y_0)^2 + (z - z_0)^2} \tag{3.1}$$

where $x_0$, $y_0$ and $z_0$ are the 3D Cartesian coordinates of the intended air vehicle on x-axis, y-axis and z-axis respectively, while x ,y and z are the coordinates of GS. The GS will emit an omni directional radio wave communication signal from ground towards the target drone located in 3D space. The emitted signal is supposed to transmit desired data to target drone directly which is commonly termed as line-of-sight signal (LoS). According to the presented environment, there could be multiple flying vehicles around the intended air vehicle that may disturb the direct radio waves. Hence, the target drone may receive a number of various reflected, diffracted or scattered propagating signals from the nearby scattering aerial vehicles via different propagation paths. These reflected signals are generally termed as non-line of sight signals (NLoS). These signals with different propagation lengths may arrive at the target drone with different time delays. For some scattering drones located at similar distances from the target drone, the propagation lengths may be equal and the signals could arrive at the receiver at the same time, hence generating the same propagation delay. However, the existence of the safe separation distance helps to increase the uniqueness of propagation paths among the aerial vehicles to avoid the repetition of the same propagation paths.

The reflections by surrounding nearby aerial vehicles may cause multipath fading scenario between GS and target drone resulting in constructive or destructive interference which could degrade the performance of communication. However, variations in time delays of the arriving signals help to create a rich scattering environment that supports MIMO processing and results in increasing data rates.

## 3.2 General Assumptions

1. For simplicity, a single GS is considered to provide network coverage to all air vehicles flying randomly at different altitudes.

2. To avoid collision among drones the safe separation distance between air vehicles is kept at 10m.

3. Each drone has the ability to reradiate the incident signal in omni directions. The reradiation from these scattering drones have different properties that depends on their spatial location and orientation in 3D space. The spatial location of aerial vehicles is considered as the most important factor in defining the incidence and reflection angles of multipath components moving towards the target drone.

4. To keep the model simple, we assume a single bounced multipath component of the transmitted radio wave. This means that the signals received at the target drone from GS after reflection from more than one surrounding aerial vehicles are not considered

5. The position of GS is kept at the center of the three-dimension space and can be represented with coordinates (0,0,0). The exact location of each and every aerial vehicle can be determined by the Cartesian coordinates ($x_k$, $y_k$, $z_k$) and can be transformed to polar coordinates.

6. Transmitting antenna of every drone is omni-directional which can transmit signals isotrophically in all directions.

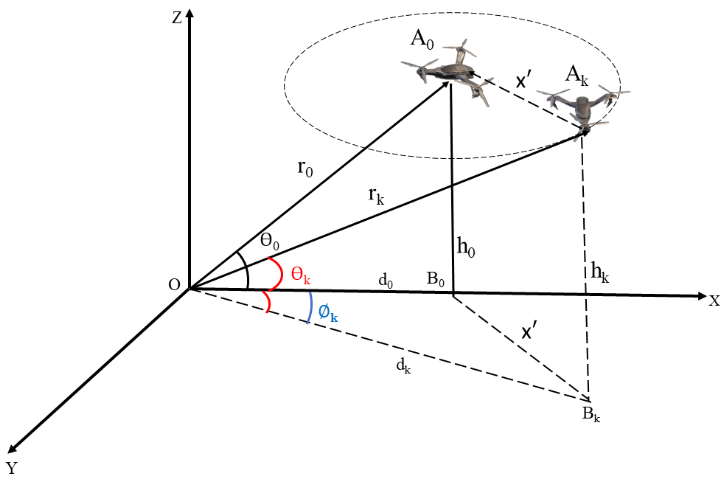


FIGURE 3.2: Proposed model

## 3.3 The Proposed Multi Ray Channel Model

Ground to Air communication scenario depicted in Fig. 3.1 can also be illustrated in 3D co-ordinates as shown in Fig. 3.2. The aerial vehicle of interest $A_0$ needs a reliable communication system to communicate with the GS located at the origin O (0,0,0). The characteristics of the wireless communication channel like path LoSs and received power etc., depend on many factors including the propagation paths between air vehicle and GS.

Consider $\Delta A_0OB_0$ as shown in Fig.3.2, where $h_0$ is the height of the aerial vehicle of interest $A_0$ and $\theta_0$ is its elevation angle. The shortest aerial distance between the intended aerial vehicle and GS can be calculated as

$$r_0 = \frac{h_0}{\sin\theta_0} \tag{3.2}$$

$r_0$ in Eq (3.2), can be termed as the LoS component of the signal transmitted from GS and received at $A_0$. Besides the LoS component, several multipath components are also received at $A_0$ due to the presence of other aerial vehicles known as scatterers that may also be flying in the nearby surrounding area.

To find the position of a scatterer, consider $\Delta A_kOB_k$ as shown in Fig. 3.2, where $h_k$ is the height and $\theta_k$ is the elevation angle of a scatterer. The shortest aerial distance between GS and $A_k$, denoted by $r_k$ can be calculated as

$$r_k = \frac{h_k}{\sin\theta_k} \tag{3.3}$$

These scatterers may be located at different positions in the air and reflect the radio waves towards the intended drone. This results in creating a multipath scenario between the GS and intended aerial vehicle.

The path length between the intended drone and scatterer plays a vital role in defining the time delay of the received signal. A nearly located scatter may have a lesser time delay as compared to a far-away scatterer. The distance from the intended air vehicle to any scatterer can be calculated by using the law of cosines. For example, the link between GS and $A_0$ can be determined by the LoS and the diffused component scattered by $A_k$. The relationship between the propagation path lengths of these components can be expressed using law of cosines as

$$x_k'^2 = r_0^2 + r_k^2 - 2r_0 r_k \cos(\phi_k) \tag{3.4}$$

where $x_k'$ denotes the separation between the scattering object $A_k$ and the intended vehicle $A_0$ and $\phi_k$ is the azimuth angle between their projections on the ground. The Eq (3.4) can be simplified further as

$$x_k'^2 = (r_0 - r_k)^2 + 2r_0 r_k(1 - \cos\phi_k) \tag{3.5}$$

Replacing the trigonometric value $1 - \cos\phi_k$ by $\sin^2(\frac{\phi_k}{2})$, we get

$$x_k'^2 = (r_0 - r_k)^2 + 4r_0 r_k \sin^2(\frac{\phi_k}{2}) \tag{3.6}$$

Putting the values of $r_0$ and $r_k$ from Eq (3.2) and Eq (3.3), Eq (3.6) becomes

$$x_k'^2 = \left(\frac{h_0}{\sin\theta_0} - \frac{h_k}{\sin\theta_k}\right)^2 + 4\frac{h_0}{\sin\theta_0}\frac{h_k}{\sin\theta_k}\sin^2(\frac{\phi_k}{2}) \tag{3.7}$$

$$x_k' = \sqrt{\frac{(h_0\sin\theta_k - h_k\sin\theta_0)^2}{(\sin\theta_0\sin\theta_k)^2} + \frac{4h_0h_k}{\sin\theta_0\sin\theta_k}\sin^2(\frac{\phi_k}{2})} \tag{3.8}$$

Re-arranging the above equation, $x_k{}'$ becomes

$$x_k' = \frac{1}{\sin\theta_0 \sin\theta_k}\sqrt{(h_0 \sin\theta_k - h_k \sin\theta_0)^2 + 4h_0 h_k \sin\theta_0 sin\theta_k \sin^2(\frac{\phi_k}{2})} \tag{3.9}$$

The above equation gives the separation between the intended aerial vehicle $A_0$ and the scattering air vehicle $A_k$. Let $x''_k$ be the distance traversed by radio wave that travels from GS to the intended aerial vehicle $A_0$ via the scattering air vehicle $A_k$ can be termed as the length of the non line- of-sight signal (NLoS) component. It can be found as

$$x_k'' = r_k + x'_k \tag{3.10}$$

Putting the values of $r_k$ and $x_k{}'$, Eq (3.10) becomes,

$$x_k'' = \frac{h_k}{\sin\theta_k} + \frac{1}{\sin\theta_0 \sin\theta_k}\sqrt{(h_0 \sin\theta_k - h_k \sin\theta_0)^2 + 4h_0 h_k \sin\theta_0 \sin\theta_k \sin^2(\frac{\phi_k}{2})} \tag{3.11}$$

Re-arranging the above equation, the propagation path of the scatter or reflected signal can be given as:

$$x_k'' = \frac{1}{\sin\theta_0 \sin\theta_k}\left[h_k \sin\theta_0 + \sqrt{(h_0 \sin\theta_k - h_k \sin\theta_0)^2 + 4h_0 h_k \sin\theta_0 \sin\theta_k \sin^2(\frac{\phi_k}{2})}\right] \tag{3.12}$$

Each scattering vehicle has a unique path length. In the presence of multiple aerial vehicles acting as scatterers, many reflected signals may arrive at the intended aerial vehicle, resulting in the generation of a multipath environment.These multipath signals arrive at the intended air vehicle $A_0$ with different time delays. The time delay $T_k$ for a propagating signal can be determined as

$$T_k = \frac{x_k''}{c} \tag{3.13}$$

Where $x_k''$ is the distance between GS and intended aerial vehicle and c is the speed of light. Signals with shorter path lengths will have a lesser time delay and arrive quite earlier, while the signal copies generated by scatterers located far-away will follow longer routes and arrive with more time delays. The difference in path lengths or arrival time can be termed as path difference. To determine the value of path difference, the LoS signal component is subtracted from scatter reflected signal. The equation can be written as

$$\Delta x_k = x_k'' - r_0 \tag{3.14}$$

Putting the values of $x_k''$ and $r_0$, the equation can be written as

$$\Delta x_k = -\frac{h_0}{\sin\theta_0} + \frac{1}{\sin\theta_0 \sin\theta_k} \left[ h_k \sin\theta_0 + \sqrt{(h_0 \sin\theta_k - h_k \sin\theta_0)^2 + 4h_0h_k \sin\theta_0 \sin\theta_k \sin^2(\frac{\phi_k}{2})} \right] \tag{3.15}$$

$$\Delta x_k = \frac{1}{\sin\theta_0 \sin\theta_k} \left[ h_k \sin\theta_0 - h_0 \sin\theta_k + \sqrt{(h_0 \sin\theta_k - h_k \sin\theta_0)^2 + 4h_0h_k \sin\theta_0 \sin\theta_k \sin^2(\frac{\phi_k}{2})} \right] \tag{3.16}$$

The value of $\phi_k$ can be determined as follows.

$$\phi_k{}' = \phi_k - \phi_0 \tag{3.17}$$

Where $\phi_0$ is the azimuth angle of intended vehicle, it is assumed to be zero.
Putting $\phi_0$=0, Eq (3.17) becomes $\phi_k' = \phi_k$.
To further simplify Eq (3.16), we consider a term in Eq (3.16) for further simplification

$$(h_k \sin\theta_0 - h_0 \sin\theta_k) \tag{3.18}$$

Putting the values of sin$\theta_0$ and sin$\theta_k$ from Eq (3.2) and Eq (3.3), we get

$$h_k \sin\theta_0 - h_0 \sin\theta_k = \left(\frac{h_k h_0}{r_0} - \frac{h_0 h_k}{r_k}\right) \tag{3.19}$$

$$= h_0 h_k \left(\frac{1}{r_o} - \frac{1}{r_k}\right) \tag{3.20}$$

Simplifying the above equation, we have

$$h_k \sin\theta_0 - h_0 \sin\theta_k = h_0 h_k \left(\frac{r_k - r_0}{r_o r_k}\right) \tag{3.21}$$

Replacing $h_0/r_0$ and $h_k/r_k$ by sin$\theta_0$ and sin$\theta_k$ as per Eq (3.2) and Eq (3.3), the above equation becomes

$$h_k \sin\theta_0 - h_0 \sin\theta_k = \sin\theta_0 \sin\theta_k (r_k - r_o) \tag{3.22}$$

$$\frac{h_k \sin\theta_0 - h_0 \sin\theta_k}{\sin\theta_0 \sin\theta_k} = r_k - r_o \tag{3.23}$$

Similarly, the above Equation can also be written as

$$\frac{h_0 \sin\theta_k - h_k \sin\theta_0}{\sin\theta_0 \sin\theta_k} = r_0 - r_k \tag{3.24}$$

By rearranging Eq (3.16), we get

$$\Delta x_k = \frac{h_k \sin\theta_0 - h_0 \sin\theta_k}{\sin\theta_0 \sin\theta_k} + \sqrt{\frac{(h_0 \sin\theta_k - h_k \sin\theta_0)^2}{\sin^2\theta_0 \sin^2\theta_k} + \frac{4 h_0 h_k \sin^2(\frac{\phi_k}{2})}{\sin\theta_0 \sin\theta_k}} \tag{3.25}$$

Putting the values of Eq (3.23), (3.2) and Eq (3.3) in the above equation , the final equation for path difference becomes as follow

$$\Delta x_k = (r_k - r_0) + \sqrt{(r_0 - r_k)^2 + 4 r_0 r_k \sin^2(\frac{\phi_k}{2})} \tag{3.26}$$

$$\Delta x_k = (r_k - r_0) + \sqrt{r_0^2 + r_k^2 - 2 r_0 r_k + 4 r_0 r_k \sin^2(\frac{\phi_k}{2})} \tag{3.27}$$

$$\Delta x_k = (r_k - r_0) + \sqrt{r_0^2 + r_k^2 - 2r_0 r_k (1 - 2\sin^2(\frac{\phi_k}{2}))} \tag{3.28}$$

$$\Delta x_k = (r_k - r_0) + \sqrt{r_0^2 + r_k^2 - 2r_0 r_k \cos\phi_k} \tag{3.29}$$

where $r_k$ and $r_0$ are the respective path lengths of scattering air vehicles and intended air vehicle while $\phi_k$ is the azimuth angle between them.

# Chapter 4

# Results Description and Comparative Analysis

This Chapter presents the simulation results of multi-ray model developed in Chapter 3. In section 4.1, the simulation setup and various propagation parameters are discussed for two communication link scenarios. The communication link scenarios are presented in section 4.2. In section 4.4, impact of various factors on the received power is analyzed.

## 4.1 Model Implementation Setup

In this section, a quasi-realistic propagation scenario is created in MATLAB®to analyze and validate the functionalities of the proposed model. The model can be considered similar to the real communication scenario as it accommodates random scatterers around the intended air vehicle. For the protection of the air vehicles, the safe separation distance is kept according to the requirement of applications. The model can be used to analyse the impact of various factors such as altitude, and distance etc., on the channel in G2A and A2A communication systems.

In order to implement the proposed model, the intended air vehicle and scatterers

Table 4.1: Simulation setup

| Simulation Parameter | Specification |
|---|---|
| Carrier Frequency | 2.4 GHz |
| Transmit Power | -22.14 dBm |
| Tx Antenna Gain | 3.9 dBi |
| Rx Antenna Gain | 3 dBi |
| Transmitter Height (G2A) | 1.7 m |
| Transmitter Height (A2A) | 20 m |
| Safe Separation Distane | 3 m |

are considered to be located at altitude of 20 m from BS maintaining safe separation distance ($d_s$) of 3 m to avoid collision among the air vehicles. The ground station is located 1.5m above from the ground surface for the scenario of G2A communication, while it is kept at 20 m for the scenario of air-to-air communication. A total number of 200 scattering air vehicles are considered with the intended air vehicle. The essential configuration details are listed in Table 4.1. As drones are built with reflective materials therefore the received signal may get reflected, which may create a multipath environment around the intended drone. The reflection properties of the scattering air vehicles are obtained through Radar Cross Section (RCS). Spatial Reflection Coefficient (SRC) and RCS are inter-dependent on each other as discussed earlier in section 1.3.3. The reflection properties of the incident signal hitting the surfaces of aerial vehicles are obtained using a facet-based drone model namely Parrot Anafi and MATLAB®based RCS estimation tool, EPOFACET [50]. The drone model is illustrated in Fig. 4.1.

## 4.2 Communication Link Scenarios

Since, the use of aerial vehicles has rapidly increased in various fields of human and non-human intervention, including security, entertainment and medical purposes. Aerial vehicles can be applied to a wide range of applications, various missions and operations.These applications give rise to specific communication link scenarios.

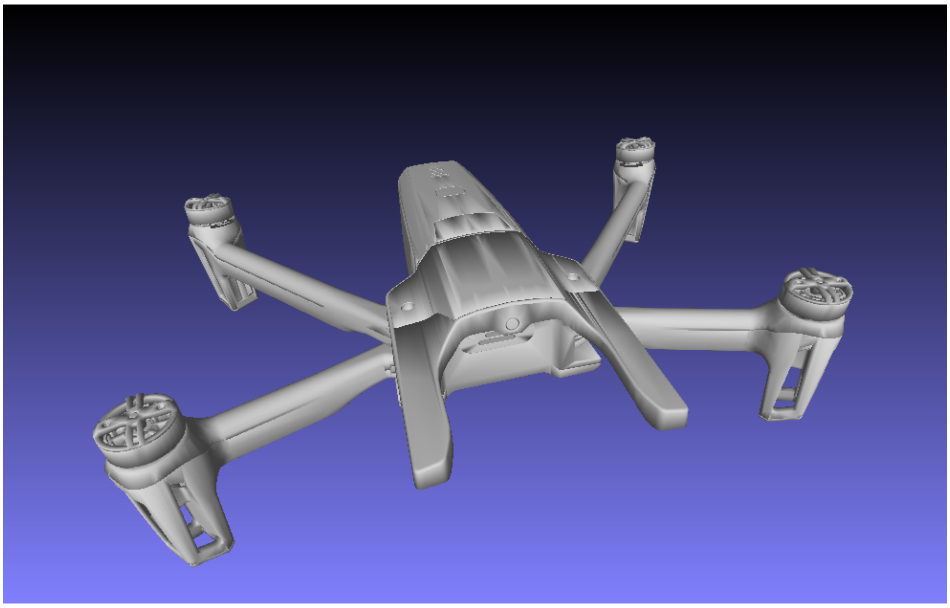

FIGURE 4.1: Facet-based model of Parrot Anafi Drone

In general, the following communication link scenarios can be considered, which are discussed as follows.

### 4.2.1 Ground-to-Air and Air-to-Ground Communication

In this case, the transmitter is at the ground which sends signal to the aircraft of interest in the air as illustrated in Fig. 4.2. However, the same signals are reflected by the surrounding aerial vehicles and their delayed versions are received at the intended air vehicle. During the last few years, Unmanned Aerial Vehicles (UAVs) have gained immense popularity due to their use in various applications such as civil, military, and commercial applications etc. The use of UAVs in industrial applications has further enhanced its usability and proved to become a versatile and powerful industrial tool of the current time. They have also been introduced in various commercial, security, entertainment, medical, and telecommunication-related applications as a network. For instance, in the Olympics 2018, 1218 intel's drones, named shooting stars, were used to perform Olympics fireworks, whereas, in Tokyo 2020 Olympics games, 1824 drones were flown with super bright Light Emitting Diodes (LEDs) to form the Olympics emblem in the sky [1].

Drones are frequently used in event opening ceremonies especially at new year

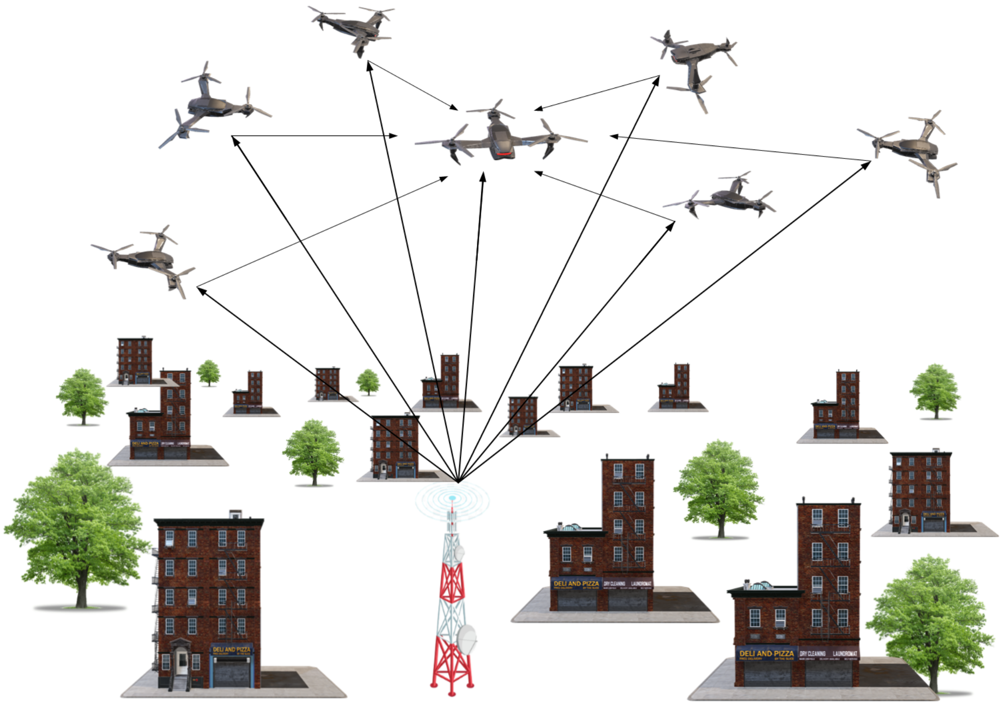

FIGURE 4.2: Ground-to-air communication

evenings to entertain people. At new year night of 2022, drone shows are performed in many countries around a world. 500 drones were used in London by sky magic to perform the drone show [51]. Similarly, 452 drones were used in UAE for creating new year visuals in the sky [52]. Similarly in China [53], USA [54] drones are used in new year celebration events.

In various military applications, a network of drones is used to work in clusters and to perform instructive operations collaboratively. The use in military applications is not limited to provide data coverage in abandoned areas, but the drones are capable to assist in various military operations and perform military tasks instantly. A network of drones can also be used for a mass destruction whenever it is required [55][56]. Moreover, Amazon has also launched shipment drones to deliver shipments to their clients [ref]. The project was named as Amazon Prime air, it has the ability to deliver shipments in 13 minutes over 07 miles [57]. Many other delivery providing companies are adopting the use of drones, recently Food Panda has launched its drone services named as Pandafly in Islamabad Pakistan [58].

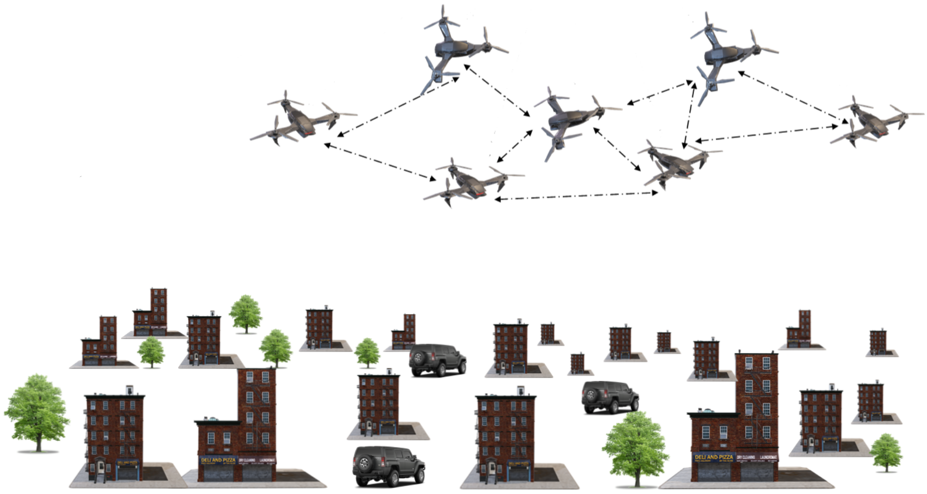

FIGURE 4.3: Air-to-air communication

### 4.2.2 Air-to-Air Communication

In air-to-air communication scenarios, an air vehicle connected with the ground base station or satellite acting as a transmitter in the air to deliver control and data packets to other vehicles of the network as shown in Fig. 4.3. Relaying data from one vehicle to another vehicle extends the coverage of the network. In A2A communication, a strong LoS communication link may be established between transmitter and receiver as the transmitted radio signal may not be disturbed by any other obstacles except the nearby proximate air vehicles. Besides the existence of very few scatters, specifically air vehicles, air-to-air communication also experience very few ground reflections.

In the case of multiple drones flying together, the surrounding aerial vehicles may be considered as the major obstacles. These scattering aerial vehicles have reflecting surface bodies that may reflect the transmitted signal in all directions and affect the channel characteristics. In order to examine the channel characteristics, various factors that impact the signal propagation are considered in the simulation setup.

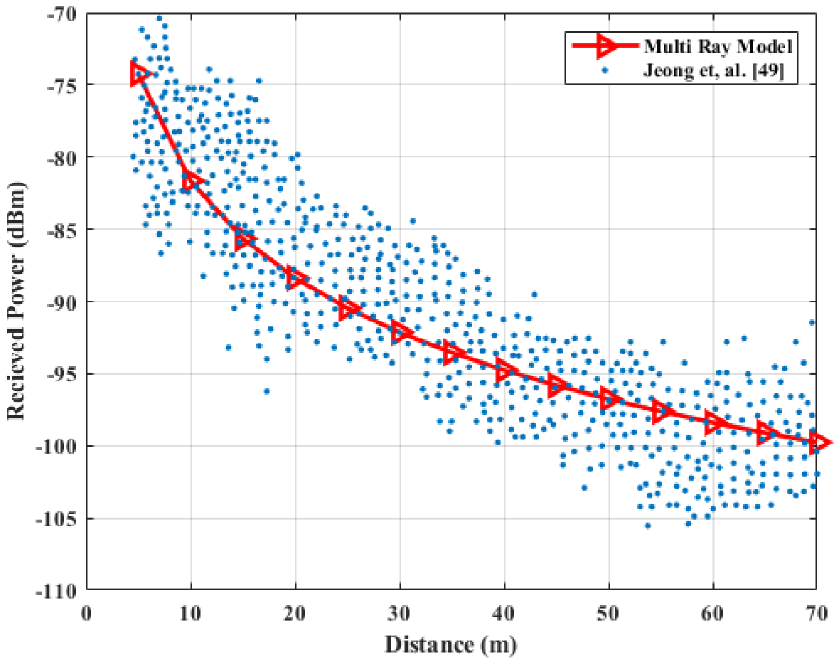


FIGURE 4.4: Result validation through measured data with K=200, $d_s$=3 m

## 4.3 Validation of Multi Ray Model through Field Measurements

In order to verify the validity of the proposed model, the results are compared with the measurements data. The proposed model is implemented on the concept of ray-tracing. The simulation environment consists of randomly placed scatterers. For ease of simulation, a total of 200 scatterers were assumed to fly around the intended aircraft. The results are compared with the measurement data obtained by Jeong et al.[49] and shown in the Fig. 4.4. The comparison shows that the proposed model better fits with the measurement results.

## 4.4 Analysis of the Impact of Various Factors on the Received Power

In wireless communication system, characteristics of radio signal such as received power and path loss depend on channel propagation. Received power is considered an important parameter to evaluate the performance of the communication link in terms of reliability and efficiency. A radio propagation channel containing various scatterers reflects the transmitted radio signal in many directions which results in the generation of multipath environment. These multipaths can cause constructive or destructive interference and may affect the received power. In order to implement a model with ray tracing, these multipath signals are assumed to be summed in accordance with their delays to obtain the receive power. The characteristics of multipath signals may change with changes occurring in the position of scatterers, transmitter or receiver. For this purpose, various factors are considered to determine their impact on the received power. These factors include altitude of the receiver, number of drones in the vicinity of the receiver and inter-drone and, transmitter-receiver separation distances and propagation. The impact of each factor is discussed as follows.

### 4.4.1 Impact of the Altitude of the Receiver on the Received Power

Since, the prime objective of the aerial vehicles is to perform aerial tasks without any hindrance; therefore, it is necessary to examine the network performance consciously. The drone movements could not be expected to follow a particular trajectory because they have to perform their tasks by achieving any arbitrary optimal path. The path could be of any arbitrary shape with different altitudes and distances. The aerial vehicles follow its path according to the need of environment, unlike the conventional ground communication system they can fly to certain altitudes in a region where the transmitted signal can be obstructed by obstacles, such as buildings and trees, to obtain better propagating conditions and improve the estimation of the received power. In order to observe the performance of aerial vehicles when they are dedicated to flying towards the sky, it is needed to implement the model at different altitudes.

#### 4.4.1.1 Ground-to-Air Scenario

In G2A scenario, the scattering air vehicles along with the intended air vehicle are located in the air positioned at different altitudes while the base station is located 1.5 m above the ground surface. The ground station emits a radio signal towards the intended air vehicle, which arrives at the intended air vehicle with many reflected delayed signals. The delayed signals are basically the result of the reflections from the scattering objects or air vehicles. As the altitude of aerial vehicles increases, the vertical distance of all air vehicles (including the intended and scatterers ones) from the BS increases which results in increase in a sharp decrease in the received power caused due to path loss and constructive and destructive interference as shown in Fig. 4.5. In this scenario, altitudes of 20 m, 30 m, 40 m, 50 m , 60 m, 70 m, 80 m and 90 m were considered for simulation. From the obtained results, it is observed that the received power decays with respect to the increase in altitudes.

#### 4.4.1.2 Air-to-Air Scenario

In A2A scenario, the scattering air vehicles along with intended air vehicle are located in air at different altitudes while the Base station is also located in air at altitude of 20 m. The altitude of scatterer air vehicles shifts to new position along with the intended air vehicle, while the location of BS remains at the same altitude. The impact of altitude on received power is shown as in Fig. 4.6, where altitudes of 20 m to 90 m were considered with a fix step of 10 m. From the obtained results, it is observed that the received power decays with respect to the increase in altitudes. The model is implemented with 200 aerial vehicles having safe separation distance of 3 m to examine the variation in signal power, affected by multipath components.

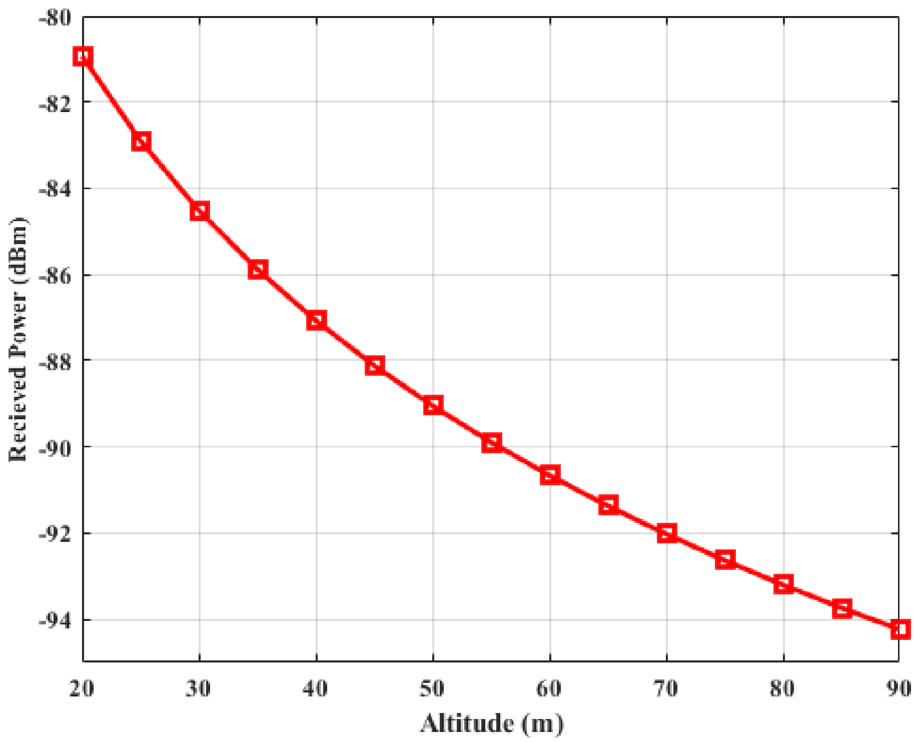


FIGURE 4.5: Impact of the increasing altitude of the receiver on received power in ground-to-air communication link scenario with K = 200, $d_s$=3 m

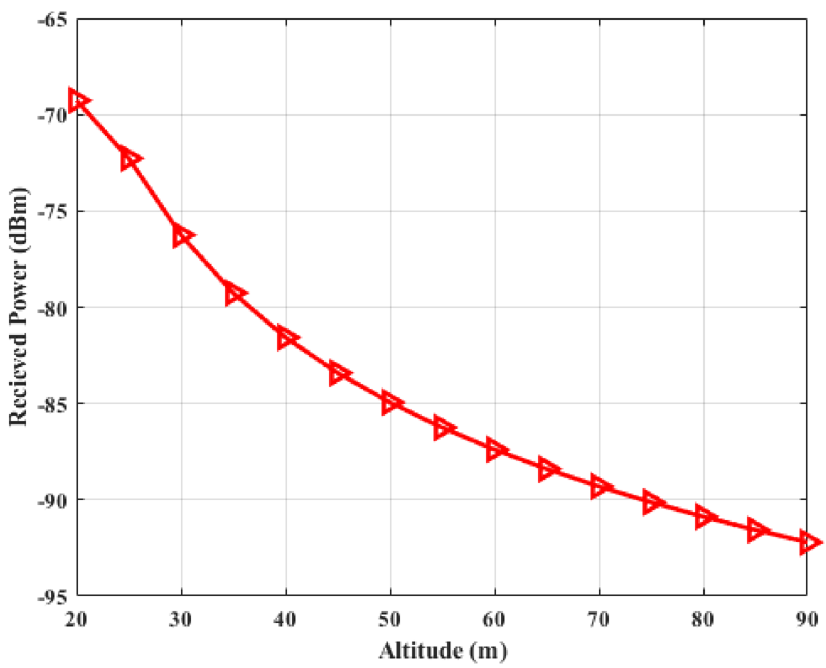


FIGURE 4.6: Impact of the increasing altitude of the receiver on received power in air-to-air communication link scenario with K = 200, $d_s$=3 m

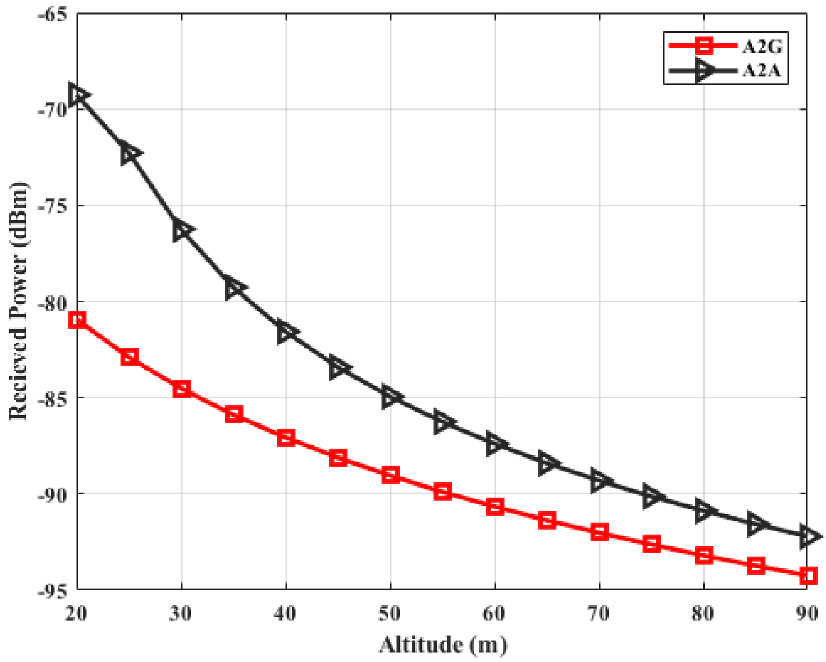


FIGURE 4.7: Comparative analysis of received power in G2A and A2A communication links

#### 4.4.1.3 Comparative Analysis

Fig. 4.7 represents a comparative analysis of the received power against altitude in both G2A and A2A communication link scenarios. Since, in air-to-air communication scenario, the transmitting air vehicle is flying in the sky; therefore, the received signal strength is high as compared to the scenario of ground-to-air communication.

### 4.4.2 Impact of the Horizontal Flight of the Receiver on the Received Power

Aerial vehicles are primarily used to perform remote operations over a certain distance. To perform a remote operation such as delivery, or search and rescue missions, the aerial vehicles need to move away from the BS for long distances. For timely access, initially, the aerial vehicles move in an upward direction towards the sky at a certain altitude and then continues its flight only in the horizontal

direction. The aerial vehicle travels a long-range of horizontal distances to complete its operation. As the distance between aerial vehicles and GS increases, the aerial vehicles may experience more possible obstacles and reflections from the ground as well as from the nearby surroundings that may increase the multipaths at the intended air vehicle. As a result, the intended air vehicle receives more signal copies with different time delays that result in constructive or destructive interference and degrade the power of received.
In order to examine the channel characteristics for aerial vehicles when they are moving in the horizontal direction, it is needed to implement the model for different distances. This is because, the network of flying things is not limited to provide access over a small region, instead the network of flying things is used to enhance the network coverage. Therefore, it is essential to measure the performance of the network when the vehicles are positioned over a large area.

#### 4.4.2.1 Ground-to-Air Scenario

In this scenario, the model is evaluated for horizontal distances ranging from 5m to 75 m with a fix step of 10 m as shown in Fig. 4.8. The obtained results show that received power decreases with an increase in horizontal distance. From simulations, it is observed that the received power at distance of 5m is measured to be -81 dBm while at distance of 75 m it is observed to be -94 dBm. It has been examined that when aerial vehicles move away from the BS, the signals arriving to the intended air vehicle via scattering air vehicles experience more delay, hence, degrade the power of the received signal.

#### 4.4.2.2 Air-to-Air Scenario

In this scenario, the proposed model is evaluated when the BS is located in the air. Both the transmitter and the intended air vehicle are positioned in air. The intended air vehicle may observe several multipath signals from proximate air vehicles, which act as scatterers. From simulations, it is observed that the received

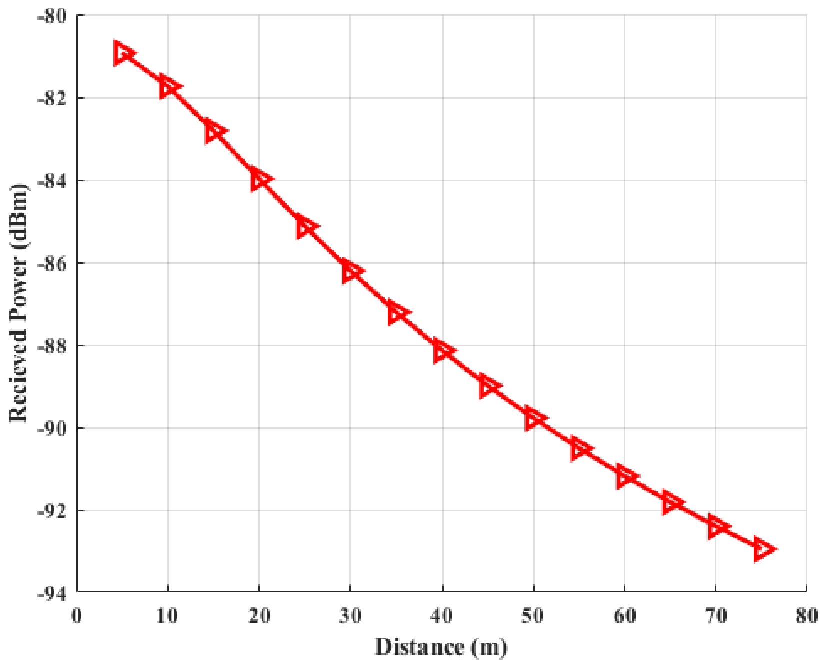


FIGURE 4.8: Behavior of the received power against increasing horizontal distance in ground-to-air communication link scenario with K = 200, $d_s$=3 m

signal strength measured at altitude of 20 m and distance of 5 m is -69 dBm, while it is measured -93 dBm at distance of 75m. It is also observed that the received signal power decreases with an increased in horizontal distance due to path loss and constructive and destructive interference as shown in Fig. 4.9. Moreover, it is also observed that the overall impact of the increase in horizontal and vertical distances is almost same.

#### 4.4.2.3 Comparative Analysis

Fig. 4.10 shows a comparative analysis of the received power against horizontal distance in both G2A and A2A communication link scenarios. Since, in air-to-air communication scenario, the base station and air vehicles including intended air vehicle and scattering air vehicles are present in the sky; therefore, the received power of a radio signal is high as compared to the scenario of ground-to-air communication.

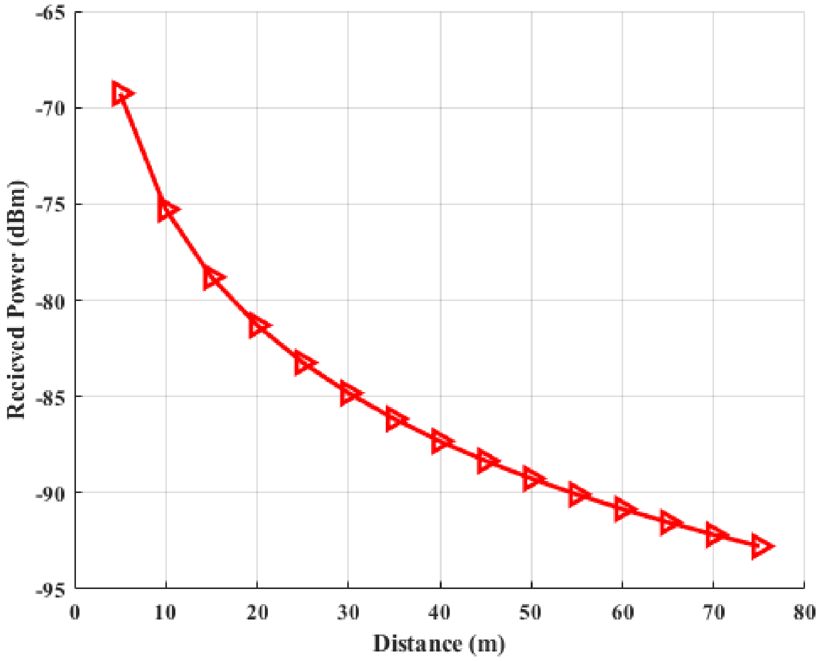


FIGURE 4.9: Behavior of the received power against increasing horizontal distance in air-to-air communication link scenario with K = 200, $d_s$=3 m

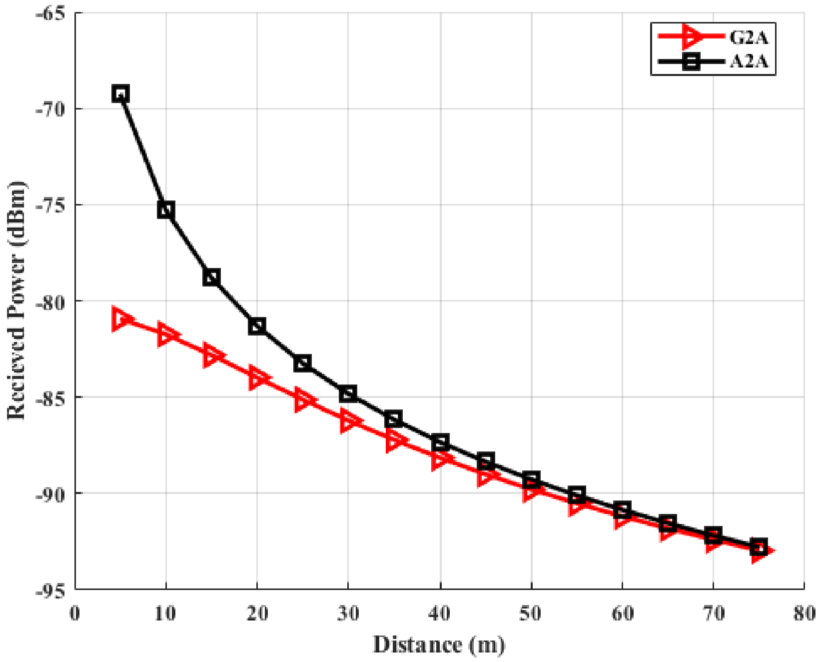


FIGURE 4.10: Comparative analysis of received power in G2A and A2A communication links

### 4.4.3 Impact of Increase in Number of Flying Vehicles on the Received Power

In order to perform an activity through a network of aerial vehicles, a specific number of drones are assigned for its completion. The operation may also consist of different activities or tasks. Depending upon the nature of the operation or including tasks, the number of assigned drones may be increased or decreased to speed up the completion of activity/task. The number of aerial vehicles may also vary with other multiple operations performing in the same coverage area. In such a scenario, the increase or decrease in the number of aerial vehicles in fixed covering area vary the reflections and multipath signal of transmitted radio wave. By increasing the number of aerial vehicles, the path lengths and time delay of signal copies become shorter, causing more rapid fluctuation in received power and vice versa.

To study the effect of the number of drones on channel characteristics, it is necessary to implement the model for different numbers of UAVs. It is observed from the obtained results as shown in Fig. 4.13. that receive power decays with the increase in the number of aerial vehicles. In this set of simulations, a different number of aerial vehicles are considered such as 5, 100,150, 200, and 455 drones. The simulations were performed at 2.4 GHz frequency. In order to avoid possible collision among the aerial vehicles, a safe separation distance of 3 m is maintained between aerial drones.

#### 4.4.3.1 Ground-to-Air Scenario

In this scenario, different number of aerial vehicles were considered along the intended air vehicle to evaluate the performance of model in term of received power. The obtained results show that increase in number of aerial vehicles causes a decrease in the received power. From simulations, it is observed that the received power for 5 aerial vehicles is measured to be -91 dBm while for 455 aerial vehicles it is observed to be -115 dBm as shown in Fig. 4.11. It is examined that when

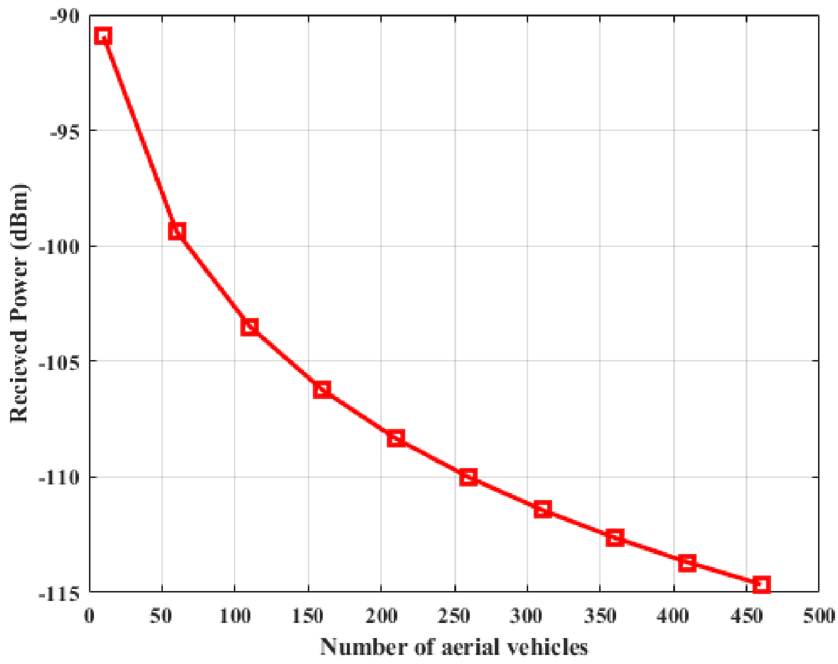


FIGURE 4.11: Impact of the increasing number of aerial vehicles on received power in ground-to-air Communication link scenario with K = 200, $d_s$=3 m

the number of aerial vehicles is increased, the transmitted signal experience more scatterers which results in increase in reflection and multipath. The intended air vehicle receives more copies of transmitted signal via multipath, hence, degrade the power of the received signal.

#### 4.4.3.2 Air-to-Air Scenario

In this scenario, the proposed model is evaluated by varying the altitude of BS. The BS is a flying air vehicle which transmit a radio wave from air. The scattering air vehicles are also flying around the intended air vehicle. The intended air vehicle may observe several multipath signals from proximate air vehicles, which act as scatterers. From simulations, it is observed that the received signal strength measured at 5 drones is -79 dBm, while it is measured -103 dBm for 455 drones. Since, in air-to-air communication scenario, the transmitting air vehicle is flying in the sky; therefore, the received signal strength would be high as compared to the scenario of ground-to-air communication. It is also observed that the received signal power decreases with an increase in number of aerial vehicles due to the

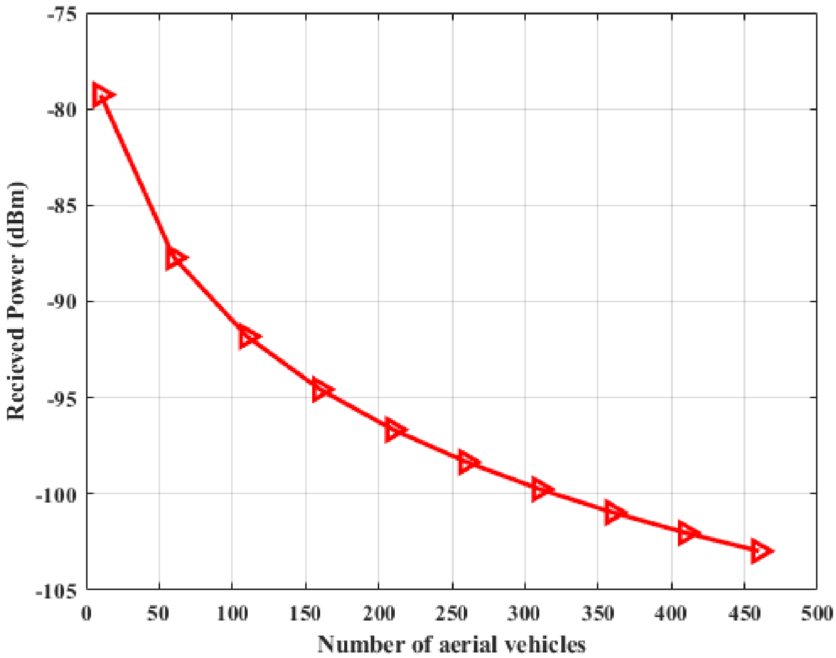


FIGURE 4.12: Impact of the increasing number of aerial vehicles on received power in air-to-air communication link scenario with K = 200, $d_s$=3 m

increase of multipath signals. The increasing multipath signals may affect the signal power as a result of constructive and destructive interference, as shown in Fig. 4.12.

#### 4.4.3.3 Comparative Analysis

A comparative analysis of the received power and number of aerial vehicles in both G2A and A2A communication link scenarios are illustrated in Fig. 4.13. Since, in air-to-air communication scenario, the transmitting air vehicle is flying in the sky; therefore, the received signal strength is high as compared to the scenario of ground-to-air communication.

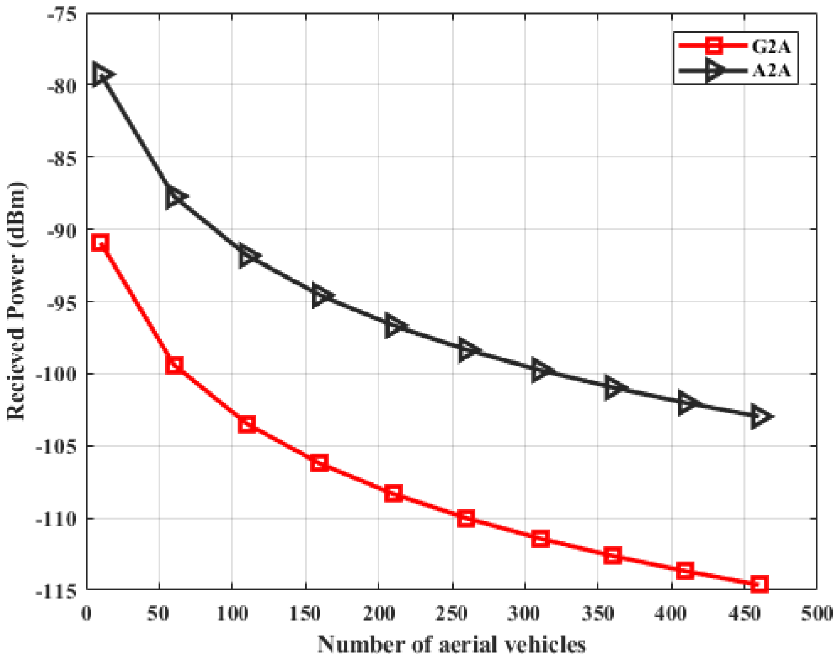


FIGURE 4.13: Comparative analysis of received power in G2A and A2A communication links

### 4.4.4 Impact of Increase in Propagation Distance on the Received Power

Aerial vehicles may adopt different direction of movement in air, according to the need of their operation, they can fly in any direction i.e., move freely towards right, left or move upward in vertical direction or cover horizontal distance. Mostly, in normal situation, aerial vehicle flies in both vertical and horizontal directions to achieve their target position easily. The motion of air vehicles in both horizontal and vertical directions at same time can be termed as propagation distance. In this scenario, as the air vehicles change their position instantly in both direction, a random shift in phase is expected to occur due to change in incident angle. The change in phase of air vehicles will lead a change in measured value of RCS which may affect the received power at the intended air vehicle. In order to examine the channel behavior when drones are moving in both vertical and horizontal direction, it is needed to perform simulations of such scenario for multipath environments. It is very clear from the simulation results that signal power degrade with increasing propagation distance.

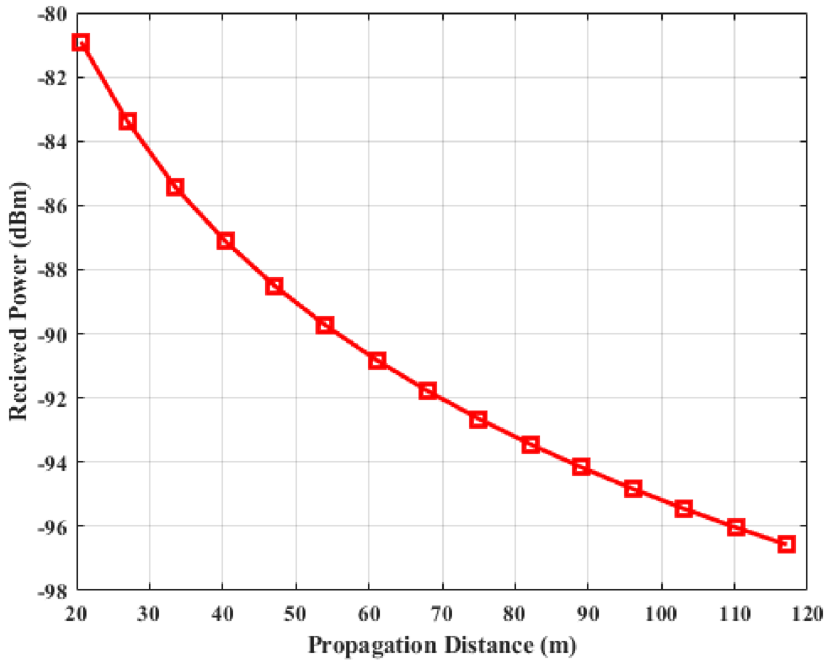


FIGURE 4.14: Behavior of the received power against propagation distance in Ground-to-air communication link scenario with K = 200, $d_s$=3 m

#### 4.4.4.1 Ground-to-Air Scenario

In this scenario, the position of BS is fixed on ground surface while scattering air vehicles along with intended air vehicle are shifted to new positions in air. The position of aerial vehicles are shifted in both horizontal and vertical direction at same time. In order to study the channel behavior for such scenarios, the model is evaluated for different covered distances ranging from 20 m to 118 m as shown in Fig. 4.14. The obtained results shows that received power decreases with an increase in propagation distance. From simulations, it is observed that when the BS is located at altitude of 1.5 m and the air vehicles are positioned at altitude of 20 m and horizontal distance of 5 m, the received signal strength measured is -81 dBm, while it is measured -97 dBm, when scattering vehicle are located at distance 75 m and altitude of 90 m and the base station is located at same position i.e. 1.5 m. It is examined that when the vertical and horizontal distances vary at the same time, the power of the received signal degrade sharply .

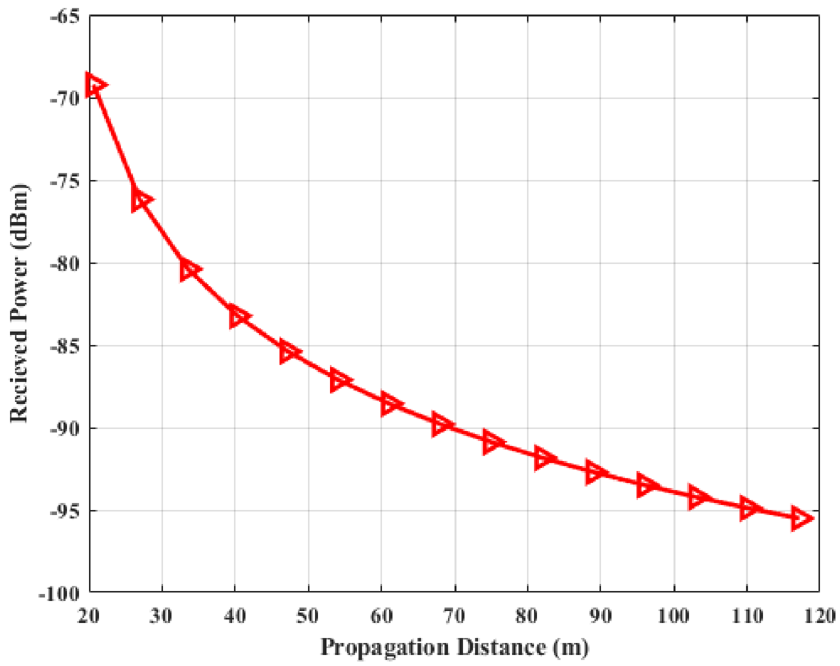


FIGURE 4.15: Behavior of the received power against propagation distance in air-to-air communication link scenario with K = 200, $d_s$=3 m

#### 4.4.4.2 Air-to-Air Scenario

In this scenario, both the transmitter and the intended air vehicle are positioned in the air. The scattering air vehicles are also positioned in air around the intended air vehicle, which act as scatterers. From simulations, it is observed that when the BS is located at altitude of 20 m and the air vehicles are positioned at altitude of 20 m and horizontal distance of 5 m, the received signal strength measured is -69 dBm, while it is measured -95.5 dBm, when scattering vehicle are located at distance 75 m and altitude 90 m and the base station is located at same position of 20 m. The increase in power decay is shown in Fig. 4.15.

#### 4.4.4.3 Comparative Analysis

Fig, 4.16 represents a comparative analysis of the received power against propagation distance in both G2A and A2A communication link scenarios. The received signal strength is high in air-to-air communication scenario as compared to the scenario of ground-to-air communication because the transmitting air vehicle is flying in the sky along with other aerial vehicles.

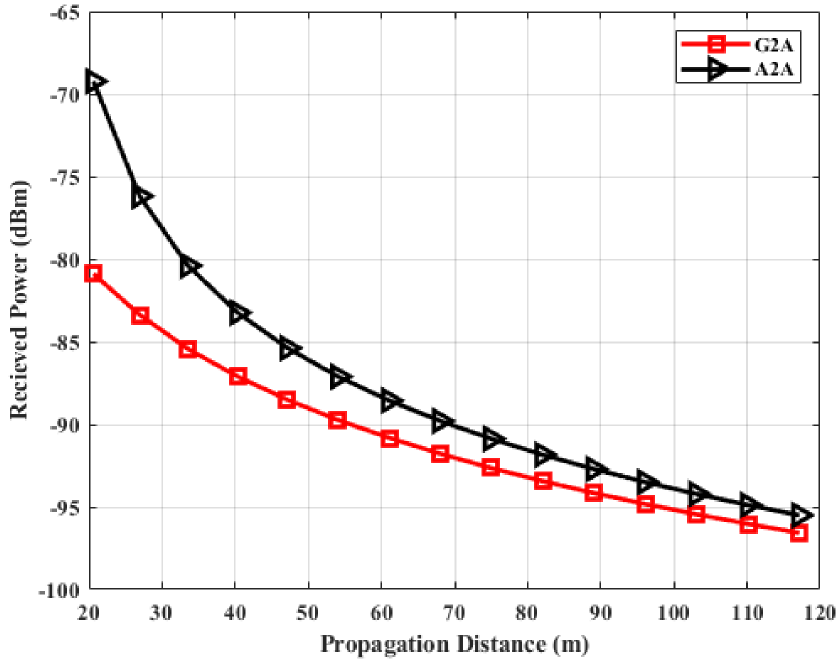


FIGURE 4.16: Comparative analysis of received power in G2A and A2A communication links

### 4.4.5 Impact of Increase in Inter-Vehicle Separation Distance on the Received Power

In many operations such as search and rescue or war field combats, the aerial vehicles move randomly in all directions to perform their activities. As a result, the area covered/occupied by aerial vehicles become changes, i.e., expand or shrink. In such scenarios, the drones located near to each other may go far away from one another or vice versa. This shift in the positions of scattering aerial vehicles from the intended air vehicle changes the path length of multipath signals, resulting in variation in time delay. The time delay for a scatterer vehicle located near to the intended aerial vehicle, increases as it shifts to a faraway position.

Similarly, in this way, the time delay for a distant scatterer decreases as it moves towards a nearer position. In this way, this scenario may also be referred to as a

situation where multiple activities may perform in the nearby area. This movement of the aerial vehicles, to spread out or gather together, changes the occupied area of the drone network, which results in an increase or decrease in radius. The change in radius in network of aerial vehicle result in variation of reflections and multipaths which disturb the received signal.
In G2A communication system, aerial networks having larger separation distance may also experience more obstacles and ground reflections as compared to small separation distance. In order to study the channel characteristic when aerial vehicles fly at different distances from the intended air vehicle, it is needed to perform simulations of such scenarios for multipath environments. From the simulations, it is observed that the received signal power at the intended air vehicle covering a separation distance of 5 m is measured relative high as compared to a separation distance of 25 m. This is due to the fact that a larger number of drones can be accommodated in bigger radius as compared to the smaller radius, which impact in decrease in the received signal power.

#### 4.4.5.1 Ground-to-Air Scenario

In this scenario, the model is evaluated for different inter-vehicle separation distances ranging from 5 m to 75 m with a fix step of 10 m as shown in Fig. 4.17. The obtained results show that received power decreases with an increase in radius. From simulations, it is observed that the received power is measured to be -96 dBm for the separation of 25 m. The received power decreases to -115 dBm for a separation of 25 m. It is examined that when the inter-vehicle separation increases, the number of drones also increases that results in generation of more multipath signal towards the intended air vehicle, hence, degrade the power of the received signal.

#### 4.4.5.2 Air-to-Air Scenario

In this scenario, the proposed model is evaluated for varying the separation distance of aerial vehicles around the intended air vehicle when both the transmitter

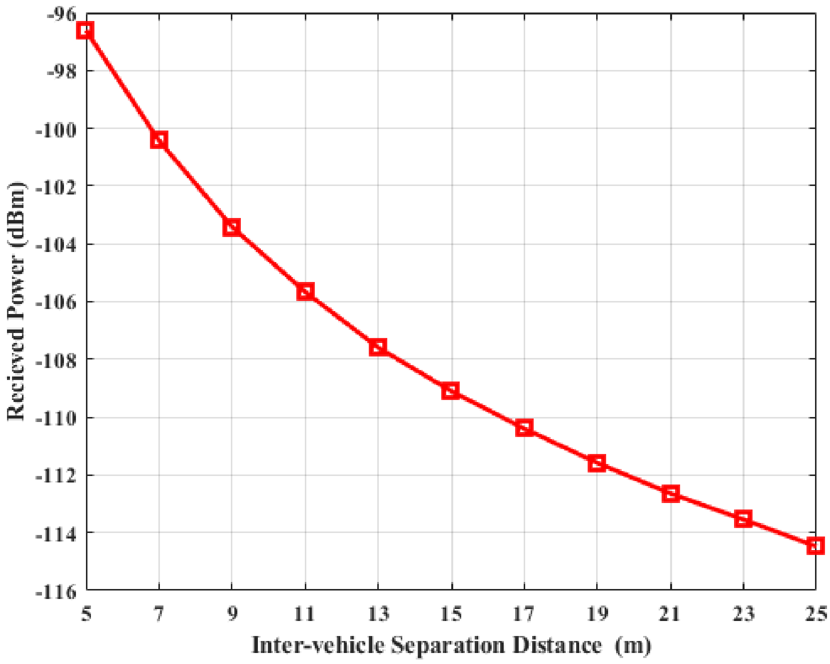


FIGURE 4.17: Behavior of the received power against increasing inter-vehicle separation distance in ground-to-air communication link scenario with K = 200, $d_s$=3 m

and air vehicles are positioned in air. The intended air vehicle may observe several multipath signals from proximate air vehicles only, as there are very less opportunity of any other scattering objects. From simulations, it is observed that the received signal strength measured at separation distance 5 m is - 85 dBm, while it is measured -103 dBm at separation distance of 25 m. Since, in air-to-air communication scenario, the transmitting air vehicle is flying in the sky; therefore, the received signal strength would be high as compared to the scenario of ground-to-air communication. It is also observed that the received signal power decreases with an increased in inter-vehicle separation distance, as larger separation distance will accommodate a greater number of air vehicles that reflects more multipath signals towards the intended air vehicle. The increase in multipath signals may affect the signal power as a result of constructive and destructive interference, as shown in Fig. 4.18.

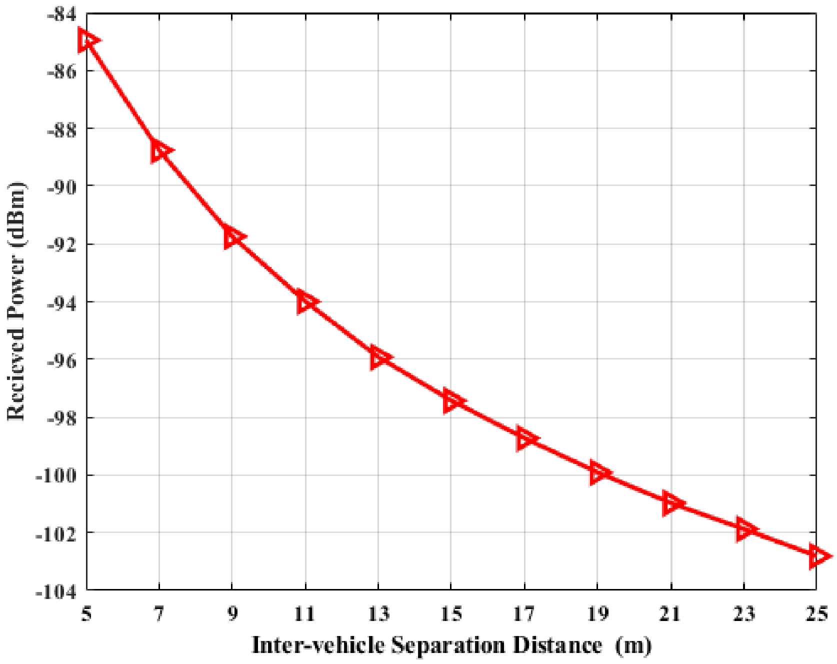


FIGURE 4.18: Behavior of the received power against increasing inter-vehicle separation distance in air-to-air communication link scenario with K = 200, $d_s$=3 m

#### 4.4.5.3 Comparative Analysis

Comparison between G2A and A2A scenario in terms of received power and inter-vehicle separation distance is shown in Fig. 4.19. It is observed from the obtained results that the received power of a radio signal is high as compared to the scenario of ground-to-air communication. The difference in received power is due to the presence of BS in air.

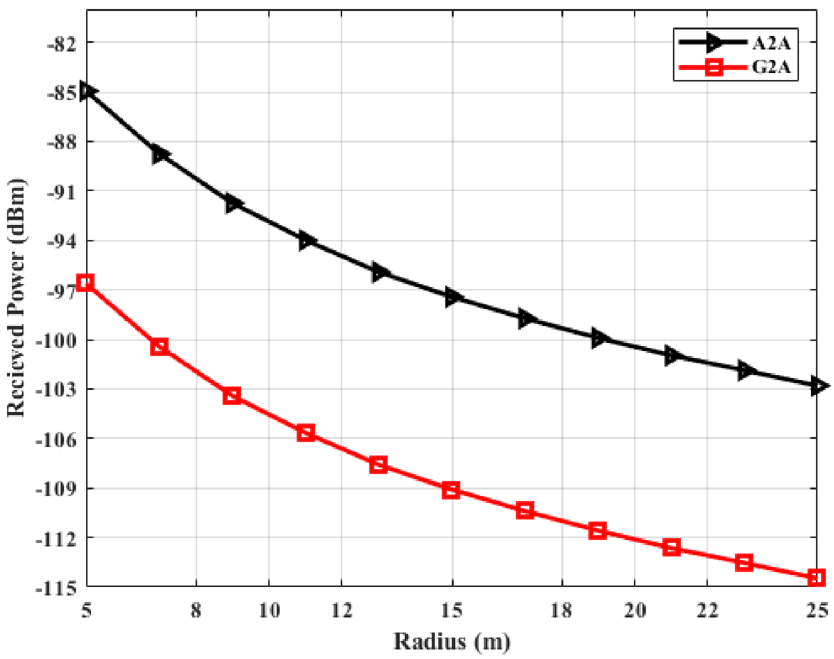


FIGURE 4.19: Comparative analysis of received power in G2A and A2A communication links

# Chapter 5

# Conclusion and Future Directions

This Chapter concludes the research work performed throughout in this thesis. Section 5.1 presents a brief summary of this thesis. Section 5.2 discusses the possible future work.

## 5.1 Thesis Summary and Conclusion

In this research work, existing work on multipath channel modelling for the network of flying things has been intensively reviewed and properly commented wherever needed. It has been noticed that most of the studies regarding G2A and A2A communication is generally assumed to be of line-of-sight (LoS) communication only. For this particular purpose, multipath channel models have been analysed in terms of various parameters in G2A communication links. Furthermore, the study disproved the assumption that communication link consists of LoS component only by elaborating the multipath phenomenon due to the inclusion of multiple air vehicles around the intended air vehicle. The study has observed that since, the drones or air vehicles are built with a reflective surface; therefore, the reflected rays from the proximate air vehicles may become sources of interference for the intended air vehicle. In this way, the existence of multipath environment in network of flying things has been explored. On the basis of all these available information, a closed-form expression for the path difference of the reflected ray with the LoS ray in multipath fading environment has been proposed in a network of flying things. This path difference is further utilized to calculate the received power at the intended air vehicle as a result of the combination of the LoS and diffused components reflected from the surrounding air vehicles.The model has been developed on assumption of single bounced multipath components of transmitted radio wave. In other words, the signals received to the target drone from GS after reflection of more than one surrounding aerial vehicle have not been considered. The proposed multi ray model justifies its existence and provides an insight to realistically analyze the G2A and A2A multipath environments. The proposed multi ray model has been designed on the basis of geometrical positions of the air vehicles and a closed form analytical expression of the received power in multipath environment has been formulated for G2A and A2A communication link. The impact of various factors on channel performance regarding received power have been investigated in A2G and A2A communication links. For this complex calculation and computation, a quasi-realistic propagation scenario was created in Matlab®. The scattering air vehicles reflect the transmitted signal towards the intended air vehicle, the intensities of reflected signals (SRC) were obtained through bistatic radar cross section (BRCS). The numerical values of BRCS have been computed by a facet-based model of drone namely Parrot Anafi with Matlab®-based RCS estimation tool known as EPOFACET. It has been examined from the obtained results that multipath propagation degrades the signal performance. In order to validate the expression of the proposed multi-ray channel model of network of flying things, the results have been compared with the measurement data.

## 5.2 Future Research Directions

The proposed multi ray model is capable to analyze the performance of communication link in G2A and A2A environments. The model may not only be utilized to estimate the received power of a radio signal, received at the intended air vehicle in the presence of other near by surrounding scattering air vehicles but can be also used for the purpose of simulating an exact scenario of G2A and A2A environments. In order to make the model applicable to more complex applications like synchronization of thousands drones, further research work is needed. It can be used to increase the data rates by incorporating MIMO systems. The proposed model can also be investigated for reliability and scalability studies when multiple base stations are available with different transmitting powers. In practical scattering environments, multi bounce signals are also expected to be received at the intended air vehicle and may result in variations in the received power. This aspect also needs to be explored as a future study in order to avail more accurate estimates of the received signal strengths.

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