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Link-level Performance Modelling for Next-Generation UAV Relay with Millimetre-Wave Simultaneously in Access and Backhaul

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Abstract

Objectives: The ultimate goal of this study is to explore, analyse, and evaluate the use of mm Wave in access and backhaul network simultaneously for the use of UAVs in Next-Generation Wireless Networks (5G). **Methods/statistical analysis**: Future wireless communication, especially the densified 5G network, will bring numerous innovations to the current telecommunication industry and will support a 100-fold gain in throughput, 100-folds in connection for at least 100 billion devices, and a 10 Gb/s individual user experience capable of extremely low latency and response times. In such scenarios, the use of Unmanned Aerial Vehicle (UAV) as Base Stations (BS) becomes one of the viable options for providing 5G services. **Findings**: This study analyses and describe the distinctive rich characteristics of mmWave propagation. In-depth literature review has been conducted. End-to-end equations have been derived for calculating power received by the end-user while getting coverage through amplify-and-forward UAV relay. Using ray racing simulator, effectiveness of diffracted, reflected, and scattered paths versus direct paths has been shown in tiny wavelength frequency band. **Application/improvements**: Huge continuous bandwidth availability in mmWave has increased its lucrativeness in radio communication. Smart integration of UAVs in 5G network needs efficient placement mechanism for providing blazingly fast wireless cellular network services. This fundamental study will facilitate further research in exploring UAV-supported 5G network at unparalleled mmWave frequency band.

Keywords: Unmanned Aerial Systems (UAS), Unnamed Aerial Vehicle (UAV), Communication Resource Management (CRM), Edge Computing at RAN (EC-RAN), Core Network (CN), Customer Quality Experience (CQX), Free-space Optical Communication (FSO), Aerial Network (AN), Key Point indicator (KPI), Fronthaul (FH), Backhaul (BH)

1. Introduction

Radio communication evolved a lot over the past 40 years. In this perspective, access to cellular part will be very dense to support 10 Gbps data transfer rate and 1 millisecond latency of future wireless networks. In this context, mmWave can fulfil the scarcity of bandwidth, and it has been trialled in many cases for access or backhaul communication, but its potential for use simultaneously for both access and backhaul link is still under research and needs to be explored further. Moreover, the other challenges which are not yet answered include the practical issues in the implementation of such scenarios pertinent to fulfilling the cellular mobile industry norms and standards. Use of UAVs in cellular communication has gained a profound interest both from the academia and mobile network organisations.[1,2]

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Modernisation and novelties in UAV research and technology has resulted in unwrapping of new opportunities, especially its unparalleled productivity in deployment of cellular communications by providing coverage, scalability due to line-of-sight (LoS) link, and tractable movement in three-dimensional (3D) space in two most needed scenarios: i) re- establishing communications shortly after a disaster, to ensure lives are not lost and communities move towards an earliest recovery, and ii) enhancing network capacity in sports events, concerts, and high-level inaugurations.[3–5]

In addition to the aviation regulations about the UAVs, the key areas which require in-depth study are UAV channel modelling, UAV deployment, cellular network planning with UAVs, resource management, energy efficiency, and its trajectory optimisation. The super-connected era of 5G, possibly having mmWave, is anticipated to facilitate building of multi-gigabit bandwidth for evolving applications, that is, augmented reality/virtual reality traffic, generation of million minutes of video content per second in 2021, and doubled growth in global mobile data traffic as fixed IP traffic from 2016 to 2021.[6–8] The main transformations brought about in cellular mobile communication by 5G became possible because 5G was developed and implemented by using wider spectrum allocations at tiny Wave frequency bands, higher data rates in larger portions of the coverage area, little outage probability, pencil beam forming antennas at both TX and RX, longer battery life, and lower OPEX/CAPEX costs. The two most promising benefits of mmWave are: i) huge bandwidth availability between 30 and 300 GHz; around 200 times more spectrum as compared to the current cellular network; ii) generation of beam-forming with very high gain due to multiple antenna systems which can offer a transmission range that exceeds by more than 130 m in one direction,[9–11] and in some specific scenarios coverage can reach up to 200m.[12] Nevertheless, the critical challenges of using mmWave in wireless cellular network are propagation loss and sensitivity to blockage, which are highlighted in Figure 1.

This study comprises six sections. Section I is based on Introduction. Section II, Background and Literature Review, highlights the work done and presents an analysis of review of literature on past research studies in this field. Section III discusses the System Architecture. Section IV is focused on link-level performance modelling. Section V describes Propagation Modelling in Ray Tracing

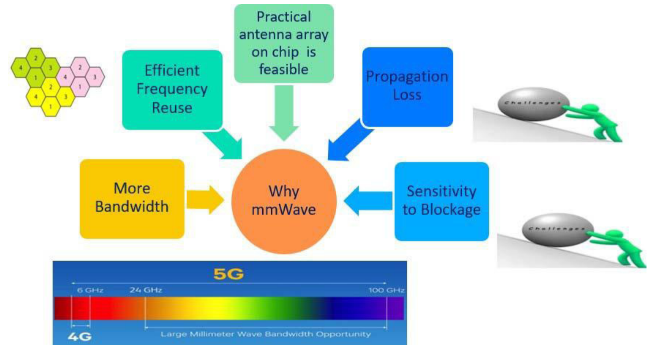

Figure 1. Benefits and challenges in using mmWave.

Simulations. In Section VI, end-to-end equations have been derived for calculating power received by end-user while getting coverage through amplify-and-forward UAV relay. At the end, Section VII concludes the study with discussion.

2. Background and Literature Review

Use of UAV in cellular network is one of the key areas of study both in academia and industry, in terms of its future attractiveness in wireless communication. In,[13] the authors describe the opportunities and challenges of UAVs in wireless communication technologies. First, an overview of UAV-supported wireless communications is presented as summarising the basic networking architecture for three practical scenarios: i) UAV-aided ubiquitous coverage under the overloaded base station (BS) or malfunctioning BS, ii) UAV-BS relaying, and iii) UAV-BS data and information collection. The study also provides an overview of the UAVs' main channel characteristics and design considerations taking into account both UAV–ground and UAV–UAV channel models. Finally, enhancing techniques that utilise the UAVs mobility is also discussed. Results are presented based on simulation under specific system parameters for path loss with static and mobile relaying. Results demonstrate that UAV flies between the TX and RX aiming to reduce the link distances during both UAV information reception and relaying phases (data ferrying or load carrying and delivery). The authors conclude that: i) on-demand UAV systems are more cost-effective and can be much more swiftly deployed; suitable for unexpected or limited-duration missions, ii) short-range Light of Sing (LOS) leads to noticeable performance improvement over direct communication between TX and RX, and iii) UAV-controllable movement opens new opportunities for improving performance. Finally, the authors pointed out that effective resource management for UAV communication systems is needed. In addition, impact of Doppler shift due to high relative velocity of UAV-BS is an open area of study. Even if the study has done a good coverage of the challenges that UAVs communication faced, there are some missing points of this study; for example, using the specific frequency bands of mmWave for UAV–UAV links to be used is not discussed.

In,[14] the bandwidth requirement for future Unmanned Aerial System (UAS) was described. There is also an overview about new predictive models and evolving spectrum sharing technologies for UAS. Initially, the authors highlighted that a UAS communications cell in terms of its 3D shape. As per the authors, cell varies in relation to different flight parameters (speed, height, etc.) and services. Mathematical equations were used to predict numbers of UAVs in order to determine RF spectrum requirements. Results indicate a significant increase in commercial UAVs which are expected to outnumber public agency UAVs, especially for dense urban environments. The authors conclude that: i) UAV growth and RF spectrum are intertwined, that is, huge spectrum is required for a growing number of UAVs, ii) suitability of OFDM sub-carrier frequency spacing is lessening inter-carrier interference (ICI), and iii) priority-based spectrum allocations are possible. Finally, the authors emphasise the need for careful infrastructure planning. However, the missing point in the study which required an in-depth look was the algorithm for spectrum management with UAVs route planning. In,[15] the author outlines resource allocation problem in UAVs networks with a focus on comparison of power consumption and reward. First, the authors present a demand-aware resource allocation mechanism for communication UAV network where a large UAV acts as a relay for a small team of UAVs. The relay UAV will act as a cluster head and is responsible mainly for: i) resource allocation, and ii) centralised management. For results, Stackelberg optimisation and Lagrange multiplier method have been used to find maximum throughput for each UAV. Results indicate that upper hierarchy (Command Centre) will decide the total throughput, for allocating transmission rate to the lower hierarchy based on payment ability. Nevertheless, the missing points in the study which need further exploration are: i) coordination of the current scenario with the existing heterogeneous cellular network and ii) evaluation of Command Centre capabilities.

In,[16] the authors discussed backhaul links reliability problems in wireless balloon networks and the effectiveness of UAVs relay improvement of link reliability (or connectivity). In the beginning, the authors showed that using a few UAVs as relays can enhance connectivity among Wireless Balloon Networks. Mathematical equations have been used to find out the optimal path for UAVs, which will cover link outages. Simulations have been used for UAV utility versus link availability by using three methods: i) optimal algorithm, ii) greedy algorithm, and iii) random selection. Areas needing further research as highlighted in the study include path planning for solar-powered UAVs while keeping in consideration energy constraints. However, analysis of Key Point Indicators (KPIs) for Customer Quality Experience (CQE) indicates the need further for research. In,[17] the authors present an overview on fronthaul and backhaul wireless transport over millimetre wave (mmWave) for 5G with discussion on data rate and latency for fronthaul interfaces. In the beginning, functional split between CU (Centralised Unit) and DU (Distributed Unit) in C-RAN is proposed in three splits: i) PHY-RF split, ii) Intra-PHY split, and iii) PDCP-RLC split. The authors compared data rate and latency requirements for each of the above split options, based on some assumptions such as number of antennas and number of ports. Results demonstrate that higher functional splits required low data rate and reasonably high latency and vice-versa. Moreover, the authors conclude that mmWave-based wireless backhaul/fronthaul solutions are good alternatives in contrast to optical fibre with two possible situations: i) Capped at the frequency 100 GHz including V and E bands where prototypes/commercial-grade products have appeared, ii) Bands above 100 GHz (W and D) are less intense despite their great potentials and need further exploration for real deployment. At the end, the authors pin down the need for an in-depth study and analysis of using W-Band and D-Band which offer total channel bandwidth of 17.85 GHz and 31.8 GHz, respectively. Nonetheless, the missing point in the study is to analyse the area of unifying the transport network of existing and new fronthaul/backhaul traffic into a common-haul SDN/NFV (Software-defined networks and network function virtualisation)-based packet switching network. In,[18] the author discussed the use of millimetre-wave in backhaul and access link in the current cellular network.

At the beginning, the author proposed a concept of a millimetre-wave overlay in heavily populated heterogeneous networks (HetNet), where small cell base stations using millimetre-wave are incorporated into traditional cellular networks, and there is a logical split between control and user plane. The author's main conclusions are:

- splitting user and data plan will result in activating small cells only when needed, on-demand data coverage, which means energy saving too;
- license-free 60 GHz band having 9 GHz of unbroken spectrum having high propagation loss in free space due to oxygen absorption which comforts the interference between neighbourhood connections;
- millimetre-wave outdoor channels RMS delay spread is in the same range as indoor and in-cabin propagation.

Wider bandwidth availability in mmWave has attracted researchers' attention for its use in next-generation wireless networks. Reduced antenna size at the tiny wavelength band has made it even more suitable in terms of lighter weight as payload in aerial communications.[19] In addition to this, multi-stream, multi-beam, and multi-user (MU) communications features are another positive aspect of utilising mmWave band. Till now, there is only limited prior work on mmWave Air-to-Air and Air-to-Ground channel modelling, which are different from terrestrial channels, that is, having lesser path loss exponent and smaller small-scale fading. However, mmWave links constrain UAVs from using high altitude due to its intrinsically high path loss with growing distance from transmitter to receiver, so terrestrial channel models can be applied to mmWave aerial communication as well in scenarios where UAV will be placed at the same height as that of the terrestrial base stations.

3. System Architecture Description

The proposed architecture in this article is depicted in Figure 2; the aerial-terrestrial network is based on the combination of traditional terrestrial base station (BS) communicating with UAV equipped as amplify-and-forward relay (UAV-BS). The backhaul link between BS and UAV-BS is using mmWave link. The UAV-BS is providing coverage to User Equipment (UE) through access to mmWave link as well.

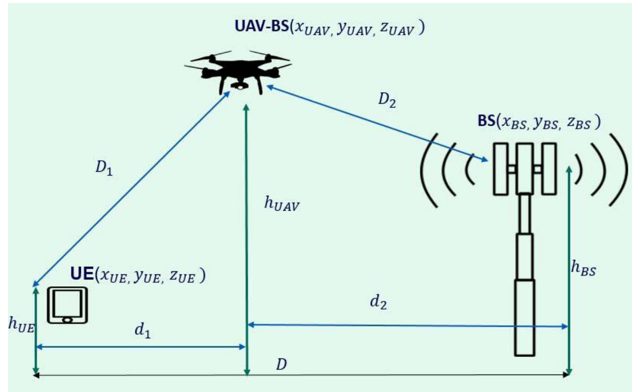

Figure 2. System architecture for aerial-terrestrial networks using mmWave; UAV is used as an amplify-and-forward relay.

Motivated by the adoption of terrestrial channel models for air-to-ground channels of static UAV-BSs, the UAV-BS is deployed as a quasi-stationary aerial BS behaving like orthodox cell tower,[20–22] (hence, Doppler effect is not considered). High-rate mmWave links constrain UAVs from using high altitude due to its intrinsically high path loss with growing distance from transmitter to receiver. Consequently, the altitude of a UAV-BS must be carefully planned. In addition, the intrinsically high path loss feature of mmWave to distance necessitates the optimal deployment of mmWave UAV-BS, taking into consideration the three-dimensional (3D) distance analysis from transmitter to receiver. Isotropic antennas are considered, because standards bodies are typically interested in isotropic or omnidirectional models, particularly for NLOS links, since arbitrary antenna patterns and MIMO processing simulation and analysis are easy to conduct available isotropic antenna models. Unlike the terrestrial BS, UAV-BS can provide a dynamic coverage and now has become more mature in terms of light weight and longer battery life.[23] UAV-BS is deployed as Layer 1 amplify-and-forward relay which can readily be incorporated in a cellular communication system. In an amplify-and-forward relay, signals received from Tx will be relayed (amplified and forwarded) to the respective Rx. This is called repeater or booster, or more specially, an amplify-and-forward relay. One major disadvantage of such relay is that noise will also be amplified with the desired signal. However, the simplicity and inexpensiveness of this relay far outweigh the benefits. System parameter and notations are described in Table 1. AQ4

Table 1. Notation and parameters used for modelling

Description	Parameter	Unit
Unmanned aerial vehicle-BS	UAV-BS	–
User equipment	UE	–
BS Coordinates	(x_{BS}, y_{BS}, z_{BS})	–
UAV-BS coordinates	$(x_{UAV}, y_{UAV}, z_{UAV})$	–
UE coordinates	(x_{UE}, y_{UE}, z_{UE})	–
BS height	h_{UE}	m
UAV-BS height	h_{UAV}	m
UE height	h_{UE}	m
3D distance between BS and UAV-BS	D_2	m
3D distance between UAV-BS and UE	D_1	m
Horizontal distance between base station and UAV-BS	d_2	m
Horizontal distance between UAV-BS and UE	d_1	m
Horizontal distance between BS and UE	D	m
UE received power via direct path	P_{UE-D}	dBm
UE received power via relay path	P_{UE-R}	dBm
UAV received power	P_{UAV-R}	dBm
BS transmitted power	P_{BS}	dBm
UAV transmitted power	P_{UAV-T}	dBm
BS antenna gain	G_{BS}	dBm
UAV-BS antenna gain	G_{UAV-BS}	dBi
UE antenna gain	G_{UE}	dBi
UAV-BS antenna gain	G_{UAV}	dBi
Amplification factor	β	dB

4. LINK-level Performance Modelling

At mmWave frequency band, accurate channel modelling is an important prerequisite for designing an efficient wireless communication network, especially for fostering new techniques that can comply with its propagation characteristics. Broadly, channel model can be divided into two sub-categories:

- Analytical models: These are used for the mathematical analysis of channel.
- Physical models: These are used for exploring the electromagnetic properties of the signal from transmitter to receiver.[24]

Analytical models are either propagation-based or correlation-based, while physical models are either deterministic or stochastic, as illustrated in Figure 3. Also, the propagation-based Friis Transmission Equation is considered for analysis and observations.[6,7]

4.1. Direct Path (BS-UE): Friis Transmission Equation

Mathematical modelling is the backbone in understanding wireless signal propagation characteristics. It is helpful in the optimisation of processing methods; for example, it gives us a recipe as to how to simplify the observed phenomenon and to arrive at a computationally tractable description. Using Friis Transmission Equation, and referring to Figure 4, power received by UE is given by[25]:

$$PUE-D = PBS + GUE + GBS - 20\log_{10}\left(\frac{\lambda}{4\pi D_2}\right) \quad (1)$$

where:

- P_{UE-D} is the UE received power in dBm,
- P_{BS} is the BS transmitted power in dBm,
- G_{BS} is the BS antenna gain,
- G_{UE} is the UE antenna gain,
- λ is wavelength of the transmitted signal in m,
- D is the distance between BS and UAV-BS and it is calculated by distance formula.

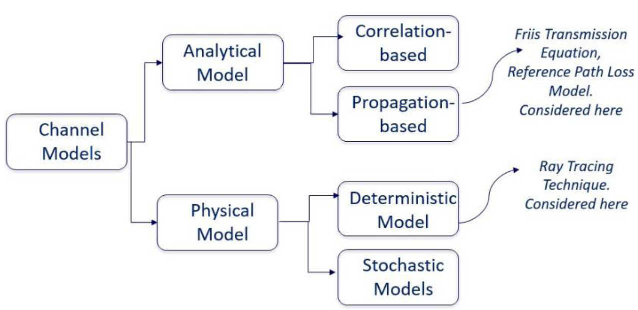

Figure 3. Channel models techniques explored in this article.

Figure 4. Base station to user equipment communication.

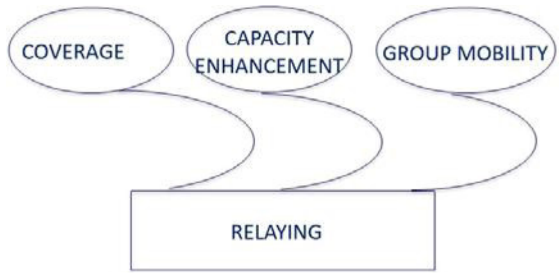

Figure 5. Relaying in cellular networks.

4.2. Relay Path (BS-UAV-UE): Friis Transmission Equation

1) Relaying and Cooperative Diversity Protocols: Relaying is a promising aspect of future wireless networks. 3GPP Release 10/11 (LTE-A) and IEEE 802.16j are visualised in the application cases scenarios, as illustrated in Figure 5.

- **Capacity Enhancement:** UAVs have great potential for augmenting the capacity of cellular networks, that is, to increase data rate, densifying an existing network, and to cope with high traffic demands especially in dense urban areas or special events. Besides the long-range connectivity, multiple UAVs anchorage can facilitate better load balancing and traffic offload.[26]
- **Group Mobility:** The mobility models are application-dependent, for example, aggregating traffic of group users within a high-speed train or bus. Group mobility in mobile networks can cause degradation in network quality because of dynamic changes of network utilisation.
- **Coverage:** To provide UEs signals of an acceptable network acquisition, especially in black or shadowed zones. Cellular connectivity for UAV systems is interesting because it promises coverage beyond the visual line of sight scenarios.
- Different cooperative diversity protocols can be employed in this context. UAVs integration as relay into Next-Generation Wireless Network needs efficient placement of UAVs to enhance overall system efficiency. Broadly, cooperative diversity protocols can be classified into three categories based on the type of processing and requirements by relay and destination terminals, as highlighted in Figure 6.[27]
- **Fixed Relaying:** Relay works as an amplify-and-forward, that is, amplify the received signal subject to their power constraint or decode and forward relay and then re-transmit the signal.[28]

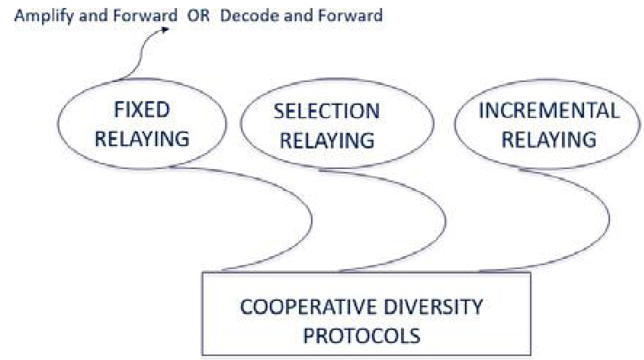

Figure 6. Cooperative diversity protocols.

- **Selection Relaying:** Adaptive strategies are followed. Relay selects a suitable cooperative/no cooperative action based on Signal-to-Noise Ratio (SNR) between the transmitted terminal and the relay.
- **Incremental Relaying:** It enhances spectral efficiency of both selection and fixed relaying by getting limited feedback from the destination terminal and relaying when required.

Using Friis Transmission Equation, and referring to Figure 7, power received by UE is given by[25]:

$$PUE - D = PBS + GUE + GBS - 20\log_{10}\left(\frac{\lambda_2}{4\pi D_2}\right) \quad (1)$$

where:

- P_{UAV-R} is the UAV received power in dBm,
- P_{BS} is the BS transmitted power in dBm,
- G_{UAV} is the UAV-BS antenna gain (assuming same antenna gain at receiving and transmitter side of the UAV),
- G_{BS} is the BS antenna gain,
- λ_2 is wavelength of the transmitted signal in m,
- D_2 is the distance between BS and UAV-BS and it is calculated by distance formula:

$$\text{Let } k_2 = \left(\frac{\lambda 2}{4\Pi D_2}\right)$$

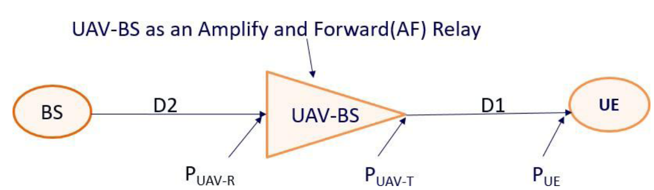

Figure 7. End-to-end representation of the BS-to-UE communication using a relay node.

Then,

$$PUACV-R = PBS + GUAV + GBS - 20\log_{10}\left(\frac{K_2}{D_2}\right) \quad (2)$$

Deploying UAV-BS as amplify-and-forward relay,

$$PUAVT = \beta + PUAV - R \quad (3)$$

where:

- P_{UAV-R} is the UAV received power in dBm
- β is an amplification factor in Db.

Similarly, using Friis Transmission Equation (referring to Figure 7) the power received by UE can be determined as follows:

$$PUE = PUAV + GUE + GUAV + GBS - 20\log_{10}\left(\frac{\lambda_1}{4\pi D_1}\right) \quad (4)$$

where:

- P_{UE} is the UE received power via UAV-BS in dBm,
- P_{UAV-T} is the UAV-BS transmitted power in dBm
- λ_1 is wavelength of the transmitted signal in m,
- D1 is the distance between BS and UAV-BS and it is calculated by distance formula:

Let $K_1 = \left(\frac{\lambda 1}{4\pi D_1}\right)$

$$PUE = PUAV + GUE + GUAV + GBS - 20\log_{10}\left(\frac{K_1}{D_1}\right) \quad (5)$$

Assuming the same antenna gain for the Tx and Rx sides of the UAV and using Eqs. (2), (3), and (5), the received power of the UE via UAV-BS is

$$PUE = \beta + PBS + 2GUAV + GBS + GUE - 20\log_{10}\left(\frac{\lambda 2}{4\pi D_2}\right) - 20\log_{10}\left(\frac{K_1}{D_1}\right) \quad (6)$$

From Eq. (6), the amount of power received by UE depends on three key parameters, in addition to the frequency and antenna gains:

- Distance between BS and UAV-BS (D_2),
- Distance between UAV-BS and UE (D_1), and
- Scaling factor (β).

5. Propagation Modelling in Ray Tracing Simulations

In this section, the setup of mmWave channel propagation simulation is described. Simulations are performed under different urban environments using Wireless In-Site Ray-Tracing simulator. Ray-tracing simulations provide an avenue for harvesting novel technologies. Wireless InSite's unique collection of features simplifies the analysis of complex and massive propagation problems. It has features such as X3D propagation model, diffuse scattering, MIMO beam forming, spatial multiplexing, and full communication systems analysis. Moreover, it offers the suite of empirical propagation models which are designed for urban and indoor analysis, as depicted in Figure 8.[29]

5.1. Dominant Propagation Paths

In order to explore the channel model of the UAV-BS to UE, we conducted a set of simulations. The scenario of our simulation is a semi-dense urban area for UAV-BS at the typical height of 100 m, and UEs at a height of 1.5 m in 300 m * 300 m area, for around 3,600 receiving points. Furthermore, UAV-BS was considered as stationary to lessen channel variations to help save battery and increase flight time. More reflected and diffracted paths validate the characteristics of mmWave as an excellent reflector of building materials, with the reflection coefficient as large as 0.896 for tinted glass.[30] The rest of parameters are used as described in Table 2. Interestingly as observed in Figure 9, only 2% is among the dominant propagation.

Paths (potential communication channels) reaching to the receiver points were **direct paths (LOS)**. Highest number of paths belong to **both diffracted and reflected paths**, followed by **diffracted-only paths**, and **reflected-only paths**. In addition, upon analysis of 25 propagation

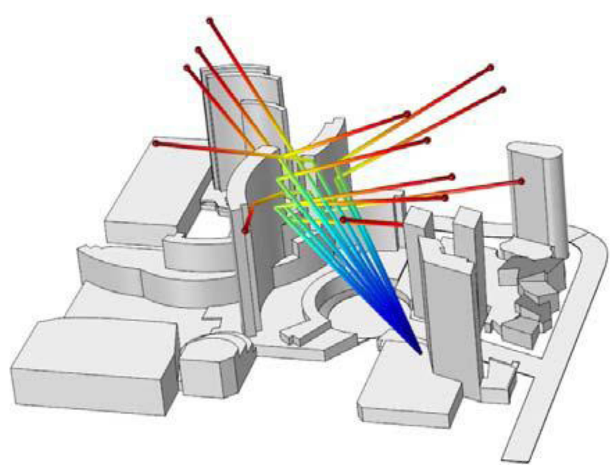

Figure 8. Example of wireless in-site ray-tracing simulator propagation paths: BS communicating with UAV-BS and UAV-BS providing coverage to ground UEs.

Table 2. Simulation parameter

Parameter	Value
Frequency	28 GHz
Antenna gain	0 dB (Isotropic)
Channel model	Free
Space number of reflection	0
Number of transmissions	0
Number of diffractions	0
Transmit power	43 dBm
Number of UEs	500

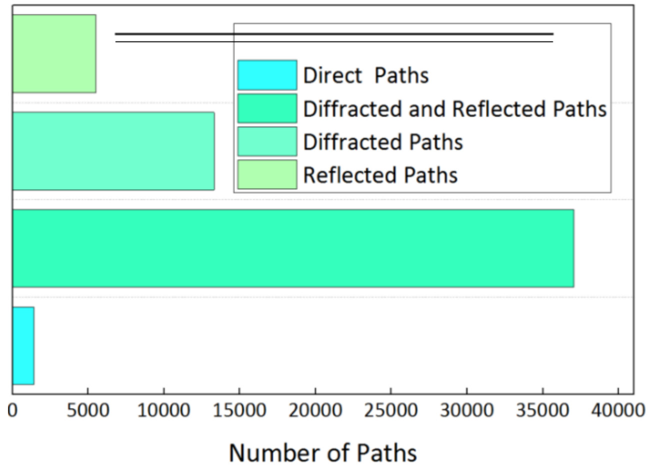

Figure 9. Propagating paths distribution.

paths at a certain receiving point, the results suggest that some paths arrived late, having more path length and high signal strength. For example, in Figure 10, propagation path at point B has a high Time of Arrival (ToA), increased path length, and good signal strength, as compared to point A. Same observations are noticeable for point D and C as well. In contrast to terrestrial BS, UAV-BS has more focused LOS paths with the ground users, lesser reflected, scattered, and diffracted paths, specifically around the UAV-BS, and in the terrain as well.

In,[31] the author deduced an analytical result for the optimal height of UAV-BS and describes the effect of blockers (human body) and its impact on the desired height, coverage radius, and the number of served users. However, from our results, we observed that for ground users, even in the case of UAV-BS, LOS or direct path is not the main source of best signals.

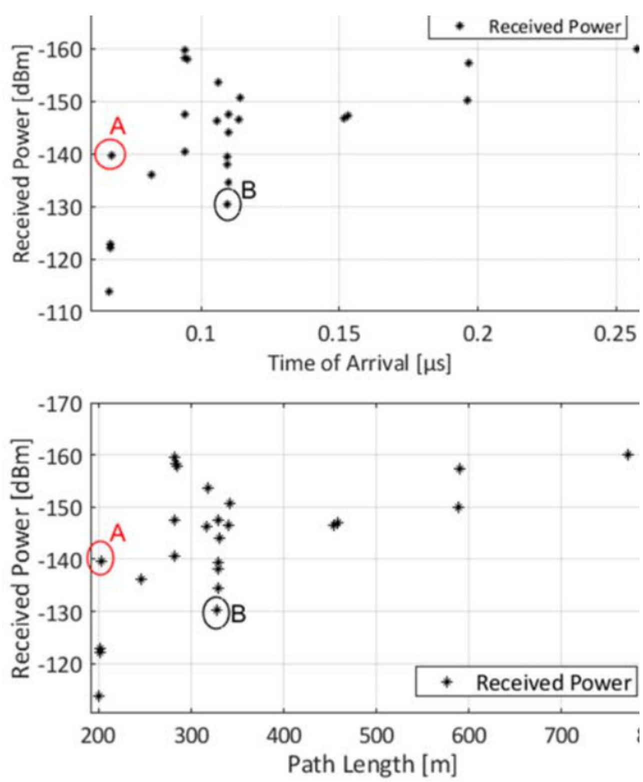

Figure 10. Received power versus time of arrival and path length.

6. Conclusion and Discussions

Modelling and Ray-Tracing Simulation capture in-depth details of polarisation and multipath propagation, permitting assessment of how the environment and the placement of communication nodes impact system performance. It can provide novel methodologies for assessing designs and planning within realistic virtual environments. The goal of the study was to evaluate mmWave in access and backhaul network simultaneously for UAV-BS. End-to-end equations have been derived for calculating received power by the end-user while getting coverage through amplify-and-forward UAV relay. Using ray tracing simulator, effectiveness of diffracted, reflected, and scattered paths versus direct paths has been shown in tiny-wavelength frequency band. The prominence of NLOS signals for ground UEs was underlined. This study will facilitate further research about UAV-supported 5G network at unparalleled mmWave frequency bands.

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