Link Budgeting and Interference Management for UAV Networks in 5G and Beyond

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ABSTRACT

UAVs have been studied and manufactured to help create wireless communications networks that are more flexible and cost-effective than a typical wireless network. These UAV networks could help bridge the digital divide in rural America by providing wireless communications service to areas where cell companies find it too expensive to build conventional cell towers. To test different aspects of a UAV based millimeter-wave frequency network, we created a MATLAB simulation. The simulation visualizes a digital twin of a farm in eastern Nebraska where UAVs are tested. The simulation allows for link budgeting and interference management calculations by accommodating changes in transmitter and receiver location, frequency of the network, power of the transmitted signal, weather conditions, and antenna specifications. The simulation is able to calculate critical network values such as signal-to-interference-plus-noise ratio (SINR), path loss, atmospheric loss, and antenna gains under dynamically changing conditions.

CCS CONCEPTS

• **Networks** → **Network simulations**.

KEYWORDS

unmanned aerial vehicles, millimeter-wave communications, terahertz communications, link budget, interference management, network simulations, 5G

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1 INTRODUCTION

Unmanned aerial vehicles (UAVs) have several practical applications in wireless communications. During a wildfire, UAVs can be used to transmit thermal images and videos [11]. In rural, mountainous, or shadowed areas, UAVs can be used in lieu of fixed base station towers to transmit cellular signals for better line-of-sight (LOS) communications and higher flexibility [9]. In congested areas, such as stadiums, they can serve as hot spots [20]. More specifically, UAVs can be used to transmit data at millimeter-wave (mmWave) (28 GHz–100 GHz) and terahertz (100 GHz–10 THz) frequencies consistently and reliably in 5G networks and beyond [2]. However, one major problem that using UAVs in a cellular network presents is that they need to be built in a manner that allows a strong enough signal to reach receivers while limiting interference and energy consumption. The antenna design, channel modeling, exact frequency of transmission, and other factors significantly affect the strength of an outgoing signal [16, 21]. These factors are considered in a process known as link budgeting [13], which measures all gains and losses in a wireless propagation channel from the energy of a signal emitted by a transmitter until the signal's final reception by the receiver. While a signal strong enough to be received is necessary, a signal that is too strong will cause that signal to be received by more than one receiver in the network. The balance between creating a strong enough signal but not too strong of a signal is interference management [17].

In this paper, we present a MATLAB simulation platform we have created during the Summer 2023 REU program to demonstrate link budgeting and interference management of a 5G UAV network in unique circumstances. In particular, we emulate a realistic wireless communication environment at different mmWave and terahertz frequencies up to 350 GHz that takes into account various practical weather conditions and study the impacts of these factors on link quality.

The rest of the paper is organized as follows: the foundations and related work are presented in Sec. 2. The methods and details of the simulation based on the Eastern Nebraska Research, Extension, and Education Center (ENREEC) farm are discussed in Sec. 3, which also include formulas used to create calculations within the simulation. The results and analyses are presented in Sec. 4. Finally, the conclusion is drawn in Sec. 5.

2 FOUNDATIONS AND RELATED WORK

2.1 Foundations of UAV Networks

In a typical wireless communications network, there is a base station such as a cell tower, and receivers such as phones connected to the network via cellular signals. These signals are directed at specific receivers when a receiver requests information. In Figure 1, a visualization of a typical wireless network is shown with the base station in red, a receiver in green with signal from the base station propagating towards it, and other receivers in black. The whole network is contained within the blue oval.

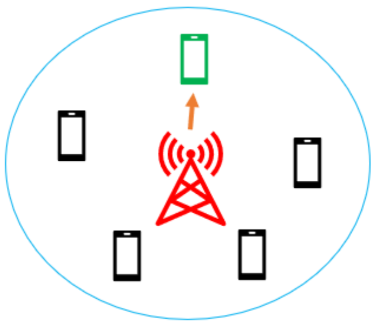

Figure 1: Cell Tower Based 5G Wireless Communications Network

Using a UAV in place of a base station creates a potentially flexible and cost-efficient means for wireless communications in areas with insufficient communications infrastructure [9]. This comes with a host of opportunities and challenges. One of the main differences between a UAV-based network and a typical base station network is that the UAV can move around freely [18]. One advantage of this is having more frequent line-of-sight (LOS) communications, especially in rural areas. Another potential advantage of a UAV network is using multiple UAVs allows the network to be reconfigured in real-time [5, 6]. A disadvantage is the UAV's limited resources, which require careful path planning while considering its total energy for the duration of the flight. This is also known as energy-efficient communication [10].

There are several ways for the UAV to minimize signal losses while conserving energy that would not be possible for a typical base station. UAV-enabled mobile relaying requires the UAV to stay in an optimal position and/or move continuously between users to minimize the distance a signal has to travel. In this scenario, when considering link budgeting, path loss is directly proportional to distance and frequency [21], and improved UAV positioning minimizes distance from mobile relaying and therefore reduces losses [14]. Another way to reduce losses is to have all data transmitted and received from users to a single user closest to the UAV [9].

These loss reduction techniques are more critical in mmWave frequencies because the path loss is greater in the mmWave spectrum than in a network utilizing lower frequencies [21]. However, mmWave frequencies provide abundant bandwidth resources that can support high throughput links, and frequency bands are regulated and not freely available in lower frequency cellular networks [4].

2.2 Simulating UAV Networks

One common way to simulate mmWave signal propagation necessary for link budget and interference management calculations is through a ray tracing simulation. This simulation technique involves creating a virtual world to see scattering and loss effects based on the waves' path from transmitter to receiver [9]. In [9], researchers conduct a quantitative comparison between UAV networks with a 28 GHz frequency signal to a 60 GHz frequency signal using a ray tracing simulation. Then, they draw conclusions about the different frequencies' received signal strength and root mean squared delay spread in urban, suburban, and rural areas.

It is also possible to simulate partial aspects of link budgeting or interference. For example, in [3], different possible antenna designs such as a monopole antenna array design and a stacked microstrip antenna array design are simulated to test their gains and efficiency. Depending on the type of link budget, antenna simulations can help determine simulated gains. Many types of losses, including path loss, can be simulated through mathematical modeling [21]. From this information, appropriate antennas and loss models can be chosen to create a simulation that will be as close to the real world as possible. These simulations can make it much easier to be certain the network will maintain an appropriately strong received signal necessary for good link budgeting and interference management.

3 METHODS AND SIMULATIONS

3.1 The RuralProp Simulator

The RuralProp simulator was created in MATLAB as a digital twin to the ENREEC farm in eastern Nebraska where the Nebraska Intelligent MoBile Unmanned Systems (NIMBUS) Lab at the University of Nebraska-Lincoln tests their drones. The farm is approximately 100 meters by 100 meters. The simulator models the farm with poles 1/2 meter in diameter at each corner, storage rooms below each of these poles, and a crop field growing in an "L" shape generally towards the center of the farm. As shown in Figure 2, the RuralProp simulation with the entire visualization of the ENREEC farm and the plots produced from link budgeting and interference calculations is presented. In the simulation, the UAV position is shown in blue while the receivers' positions are shown in red. The ENREEC farm visualization is contained on the left side of Figure 2 with the control panel for the simulation shown in the top-right corner and the dynamic plots shown in the bottom-right corner.

In Figure 3, the control panel for the simulation is shown zoomed in. The control panel allows for locations of the UAV and receivers, weather conditions, frequency of the network, exact value of the transmitted power of the UAV, and height of the corn crop to be altered dynamically. In Figure 4, dynamic results produced in a test run of the simulation are shown. Four plots, including the power received, path loss, SINR values of each receiver, and the altitude of the UAV are displayed. The changes within the simulation that occur when results are being created include changes in UAV and receiver locations, frequency of the network, the number of receivers, and the weather conditions. In this particular instance, only locations of the UAV and receivers change over the time dynamic results were created. However, there are other dynamic changes possible such as differences in atmospheric loss from a weather condition change.

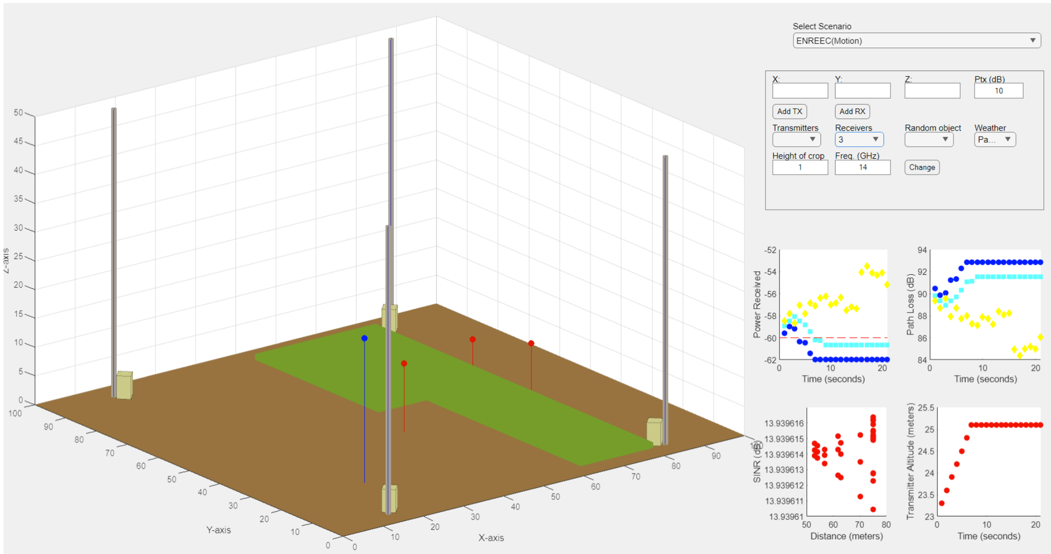

Figure 2: Full RuralProp Simulation

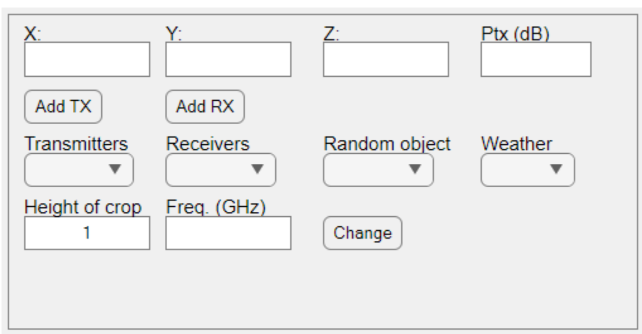

Figure 3: Control Panel for the RuralProp Simulation

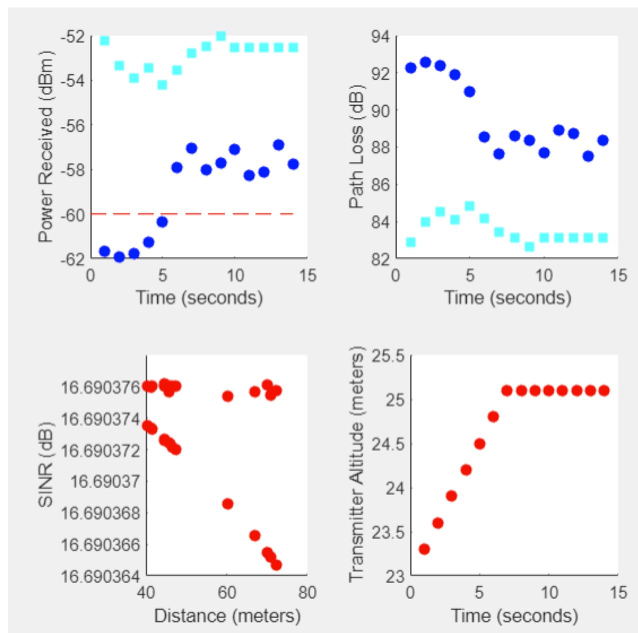

Figure 4: RuralProp Simulation Dynamic Link Budget and SINR Output

These are not shown directly by a specific plot but can be inferred from the four plots' results.

3.2 Link Budgeting

Link budget design is a critical process for the successful implementation of a UAV network. The methods used in the RuralProp simulator for link budgeting calculations are outlined below. Since the simulator is modeling rural, flat areas of Nebraska, the link budget calculations are valid when there is always line-of-sight (LOS) communication [16].

At the most basic level, wireless communications are made possible through a transmitter antenna transmitting a signal strong enough for the receiver antenna to pick it up. However, there are gains and losses between the transmitted signal's initial power and its received power. These gains and losses make up the link budget which ensures that based on a set transmitter power, the receiver antenna will pick up a signal. In mathematical terms, to meet the strength requirement for the signal to be received:

$$P_R \geq P_{\mathrm{MIN}}, \tag{1}$$

where P_R is the power received and P_{MIN} is the minimum power. The difference between the received and minimum powers, also known as the link margin (M), is calculated as [7]:

$$M = P_R - P_{\mathrm{MIN}}. \tag{2}$$

The formula for calculating received power in the overall link budget is [16]:

$$P_R = P_T + G_T + G_R - FSPL - L_{\mathrm{ATM}} - L_{\mathrm{OTHER}}. \tag{3}$$

Table 1: Explanation of parameters in link budget with approximate values

Symbol	Link Parameter	Approx. Value
P_R	Power received	-85 dBm
P_T	Power transmitted	30 dBm
G_T	Gain of trans. antenna	10 dBi
G_R	Gain of rec. antenna	5 dBi
$FSPL$	Free space path loss	120 dB
L_{ATM}	Atmospheric losses	5 dB
L_{OTHER}	Other losses	5 dB

Depending the if the strength requirement is met and what the link margin is, certain parameters can be altered to produce more or less signal based on what is needed. The parameters for Equation 3 are defined in Table 1 [19]. The approximate values in the table are gathered from a combination of a link budget created in [1] and results in this paper for atmospheric loss.

During a typical link budget calculation, some of these parameters are considered fixed in order to calculate received power. For example, in the RuralProp simulation, the power transmitted can be considered a constant. However, power received, path loss, and atmospheric loss are always variables in the RuralProp simulation. In some specific cases, there are several different ways to budget. If a network has a goal of a certain received power, it is possible to work backwards with a constant received power to find the necessary gains or losses. For example, if an antenna needs to be designed to give a certain amount of gain based on the calculated losses and the constant transmitted and received power, the link budget equation can be manipulated to accommodate this. In the RuralProp simulation, the link budgeting is based on the typical case where parameters can be changed in order to calculate a resulting received power.

3.2.1 Transmitted Power and Minimum Received Power Needed. Transmitted power (P_T) and minimum received power needed (P_{MIN}) are values essential to link budgeting [19]. For the purposes of the RuralProp simulation, they are set to arbitrary testing constants of P_T = 10 dB and P_{MIN} = -60 dB. However, they can easily be modified based on the kind of UAV and receivers that are being served within the network.

3.2.2 Antenna gains. Antenna gains are an important aspect of UAV network link budgeting [3]. In the RuralProp simulation, the antenna gains for both transmitter and receiver are assigned constant values. Typically, antennas are manufactured with the values of these gains readily available. The values in the simulation cannot be changed directly through the simulation but could be modified within the code.

3.2.3 Free space path loss. The free space path loss of the RuralProp simulator is calculated using the Friis transmission equation, a standard equation for calculating path loss [21]. The equation is

$$\mathrm{FSPL} = 20\log_{10}(4\pi f d/c), \tag{4}$$

where d is distance, indicating the path loss is a function of distance. This is constantly updated as the UAV and receivers dynamically move locations within the bounds of the simulator.

3.2.4 Weather conditions. Various weather conditions with differences in rain, clouds, and water vapor create significant change in atmospheric losses. In the RuralProp simulation, a few different weather conditions were taken into account. Six possible states of weather with clear differences in rain, clouds, and water vapor (sunny, partly cloudy, overcast, light rain, moderate rain, and t-storm) were coded into the simulation. Based on the average conditions of each state, specific values were passed into calls to MATLAB functions *gaspl()*, *rainpl()*, and *fogpl()* for atmospheric loss calculations using the ITU standard models [15].

3.2.5 Other Losses. Other losses are not modifiable within the simulation, but they are set to values that make sense for a rural farm in Nebraska and the equipment that might be used by the NIMBUS lab in the future. It can be changed within the MATLAB code if necessary. Other losses include transmitter and receiver feeder cable loss, antenna off axis loss, radome loss, polarization mismatch loss, pointing loss, implementation loss, and miscellaneous loss [19]. These were set to constant values during the initial simulation, but could be changed to make a precise calculation if necessary for specific hardware.

3.3 Interference Management

To maintain a reliable connection between the base station and a user, the interference that occurs in the UAV network must be mitigated. To do this, various methods such as beamforming and maximum ratio combining have been developed [8]. These methods aim to limit the amount of interference, thus creating a reliable connection. The interference mitigation methods that were used in the RuralProp simulation are outlined below.

3.3.1 Signal-to-Interference-Plus-Noise Ratio (SINR). The SINR is one of the most important metrics for determining interference [3]. By maximizing this value, one can determine that amount of interference that occurs between transmitters and receivers. This statistic is powerful for determining which user has the best connection to the UAV, thus allowing the UAV to focus its signal on that user. Scatterers and other user are key factors to the optimization of the SINR. Other users operating on the same frequency can cause path loss by creating interfering signals. SINR is calculated with the following equation:

$$\mathrm{SINR} = \frac{P_R}{\sum_{i=1}^{n} P_{\mathrm{I,\,i}} + P_N}, \tag{5}$$

where P_R is the received power of the intended user, $P_{I,i}$ is the interference power from the i-th user among all N users, and P_N is the noise power. In the RuralProp simulation, a selection combining algorithm aimed to determine the relationship between distance and SINR.

3.3.2 Beamforming. UAVs tend to be limited in their ability to deliver high-speed communication with a strong signal while achieving low interference. To combat this problem, a technique known as beamforming has been developed. By using beamforming, the UAV is able to determine the direction of a strong transmission and direct its signal to the desired direction, thus maximizing the SINR [9]. This technique allows a drone to achieve wider ranges of transmission with lower interference. They have the ability to direct the signal into a set direction to enhance the signal to a user [11]. This helps decrease interference in terrestrial areas by providing a more direct route to a user, eliminating much of the unwanted path loss.

3.3.3 Maximum Ratio Combining (MRC). The use of multiple antenna receivers has seen growing impacts on the SINR. The use of multiple antennas as also been explored in multiple-ratio combining (MRC) and selection combining algorithms. The MRC model tends to outperform the selection combining model because it has diversity gain [12]. It combines multiple received signals, each with various levels of independent fading, which improves the overall reliability of the model. As long as the model has appropriate weights, it tends to outperform the selection combining model and produces the optimal SINR value [3].

4 RESULTS

The RuralProp simulator incorporates several challenges into one solution. In the simulation, link budgeting and interference management coexist. It also can handle several potential types of networks. For example, mmWave frequency 5G networks can be modeled, but so could a theoretical 6G network with higher frequencies (up to 350 GHz with precise accuracy and 1000 GHz with a bit lower accuracy). The simulation also has flexibility when determining the movement the UAV and users need to make. The code could be modified for any algorithm necessary. This simulator is unique in its ability to be able to adapt to different kinds of networks, environments, and movements.

4.1 Weather Impact on Link Budgeting

A plot of the losses for the different weather conditions at a signal carry length of 100 meters and a temperature of 15 °C within a range of 10 to 350 GHz frequencies is shown in Figure 5. The plot shows that over the range of frequencies, as expected, rainier and cloudier conditions cause more signal loss. It also shows that certain frequencies tend to have more loss than others regardless of rain and clouds. The peaks and valleys in Figure 5 show frequencies that may be less and more viable transmission windows respectively. For example, around 60 GHz is shown in the plot to be a undesirable frequency but the spectrum between 70 GHz to somewhere around 170 GHz would be potentially better frequencies to use. These peaks and valleys exist because of fluctuations in losses within the standard ITU model depending on various factors including frequency [15].

Despite the several-decibel difference overall weather conditions can make as seen in Figure 5, temperature was shown to be a negligible factor in weather-based losses within the margin of -5 °C to 35 °C. Table 2 shows evidence of this trend for a 100 GHz frequency at a pressure of 971 hPa (the pressure at Lincoln, NE elevation) under the different weather conditions.

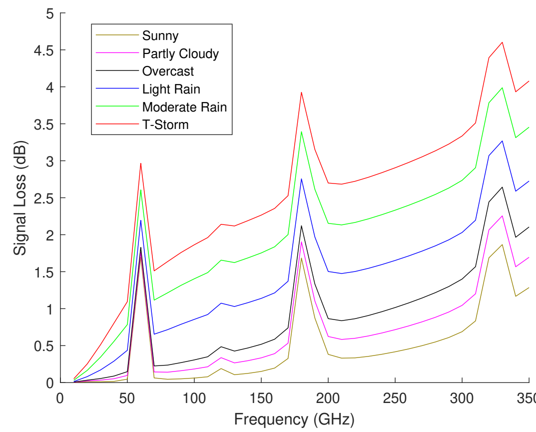

Figure 5: Weather Condition Losses vs. Frequency

Table 2: Difference in weather condition based atmospheric losses at -5 °C vs. 35 °C at 100 GHz

Weather	Loss at -5 °C	Loss at 35 °C	Diff.
Sunny	0.062 dB	0.041 dB	0.021 dB
Partly Cloudy	0.184 dB	0.128 dB	0.056 dB
Overcast	0.307 dB	0.215 dB	0.092 dB
Light Rain	0.855 dB	0.763 dB	0.092 dB
Moderate Rain	1.404 dB	1.291 dB	0.113 dB
T-Storm	1.864 dB	1.729 dB	0.115 dB

4.2 SINR vs. Distance Relationship

A plot of the relationship between SINR and distance among 20 receivers is shown in Figure 6. This predictive model of static receivers shows the relationship between SINR and distance. An inverse relationship, meaning that as distance increased, SINR decreased, was determined.

In Figure 7, we detected the same relationship between SINR and distance in the RuralProp simulation. As the receiver strayed further from the UAV, the SINR increased. Due to the inability to perform field tests, the comparison between static and dynamic results was important in determining how accurate our model was. Future studies will implement the beamforming algorithm into our dynamic simulation to determine the impact on the SINR trend. We would expect the SINR would decrease at a slower rate with the beamforming algorithm.

5 CONCLUSION

Link budgeting and interference management are two key components to any wireless communications network. The RuralProp

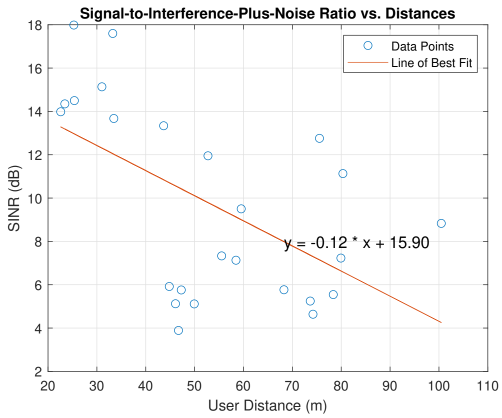

Figure 6: Expected Theoretical SINR vs. Distance

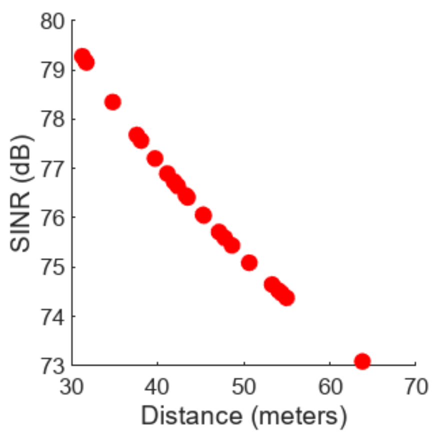

Figure 7: RuralProp Simulation SINR vs. Distance

simulation was designed to specifically test link budgeting and interference within a mmWave frequency UAV network. Using the RuralProp simulation, differences in transmitted power, antenna gains, locations of the UAV and receivers, and weather conditions along with applications of beamforming and maximum ratio combining can be assessed. We produced results showing atmospheric loss due to weather conditions in addition to the relationship between SINR and distance. Since the RuralProp simulation was designed as a digital twin to the ENREEC farm, results could be directly compared to real-world experiments at the actual ENREEC farm. These results will be valuable when planning and building future UAV networks in rural areas that could one day help bridge the digital divide in rural America.

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REFERENCES

[1] Tomohiro Akiyoshi, Eiji Okamoto, Hiroyuki Tsuji, and Amane Miura. 2017. Performance improvement of satellite/terrestrial integrated mobile communication system using unmanned aerial vehicle cooperative communications. 417–422. https://doi.org/10.1109/ICOIN.2017.7899525

[2] Yurui Cao, Sai Xu, Jiajia Liu, and Nei Kato. 2022. Toward smart and secure V2X communication in 5G and beyond: A UAV-enabled aerial intelligent reflecting surface solution. *IEEE Vehicular Technology Magazine* 17, 1 (2022), 66–73.

[3] Andreia Costa, Ricardo Goncalves, Pedro Pinho, and Nuno Borges Carvalho. 2017. Design of UAV and ground station antennas for communications link budget improvement. In *2017 IEEE International Symposium on Antennas and Propagation & USNC/URSI National Radio Science Meeting*. IEEE, San Diego, CA, 2627–2628. https://doi.org/10.1109/APUSNCURSINRSM.2017.8073356

[4] Z. Feng, L. Ji, Q. Zhang, and W. Li. 2019. Spectrum Management for MmWave Enabled UAV Swarm Networks: Challenges and Opportunities. In *IEEE Communications Magazine, vol. 57, no. 1*. IEEE, 146–153. https://doi.org/10.1109/MCOM.2018.1800087

[5] Chandima Fernando, Carrick Detweiler, and Justin Bradley. 2018. Co-Regulating Communication for Asynchronous Information Consensus. In *2018 IEEE Conference on Decision and Control (CDC)*. 6994–7001. https://doi.org/10.1109/CDC.2018.8619787

[6] Chandima Fernando, Carrick Detweiler, and Justin Bradley. 2019. Co-Regulated Consensus of Cyber-Physical Resources in Multi-Agent Unmanned Aircraft Systems. In *Electronics 2019*, Vol. 8. https://doi.org/10.3390/electronics8050569

[7] Sean Victor Hum. 2018. *Link Budget and Fade Margin*. https://www.waves.utoronto.ca/prof/svhum/ece422/notes/22-linkbudget.pdf

[8] Tomasz Izydorczyk, Mădălina Bucur, Fernando M. L. Tavares, Gilberto Berardinelli, and Preben Mogensen. 2018. Experimental Evaluation of Multi-Antenna Receivers for UAV Communication in Live LTE Networks. In *2018 IEEE Globecom Workshops (GC Wkshps)*. 1–6. https://doi.org/10.1109/GLOCOMW.2018.8644068

[9] W. Khawaja, O. Ozdemir, and I. Guvenc. 2017. UAV Air-to-Ground Channel Characterization for mmWave Systems. In *2017 IEEE 86th Vehicular Technology Conference (VTC-Fall)*. IEEE, Toronto, ON, 1–5. https://doi.org/10.1109/VTCFall.2017.8288376

[10] Babatunji et al. Omoniwa. 2022. Optimizing Energy Efficiency in UAV-Assisted Networks Using Deep Reinforcement Learning. In *IEEE Wireless Communications Letters (Volume: 11, Issue: 8)*. IEEE, 1590–1594. https://doi.org/10.1109/LWC.2022.3167568

[11] Jorge A Pardo, Wilbert G Aguilar, and Theofilos Toulkeridis. 2017. Wireless communication system for the transmission of thermal images from a UAV. In *2017 CHILEAN Conference on Electrical, Electronics Engineering, Information and Communication Technologies (CHILECON)*. CHILECON, Pucon, Chile, 1–5. https://doi.org/10.1109/CHILECON.2017.8229690

[12] S. Roy and P. Fortier. 2004. Maximal-ratio combining architectures and performance with channel estimation based on a training sequence. In *IEEE Transactions on Wireless Communications (Volume: 3, Issue: 4)*. IEEE, 1154–1164. https://doi.org/10.1109/TWC.2004.828022

[13] Campbell Sci. 2016. *Link Budget and Fade Margin*. s.campbellsci.com/documents/us/technical-papers/link-budget.pdf

[14] Yuhan Su, Minghui LiWang, Seyyedali Hosseinalipour, Lianfen Huang, and Huaiyu Dai. 2021. Optimal Position Planning of UAV Relays in UAV-assisted Vehicular Networks. In *ICC 2021 - IEEE International Conference on Communications*. IEEE, 1–6. https://doi.org/10.1109/ICC42927.2021.9500796

[15] International Telecommunications Union. 2022. *P.676 Attenuation by Atmospheric Gases and Related Effects*. https://www.itu.int/rec/R-REC-P.676-13-202208-I/en

[16] P. Usai, F. Molesti, and A. Monorchio. 2022. An Accurate Link Budget Estimation of UAV Considering the Degradation of Antenna Patterns. In *2022 IEEE International Symposium on Antennas and Propagation and USNC-URSI Radio Science Meeting (AP-S/URSI)*. IEEE, Denver, CO, 301–302. https://doi.org/10.1109/AP-S/USNC-URSI47032.2022.9887067

[17] Venugopal V. Veeravalli and Aly El Gamal. 2018. *Interference Management in Wireless Networks*. Cambridge University Press. https://doi.org/10.1017/9781316691410

[18] Z. Xiao, P. Xia, and X. Xia. 2016. Enabling UAV cellular with millimeter-wave communication: potentials and approaches. In *IEEE Communications Magazine, vol. 54, no. 5*. IEEE, 66–73. https://doi.org/10.1109/MCOM.2016.7470937

[19] C. Yan, L. Fu, J. Zhang, and J. Wang. 2019. A Comprehensive Survey on UAV Communication Channel Modeling. In *IEEE Access, vol. 7*. IEEE, 107769–107792. https://doi.org/10.1109/ACCESS.2019.2933173

[20] Yong Zeng, Rui Zhang, and Teng Joon Lim. 2016. Wireless communications with unmanned aerial vehicles: Opportunities and challenges. *IEEE Communications magazine* 54, 5 (2016), 36–42.

[21] Lai Zhou, He Ma, Zhi Yang, Shidong Zhou, and Wei Zhang. 2020. Unmanned aerial vehicle communications: Path-loss modeling and evaluation. *IEEE Vehicular Technology Magazine* 15, 2 (2020), 121–128.