Unmanned Aerial Vehicle (UAV) & Mobile to Cell Tower Communication via Intelligent Reflecting Surface (IRS)/Cell Tower Relay Network Large Scale Wireless System Python Simulation Software Program for 6G Research Documentation

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I. Introduction:

Unmanned Aerial Vehicles (UAVs) are expected to greatly impact many technology driven industries in the future, such as surveillance [1], environment monitoring [2], and especially, shipping [3]. UAVs are also expected to be the core technology in next generation wireless communication system, specifically in 6G, as their unique capabilities like mobility and the ability to reach to the height of up to 300 m will allow wider ground coverage and provide better Line of Sight (LOS) for energy & spectrum efficient UAV-ground and UAV-UAV communication [4,5].
Metasurface is a form of passive exotic material which has many unique abilities, like being able to adjust the phase & the wavelength of the incoming signal, and control the power as well as the angle of the reflecting signal [6]. Intelligent Reflecting Surface (IRS) is a technology that is built on metasurface, where the unique functionalities specified above can be controlled via an Internet of Things (IoT) connected software and hardware [7]. IRSs are predicted to solve some of the most important problems facing in Wireless Networks today, including energy consumption [8], which will become even more critical as there will be a mass demand for connectivity in the nearer future due to the increasing deployment of technologies like IoT devices [9]. One example can be shown in Figure 1. Figure 1 L) shows a regular radio environment; since the electromagnetic waves obey the law of reflection, which states that the incident angle is equal to the reflecting angle, the most energy efficient path for the transmitted signal would be to interact & reflect from the walls 2 times before reaching the receiver. In a smart radio environment setting, shown in Figure 1 R), the IRS installed on the wall can use its abilities of conserving the full energy of the incoming signal & of reflecting the signal at an angle different than the incoming angle, to make it possible for the signal to reach the receiver with only one reflection & without any energy dissipation during the reflection. There are many more complex systems that consume energy [8], for example the Cell Tower relay network, which reproduces the signals at every relay node. The energy consumption in relay network can be reduced by replacing the Cell Tower relay nodes with IRSs, which will simply reflect the signals instead of reproducing the signals before sending it to the next node every time.

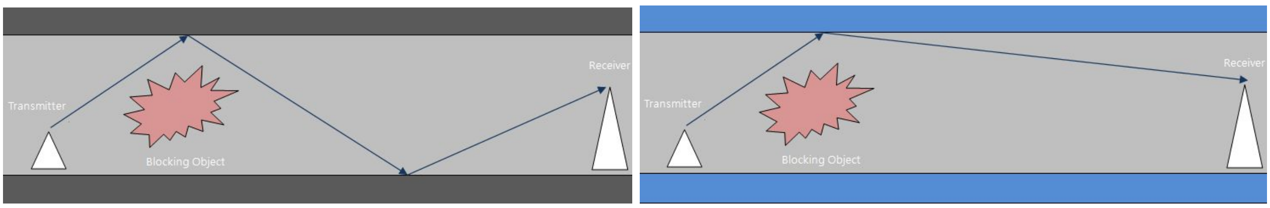

Figure 1. L: Environment without IRS on the walls. R: Environment with IRS installed on the walls

Over the past few months, there have been many studies that show the improvement in Signal to Noise Ratio (SNR) & received power at the receiver through the deployment of UAVs and IRSs, like this publication [10], where their team successfully demonstrated the practicability of the idea of using ground-based IRS for UAV-ground communication. Although these studies showed positive results, most of them did not account for the interference signals coming from the transmitters in the adjacent cells, and thus the Signal to Interference and Noise Ratio (SINR). We decided to develop a more realistic UAV, IRS, as well as IRS & UAV integrated communication simulation program by considering the presence of multiple Cell Towers, Mobile Users, UAV-Transmitters and ground-based IRSs in a set of cells, and observe how the SINR values vary with different values of the simulation parameters in order to formulate important optimization problems which will need to be further considered in the future.

II. Objective:

The objective of this simulation program is to accurately determine the SINR Outage Probability graph at each of the Cell Towers given various transmitters and IRSs in a given map, and compare how they change with different number, locations, and other relevant information of the transmitters and the IRSs, such as the different transmitting power, different number of active IRS elements in each IRS path, etc.

III. Algorithm Brief Overview:

I) Simulation Map

1) Grid System

The simulation map will be built on top of a 2-dimensional grid system, as shown in Figure 2. The main reason for using a grid system is because (as further explained in page 5) for the functionality where the User has the option to pull random locations of the IRSs through a probability distribution, having to work with finite number of location points gives the User the flexibility to balance between the accuracy and the computational cost of this process; the distance between the grid points can be reduced to increase the number of points in the selection set which leads to more accurate random selection of the IRS locations but slower computation, or the distance between the grid points can be increased to decrease the number of points in the selection set which leads to less accurate random selection of the IRS locations but faster computation. The User will specify the length & width of the grid, as well as the the distance between each point.

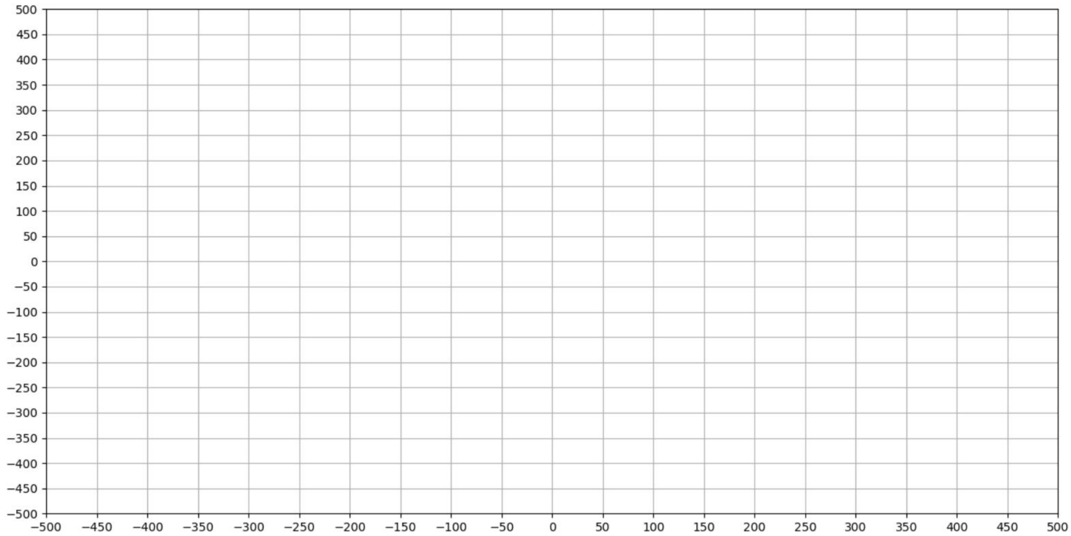

Figure 2. Illustration of the grid, given GridLength = 1000 m, GridHeight = 1000 m, and GridDistanceBetween = 50 m.

2) Voronoi Region:

There are many different shapes of cells that are being used in today's system, most traditional being the Hexagonal & Voronoi system. The type of cell used in this program is Voronoi system, which has been studied & applied in Wireless Sensor Networks as well as in 5G over the past few years [11,12]. Voronoi Cells are divided such that every point in each of the cell is closer to its corresponding Cell Tower than other existing Cell Towers in the map, as defined in [13]. This mathematical model allows for natural formations of polygons, as shown in Figure 3, which has been generated by the simulation program. As soon as the User specifies the Cell Tower locations, the function called VoronoiCellPoint considers each grid point and identifies which Cell Tower the considering grid point is the closest to. The list which contains the information of the points in each Voronoi Region is then returned, and is used for various purposes which will be further discussed later in the document, like generating random IRS relay paths.

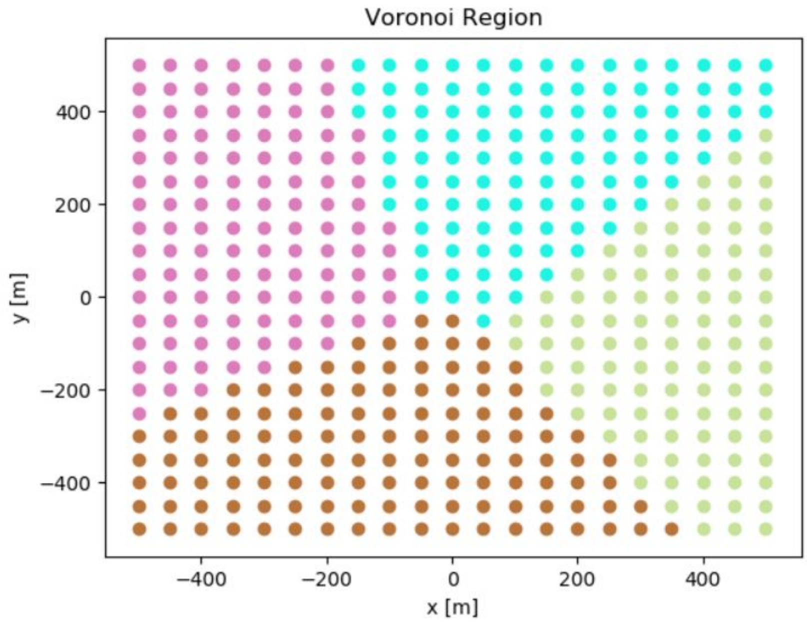

Figure 3. The map of the Voronoi Regions outputted by the simulation program with the Cell Tower locations chosen from the grid specified in Figure 2 being: [-300,100], [-100,-300], [100,200], [300,0].

II. Signal Propagation

1) Channel Modelling:

The most important aspect in developing a very realistic wireless coverage simulation is 1) choosing the channel models that suits the conditions of the simulation and 2) making absolutely no errors in the implementation process. Not just any channel models between the transmitter and the receiver were simply seeked; as the goal of this simulation was to consider both the mobiles and the UAVs as potential transmitting sources, the applied channel models needed to satisfy the transmitter height of as low as 1.50 m to account for the mobile users on the ground, to as high as 300.00 m to account for the UAVs. The reports that satisfied these conditions were 3GPP Technical Report 36.777 v.1.0.0 (2017-12) [4] and 3GPP Technical Report 38.901 v.14.3.0 (2018-01) [14], and the LOS and NLOS path loss, shadow fading (all in dB), and LOS probability models specified based on the environment, the 2-dimensional distance between the transmitter and the receiver, and the height of the transmitter were carefully integrated to the simulation program. The main limitation to this program is that for some simulation environments like Urban and Street Canyon, the channel models were formulated based on the assumption that the receiving end of the channel is of fixed height ie. 25.00 m for Urban and 10.00 m for Street Canyon; this means that if the User wants to create an IRS/Cell Tower relay network in Urban and Street Canyon, this program can only simulate IRS/Cell Tower relay network with IRS/Cell Tower heights equivalent to the values specified above. However, as shown in [14], the heights of the receiving end of the link in Rural can be flexible ie. can be between 10.00 m and 150.00 m, so the User can simulate IRS/Cell Tower relay network with IRS/Cell Tower height in this range. The main goal of the next version would be to find & integrate channel models that would provide more IRS/Cell Tower height options for Urban and Street Canyon simulation environments. To get the received power in dBm, the path loss and shadow fading values all in dB were simply subtracted from the transmitted power in dBm. The derivation leading to this equation was the following:

PL [Unitless] = PT [W] / PR [W]
10 log (PL) = 10 log (PT / PR)
10 log (PL) = 10 log (PT) - 10 log (PR)
10 log (PL) = 10 log (PT / 0.001) - 10 log (PR / 0.001)
PR [dBm] = PT [dBm] - PL [dB] qed

Another important aspect that would need to be considered is noise. The noise, with the consideration of bandwidth, is 10 log (kT<u>B</u> * B) in dB, where k = Boltzmann's constant, T = 290 K at room temperature, and <u>B</u> =

normalized bandwidth of 1 Hz [15]. This can be further expanded using the log rule, to 10 log (B) - 174. This value will be converted in Watts, and will be used for computing the Signal to Interference and Noise ratio.

2) Relay Network

Let's look at the general algorithm used to simulate IRS/Cell Tower relay network through an example shown in Figure 4, which is relatively simple, but still excellently illustrates the possible capabilities of this program. For this example, it can be assumed that there is just one antenna attached to each transmitter, and that these antennas are omnidirectional.

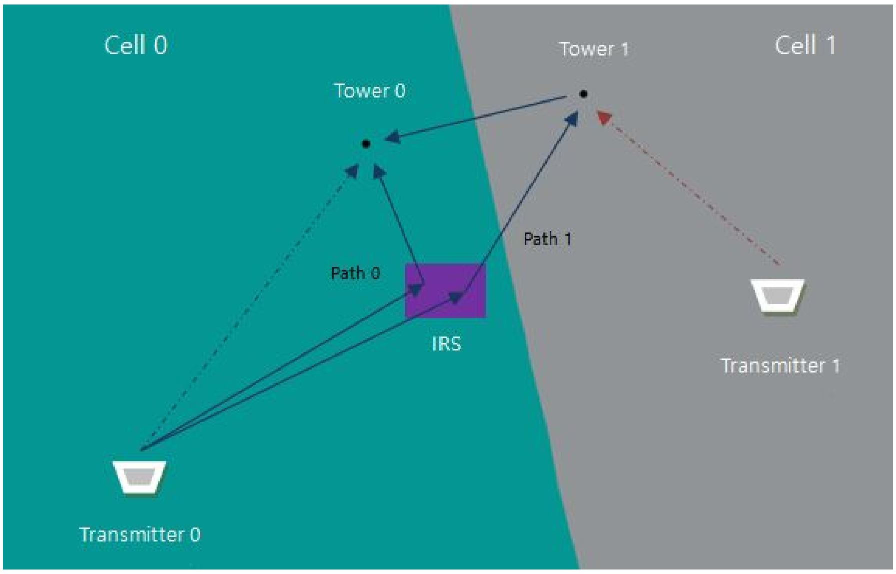

Figure 4. IRS/Cell Tower relay network example. Transmitter 0 sends signals to its intended Cell Tower 0 through path 0 (blue), path 1 (blue) and direct link (blue dotted), and transmitter 1 sends signals to its intended Cell Tower 1 through direct link (red dotted).

The first step is to consider the effect from each of the transmitter separately. For the transmitter 0 case, received power at Cell Tower 0 would be the sum of received power from path 0, path 1, and direct link, and the received power at Cell Tower 1 would be the received power from the transmitter-IRS-Cell Tower 1 path and the direct link (this would be considered as an interference for Cell Tower 1). Let's carefully examine one of the paths involving the IRS, path 0. First, the received power at the IRS is calculated using the channel models from the technical reports [4] and [14]. Prior to IRS reflecting the arrived signal to the next node in the path, the function in the program called the AmplitudeFactorIRS will have been invoked to determine whether the location of the signal is still at one of the the relay nodes ie. IRS or at the intended Cell Tower; if the function realizes that the signal reached the IRS, then a random number from a User-specified probability distribution will be multiplied to the received power, and if the function learns that the signal reached the intended Cell Tower, then the recevied power will remain unchanged. In the 1st case, where the considered signal reached one of the relay nodes ie. IRS and not at the intended Cell Tower, the received power, which have been evaluated & adjusted by the AmplitudeFactorIRS function, will now become the transmitting power of the IRS-reflecting signal and will be used to compute the received power at the next node, which is Cell Tower 0 in this example. Since the IRS is a passive element meaning it is not capable of creating energy, the reflecting signal cannot have greater power than the power when the IRS received it; the most optimal amplitude factor that can be multiplied would be 1.00 as doing this would maximize the IRS-reflecting signal [16]. So why potentially multiply by a number less than 1.00? One great instance is actually this example, where another path of the signal transmitted from transmitter 0 has unintended Cell Tower, Cell Tower 1, as one of its relay nodes. Since the signal from transmitter 0 is an unwanted signal for Cell Tower 1, which is expecting a signal from transmitter 1, path 0 would cause significant interference at Cell Tower 1. Therefore, one of the goals for the researcher using this program would be to find an optimal amplitude factor of the IRS in the form of a constant or a type of probability distribution with the values between 0.00 and 1.00, such that the received power at the intended Cell Tower is maximized (in this example, Cell Tower 0) while the interference in the adjacent Cell Towers (in this example, Cell Tower 1) are minimized.

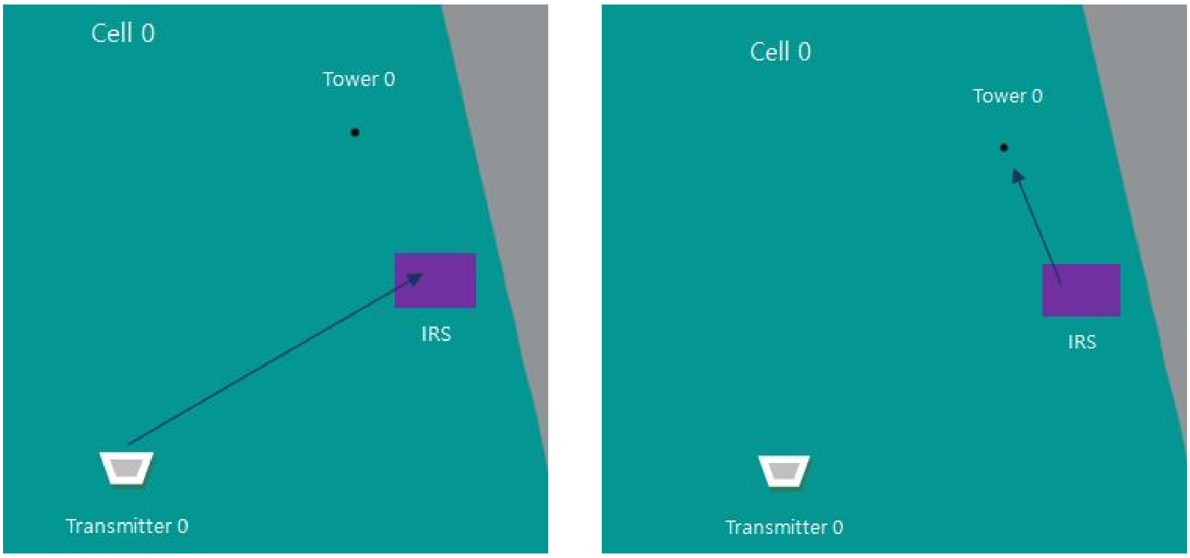

Figure 5. L: AmplitudeFactorIRS() realizes the signal is at the IRS. Thus, the received signal power is multiplied by an amplitude factor and the transmitting (reflecting) power of the signal directed from the IRS to the Tower is set to this value (amplitude factor x received signal power). R: AmplitudeFactorIRS() realizes the signal is at the Tower. Therefore, the received signal power remains unchanged, and this value is used to compute the SINR at the Tower.

As outlined in [16], IRSs has not one, but multiple elements that can each carry out the functionalities specified in the introduction, like phase shift, amplitude control, etc. Therefore, the User can provide information regarding how many IRS elements they are using in each path using the function called IRSElementsNumber. Through this tool, the User can simulate a case, like this example, where specific number of IRS elements are assigned to path 0 and the remaining number of IRS elements to path 1. Similar to the amplitude factor optimization problem discussed above, the researcher using this program can also simulate and try to understand how different distribution of the available IRS elements to the paths affect the SINRs at the Cell Towers in various scenarios.

SINR is the abbreviation for Signal to Interference and Noise Ratio as mentioned in the introduction, and it is defined as the received power from the wanted transmitter over the sum of the noise and all of the received powers from the unwanted transmitters. Once the received powers at all of the Cell Towers due to each of the active transmitting antenna have been determined, SINRs can then be calculated using the equation specified above and using WhichTransmitterforHex, which is a list provided by the User that contains the information on which transmitting antennas are aiming for each of the Cell Towers.

3) Random Path Selection

As mentioned earlier, this program gives the User the option to randomly select the IRS paths instead of them having to maunally create one. This is a very important tool because realistically, it is very difficult to test countless number of manually inputted possible IRS paths for various different settings and try to determine the most optimal paths from all of these results, especially if the size & the number of points in the cell is relatively high; it is much more efficient to seek for a random path-generating probability distribution model that is overall able to produce excellent SINR values across as many scenarios as possible. Through the list called RandomIRSandSequenceNumber, the User can specify the number of IRS paths they want in each of the cell for the case of the considering transmitter, as well as the number of IRSs they want for each path. The deafult random IRS location selecting probability distribution is uniform distribution, but the User can easily modify to a different distribution they would like in the function that processes RandomIRSandSequenceNumber & generates random IRS paths, RandomIRSLocationNew. A different & more complex distribution that the User can test with could be gamma distribution for example, in which the User could give an ID to each of the points in the considering cell and form random IRS location selecting gamma distribution from that.

IV. Guideline:

This section will describe the input parameters, which will be set in the main function in Model2.py.

- As mentioned before, the goal of the program is to compare the SINR performance at the Cell Tower between different scenarios ie. different parameter values of the dynamic objects like transmitters and IRSs. The number of scenarios is defined in the variable NumComparisonContender.

- NumTrial is the number of times the User would like to simulate each scenario. As the received power values may sometimes highly vary due to the probabilistic models in the path loss and shadow fading equations, higher value of NumTrial will yield SINR Outage Probability graphs with more solid and stable characteristics (even though it would have higher computational cost).

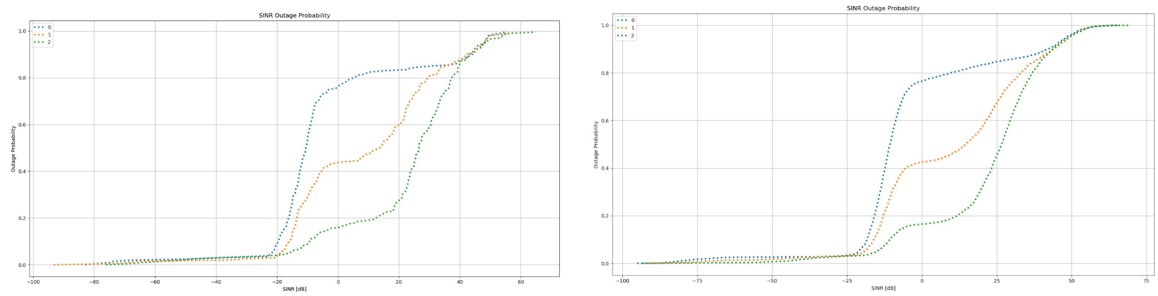

Figure 6. Each graph above is the Outage Probability graph of the exact same example simulation specified in the main function, only with different number of trials; the left Outage Probability graph is the result of 200 trials and the graph on the right is the result of 3000 trials. As it can be observed, the charasteric of the graphs become clearer as the number of trials is increased.

- ComparisonCellNumber is the Cell Tower number that the User would like to see the SINR Outage Probability graph of. The value must be between 0 the number of Cell Towers - 1.

- As mentioned earlier, the grid will act as the underlying structure of the simulation map. GridLength is the distance of the grid in the X-Axis in [m], GridHeight is the distance of the grid in the Y-Axis in [m], and GridDistanceBetween is the distance between the points on the grid in [m].

- CellTowerLocation contains the points of the Cell Towers, which are selected from the points specified in the grid. As soon as the Cell Tower locations are selected, Voronoi Region corresponding to each of the Cell Tower is created.

- CellTowerHeightEachCell contains the heights of each of the Cell Towers in [m]. In Rural environment, the Cell Tower height can be between 10.00 m and 150.00 m, in Urban, the height is 25.00 m, and in Street Canyon, the height is 10.00 m.

- SimulationEnvironment is the environment, and is chosen from: Rural, Urban, and Street Canyon.

- CenterFrequency contain the center frequencies of the signal for each scenario in [GHz]. Bandwidth contain the bandwidth of the signal for each scenario in [GHz]. eg. CenterFrequency[0] is the center frequency of the signal for scenario 0, Bandwidth[0] is the bandwidth of the signal for scenario 0.

- InfoTransmitter contains the information of the transmitting antennas (ie. the location on the grid, the transmitting power in [dBm], and the altitude in [m]) from all scenarios. InfoTransmitter[I][J][0] is the location of transmitting antenna J from scenario I, InfoTransmitter[I][J][1] is the transmitting power of transmitting antenna J from scenario I, and InfoTransmitter[I][J][2] is the altitude of transmitting antenna J from scenario I. The altitude of the transmitting antenna must be between 1.50 m and 40.00 m for Rural (not 300.00 as the shadow fading for NLOS is defined only up to 40.00 m), 1.50 m and 100.00 m for Urban (not 300.00 as the shadow fading for NLOS is defined only up to 100.00 m), and 1.50 m and 300.00 m for Street Canyon.

- Every transmitting antenna has at minimum one receiver that it aims to send its signal to, and for the remaining receivers, this signal is considered as an unwanted noise; InfoWhichTransmitterforCell specifies which Cell Tower each of the transmitting antennas indicated in InfoTransmitter is targeting. InfoWhichTransmitterforCell[I][J] contains the numbers of the transmitting antennas that are aiming for Cell Tower J in scenario I.

- InfoIRSEachCell contains the IRS/Cell Tower paths (ie. sequences of IRS/Cell Tower positions) that the signals emitted from each transmitter antenna is travelling through. InfoIRSEachCell[I][J][K][L] is transmitting antenna J's Lth IRS/Cell Tower path aiming for Cell Tower K from scenario I, and contains the IRS/Cell Tower positions of the path in sequential order. If the User wants to simulate with random IRS paths for scenario, simply specify "Random" in InfoIRSEachCell[I] and complete RandomIRSandSequenceNumber accordingly.

- RandomIRSandSequenceNumber contains information of the number of IRS paths that User would like, and the number of random IRS locations that the User would like for each IRS path. Length of RandomIRSandSequenceNumber[I][J][K] is the number of IRS paths User would like transmitting antenna J's signal to travel through to reach Cell Tower K in scenario I. RandomIRSandSequenceNumber[I][J][K][L] is the number of random IRSs User would like in transmitting antenna J's Lth IRS path aiming for Cell Tower K in scenario I. If the User does not want any IRS path ie. just want the direct link, then length of RandomIRSandSequenceNumber[I][J][K] would be 1, and the only value specified inside RandomIRSandSequenceNumber[I][J][K] would be 0. The maximum number of IRS possible in a path would be the number of points in the considering Voronoi cell (although unrealisitc).

- IRSHeightEachCell contains the height of each IRS/Cell Tower in each of the IRS/Cell Tower path in [m]. IRSHeightEachCell[I][J][K][L][M] is the height of Mth IRS/Cell Tower in transmitting antenna J's Lth IRS/Cell Tower path aiming for Cell Tower K from scenario I. In Rural environment, the IRS/Cell Tower height can be between 10.00 m and 150.00 m, in Urban, the height is 25.00 m, and in Street Canyon, the height is 10.00 m.

- IRSElementsNumber contains the number of IRS elements that each of the IRS used in each IRS path. Note that logically speaking, the number of used IRS elements per IRS is the same for all IRSs in the same IRS path, and thus, for efficency purporses, the number of used IRS elements per IRS is specified for each IRS path. IRSElementsNumber[I][J][K][L] is the number of elements used per IRS in transmitting antenna J's Lth IRS path aiming for Cell Tower J, in scenario I.

- StreetWidth and BuildingHeight refer to the mean street size and mean altitude of the architecture in the simulation map in [m], and are specified if the User is simulating in Rural environment; the average street width is 20.00 m and the average building height is 5.00 m.

V. Reference:

[1] B. J. O'Brien, D. G. Baran, and B. B. Luu, "Ad Hoc Networking for Unmanned Ground Vehicles: Design and Evaluation at Command, Control, Communications, Intelligence, Surveillance and Reconnaissance On-the-Move," ARL, Adelphi, MD, USA, Army Res. Lab. Tech. Rep. ARL-TR-3991, Nov. 2006.
[2] J. K. Hart and K. Martinez, "Environmental Sensor Networks: A Revolution in the Earth System Science?" Earth Sci. Rev., vol. 78, nos. 3–4, pp. 177–191, Oct. 2006.
[3] D. Sahota, "Internet.org Building Drones to Connect Remote Communities," Telecoms.com, Mar. 2014. [Online]. Available: http://telecoms.com/239252/internet-org-building-drones-to-connect-remotecommunities
[4] 3GPP TR 36.777: "Technical Specification Group Radio Access Network: Study on Enhanced LTE Support for Aerial Vehicles", V15.0.0, Dec. 2017.
[5] Y. Zeng, Q. Wu, and R. Zhang, "Accessing From The Sky: A Tutorial on UAV Communications for 5G and Beyond", arXiv:1903.05289, 2019
[6] N. Yu, P. Genevet, M. A. Kats, F. Aieta, J.-P. Tetienne, F. Capasso, and Z. Gaburro, "Light Propagation with Phase Discontinuities: Generalized Laws of Reflection and Refraction", Science, Vol. 334, No. 6054, pp. 333-337, Oct. 2011.
[7] C. Liaskos, S. Nie, A. I. Tsioliaridou, A. Pitsillides, S. Ioannidis, and I. Akyildiz, "A New Wireless Communication Paradigm Through Software-Controlled Metasurfaces," IEEE Commun. Mag., vol. 56, no. 9, pp. 162– 169, 2018.

[8] Renzo, M.D., Debbah, M., Phan-Huy, D. *et al.* Smart Radio Environments Empowered by Reconfigurable AI Meta-Surfaces: an Idea Whose Time Has Come. *J Wireless Com Network* 2019, 129 (2019). https://doi.org/10.1186/s13638-019-1438-9
[9] P. Hu, P. Zhang, M. Rostami, and D. Ganesan, “Braidio: An Integrated Active-Passive Radio for Mobile Devices with Asymmetric Energy Budgets”, ACM SIGCOMM, Florianopolis, Brazil, Aug. 2016.
[10] S. Li, B. Duo, X. Yuan, Y.-C. Liang, and M. D. Renzo, “Reconfigurable Intelligent Surface Assisted UAV Communication: Joint Trajectory Design and Passive Beamforming”, arXiv:1908.04082, 2019
[11] N. A. B. A. Aziz, A. W. Mohemmed and M. Y. Alias, "A Wireless Sensor Network Coverage Optimization Algorithm Based on Particle Swarm Optimization and Voronoi Diagram," *2009 International Conference on Networking, Sensing and Control*, Okayama, 2009, pp. 602-607.
[12] D. Gonzalez G. and J. Hamalainen, "Planning and Optimization of Cellular Networks through Centroidal Voronoi Tessellations," *2015 IEEE 82nd Vehicular Technology Conference (VTC2015-Fall)*, Boston, MA, 2015, pp. 1-2.
[13] Aurenhammer, F. & Klein, R. (2000) Voronoi diagrams. In Handbook of computational geometry: 201–290. Sack, J. R. & Urrutia, J. (Eds). Amsterdam: Elsevier
[14] 3GPP TR 38.901: “5G; Study on Channel Model for Frequencies From 0.5 to 100 GHz”, V14.3.0, Jan. 2018.
[15] V.S.Bagad, I.A.Dhotre, “Data Communication & Networking”, Ch. 17, pp. 19.
[16] W. Qingqing and Z. Rui, “Towards Smart and Reconfigurable Environment: Intelligent Reflecting Surface Aided Wireless Network”, arXiv:1905.00152, 2019.