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Joint Trajectory and Communication Optimization for UAV in Complex Electromagnetic Environment

Jad ABOU CHAAYA*[†], Arnaud COATANHAY*, Ali MANSOUR*[‡] and Thierry MARSAULT[§]

*Lab-STICC, UMR 6285 CNRS, ENSTA Bretagne, 29200 Brest, France

[§]Département TEC/SPC, Direction Générale de l'Armement, Maitrise de l'information, 35170 Bruz, France

Email: *firstname.LASTNAME@ensta-bretagne.fr, [†]jad.abouchaaya@ieee.org,

[‡]mansour@ieee.org, [§]thierry.marsault@intra.def.gouv.fr,

Abstract—Unmanned Aerial Vehicle (UAV) is a booming trend in major civil and military applications such, but not limited to, transportation, delivery, and surveillance missions. In order to accomplish the mission's objective, trajectory planning must be optimally achieved. The communication link established between the UAV and the ground/aerial stations is the main factor to account for designing the trajectory. However, this link is highly affected by the shape of the topography, especially when the UAV must fly at a low altitude between mountains of variable elevations. Therefore, this paper addresses the challenge of three-dimensional trajectory optimization for low/mid-altitude flying UAVs in complex propagation environments. To tackle this challenge, we propose a system model for the trajectory using the diffraction phenomenon with Multiple Knife Edge (MKE) to model the channel between the UAV and the station when the Line of Sight (LoS) is absent. Then, we propose a joint optimization to minimize the trajectory and maximize the communication quality via the Mixed Integer Linear Programming (MILP) problem design and solution. We validate the proposed approach by using real terrain profiles in the simulations with a rough topography; where the LoS propagation aspect is barely present. Our approach is able to jointly find, when physically achievable, the UAV trajectory with the shortest path and the "best feasible" communication quality.

Index Terms—Unmanned Aerial Vehicle (UAV), Trajectory Optimization, Mixed Integer Linear Programming (MILP), Multiple Knife Edge (MKE) Diffraction, Path Loss (PL) Threshold Optimization.

I. INTRODUCTION

Unmanned aerial vehicles (UAV) are expanding quickly and becoming a crucial component in basic technological systems, especially in telecommunication, wireless networks, and military fields [1] [2]. The emergence of the beyond 5G architectures allows UAVs to be used as aerial base stations for coverage and capacity enhancement. In [3], the UAV is used as an amplify and forward relay in the network; whereas in [4] and [5], it is used as a flying base station for covering wireless backhauls. The UAV plays a major role in the military context, especially for surveillance and operational missions. In all previously cited applications, the trajectory planning and optimization is very important for a successful mission accomplishment.

UAV navigation presents many constraints like flight time, energy consumption, dynamics, channel variation, propagation

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model, collision avoidance, flight altitude, and many more. Given the flight context, where the UAV should accomplish a sensitive mission with a specified task, the important aspect to consider is maintaining the communication link between the UAV and the command center. For sensitive applications, specifically the military, the trajectories may address non-classical requirements such as the low-altitude flight behavior. These requirements severely penalize the Line of Sight (LoS) between the UAV and the communicating node present at the ground or in the air. The link becomes difficult to maintain and full of communication holes especially when the terrain presents rocky topography such as mountains, hills, and cliffs. The propagation of electromagnetic waves given such environments presents a challenging issue for radio and wireless communication systems, where the LoS is barely considerable and unrealistic to account for.

In the literature, for most of the UAV's trajectory planning, the classical adopted air-to-ground propagation channel models ([6], [7], [8]) consider the urban zones and use statistical properties to decompose the channel in a LoS and non-LoS components. Such models are inadequate and unrealistic to use in the case of the challenging complex propagation environment that creates plenty of communication dead zones (due to the continuous rocky elevations). To tackle this issue, we are interested in the Multi Knife Edge (MKE) diffraction phenomenon and precisely by the Vogler [9] algorithm to compute it. We believe that in our case the diffraction model will significantly compensate for the terrain effect and explore the communication dead spots. As per our knowledge, no study in the literature adopts the diffraction phenomenon to model the channel between the UAV and the communication node. Therefore, in this paper, we consider the MKE diffraction to model the communication for the flying platform [10], [11]. Hereinafter, we propose a system model for the UAV trajectory and derive a criteria to find the optimal path with respect to the distance and the communication quality. The main contributions of this work are listed as following:

- Proposing a system model for UAV trajectory planning given terrains with rough topography that presents a complex environment for the radio propagation. To overcome this challenge, the MKE diffraction between the station and the UAV is used to model the communication for

Non-LoS (NLoS) situations, where some significant wave energy is gained thanks to this phenomenon.

- Formulating the trajectory and the communication quality optimization using a weighted multi-objective cost function to allow a tradeoff between the shortest distance and a "best feasible" communication quality in terms of path loss. The problem is formulated using the MILP scheme and solved using commercial solvers.
- Validation of the proposed system model, problem formulation, and optimization scheme using real terrain data with geographic 3D coordinates in the region of southern France at the border with Spain near the Pyrénées mountains.

II. SYSTEM MODEL

We explain the assumptions and the description of the UAV problem in II-A. Then, in section II-B, we explain the MKE diffraction. We formulate the communication model, in terms of path loss, between the UAV and the base stations in II-C.

A. Assumptions and Parameters Description

We consider a multi-purpose and long-endurance flying UAV. All possible locations for the UAV navigation during the mission time can be represented as infinity points in the 3D space. We sample this three-dimensional space to a limited number of points to produce the map in "Fig. 1". The location

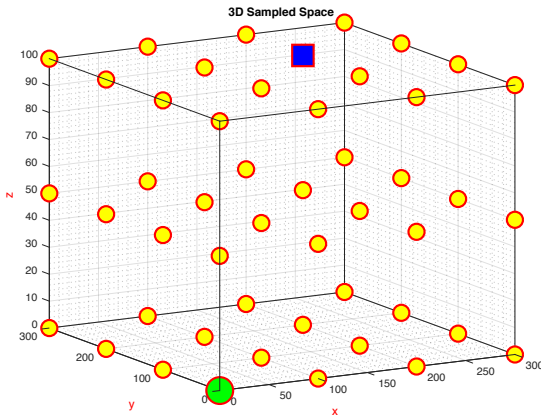


Fig. 1: The three-dimensional sampled space. The possible navigation positions for the UAV are the yellow circles \bullet . The departure and arrival locations are the green circle \bullet and the blue square \blacksquare .

map consists of a predefined number of points, where each represents a position in the 3D space. The drone flies with a velocity of $v(t)$ (m/s). The time flight is decomposed into a predefined number of time segments, where the duration of each slot is expressed in seconds. The starting position and the departure time of the UAV are selected by the user. To simplify the model and improve the operational efficiency, we assume that the UAV can fly only to one position per assigned time slot or it can hover at the same place. The spatial step of the drone is defined by its speed and the time slot duration. The arrival location of the drone is also defined by the user.

The cartesian coordinate system for the three-dimensional space is adopted for modeling. However, for simulating the real terrain environment, the geographic coordinate system is used with latitude, longitude (in degrees), and elevation (in meters). We sample the space of flight for the UAV into N total positions. The UAV i -th position is defined by a vector $\mathbf{p}_i = [x_i, y_i, z_i]^T \in \mathbb{R}^{3 \times 1}$ and $i \in \mathcal{N} = \{1, \dots, N\}$. The mission time for the UAV is sampled to T time slots using a uniform step Δt . The discrete-time is indexed by $t \in \mathcal{T} = \{1, \dots, T\}$. The takeoff position and time are determined by $\mathbf{p}_\gamma = [x_\gamma, y_\gamma, z_\gamma]^T$ and t_γ . The UAV reaches the arrival position $\mathbf{p}_\delta = [x_\delta, y_\delta, z_\delta]^T$ with the pre-assigned mission time slots T . The UAV communication link is established using a set of Ground Base Stations (GBS) with fixed locations \mathbf{p}_g indexed by $g \in \mathcal{G} = \{1, \dots, G\}$. The communication model between the position i and the GBS location g is explained in the next section.

The kinematics and dynamics of the aerial vehicle are not accounted for in this study and they will be considered in our future work. The drone motion is restricted to a moving point in space and time. Therefore, the trajectory modeling is done using a binary variable $p_{ij}[t]$ given in (1) to describe the discrete steps in space and time. The UAV moves between two positions or hovers at the same position (including the start γ and finish δ position) to respect the assigned flight time T of the mission.

$$p_{ij}[t] = \begin{cases} 1 & \text{UAV moves from } i \text{ to } j \text{ in time slot } t, \\ 0 & \text{no motion.} \end{cases} \quad (1)$$

The distance between the two positions i and j is given by $d_{ij} = \|\mathbf{p}_i - \mathbf{p}_j\|$, where $\|\cdot\|$ is the Euclidean norm operator.

B. Propagation using MKE Diffraction

The geometry description of the MKE problem is shown in "Fig. 2" where each knife-edge can be used to model the elevation point in a mountain (or any other obstacle). We

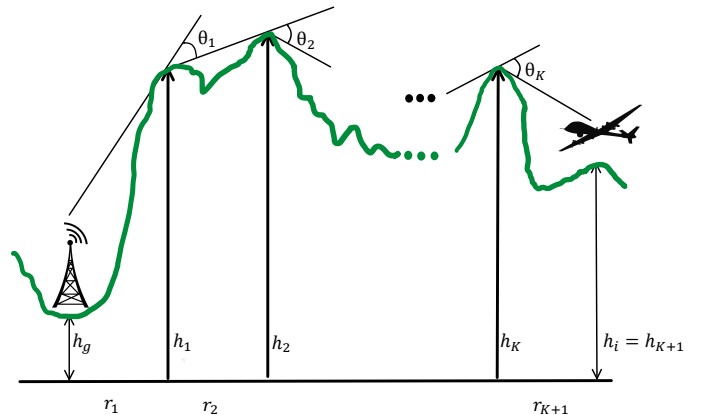


Fig. 2: The MKE diffraction geometry between a GBS and a navigation position for the flying drone where K knife edges is used to account the obstacles.

define the height of the g -th GBS, acting as a transmitter, by

h_g . The height of any i -th position (knife-edge) in the space is defined by h_i ¹. We consider K knife edges between g and i . The MKE are characterized by their heights $\{h_k\}$, diffracting angles $\{\theta_k\}$, $k \in \mathcal{K} = \{1, \dots, K\}$ and the overall distance between g and i given by:

$$R = \sum_{k=1}^{K+1} r_k \quad (2)$$

The Diffraction Loss (DL) (relative to free space) between g and i overall the distance R is given by Vogler in [9] as:

$$\text{DL}_{gi}(K) = \left(\frac{1}{\sqrt{\pi}}\right)^K C_K \exp(\sigma_K) \int_{\beta_1}^{\infty} \dots \int_{\beta_K}^{\infty} \exp(2z) \exp\left(-\sum_{k \in \mathcal{K}} v_k^2\right) dv_1 \dots dv_K \quad (3)$$

where:

$$\alpha_k = \left[\frac{r_k r_{k+2}}{(r_k + r_{k+1})(r_{k+1} + r_{k+2})} \right]^{\frac{1}{2}}, \quad k \in \{1, \dots, K-1\}, \quad (4)$$

$$\beta_k = \theta_k \left[\frac{\mathbf{i}(\pi/\lambda) r_k r_{k+1}}{(r_k + r_{k+1})} \right]^{\frac{1}{2}}, \quad k \in \mathcal{K}, \quad (5)$$

$$\theta_k \approx \frac{h_k - h_{k-1}}{r_k} + \frac{h_k - h_{k+1}}{r_{k+1}}, \quad k \in \mathcal{K}, \quad (6)$$

$$z = \begin{cases} 0, & K = 1 \\ \sum_{k=1}^K \alpha_k (v_k - \beta_k)(v_{k+1} - \beta_{k+1}), & K \geq 2 \end{cases} \quad (7)$$

$$C_K = \begin{cases} 1, & K = 1 \\ \left[R \prod_{k=1}^K \left(\frac{r_k}{r_k + r_{k+1}} \right) \right]^{\frac{1}{2}}, & K \geq 2 \end{cases} \quad (8)$$

$$\sigma_K = \sum_{k=1}^K \beta_k^2, \quad (9)$$

with $\mathbf{i} = \sqrt{-1}$ is the imaginary number. Expressing $\exp(2z)$ in (3) into a power series as $\exp(2z) = \sum_{m=0}^{\infty} \frac{(2z)^m}{m!}$, the computation of $\text{DL}_{gi}(K)$ in [9] is converted from a K -folded integral into an independent K integral computation. In addition, the author in [9] exploits the recursive computation aspect and reaches a closed form using the following identity:

$$\frac{2}{\sqrt{\pi}} \int_{\beta}^{\infty} (v - \beta)^m \exp(-v^2) dv = m! I(m, \beta), \quad (10)$$

where $m!$ is the factorial of m and $I(m, \beta)$ are the repeated integrals of the complementary error function [12]. A full and detailed proof of the recursive Vogler algorithm for the MKE diffraction is done in [10]; while, a study case with a closed form expression for $K = 4$ is provided.

¹previously defined by z_i in \mathbf{p}_i for modeling purposes using the cartesian coordinates and is considered as the terrain elevation in the simulations.

C. Path Loss for Communication Model

In the literature [8], they usually adopt the statistical air-to-ground path loss model, which is based on a probability of occurrence in a LoS or NLoS presence between the two communicating nodes. Whereas, the probability is a sigmoid-like function that mainly accounts for the elevation angle between the position of the transmitter and the receiver. As we have explained before, this air-to-ground path loss model is unreraltistic to adopt in our case, we formulate the general path loss model that includes the two propagation phenomena, diffraction and LoS by:

$$\text{PL}_{gi} = \left(\text{DL}_{gi}(K)\right) \mathbf{1}(b) + \left(\left(\frac{4\pi f}{c}\right)^2 \|\mathbf{p}_g - \mathbf{p}_i\|^2 \eta_{\text{LoS}}\right) \mathbf{1}(\bar{b}) \quad (11)$$

where, f is the system frequency (Hz), c is the speed of light (m/s) and η_{LoS} is the excessive path loss for the LoS (dB) (see [8] for more details). $\mathbf{1}(\cdot)$ is the indicator function, b is a logical variable and \bar{b} is the negation of b defined by:

$$b = h^{(\max)} > \frac{\max(h_g, h_i) - \min(h_g, h_i)}{R}. \quad (12)$$

R is given in (2), $h^{(\max)}$ is the maximum value for the height-distance ratio of the MKE which is formulated to detect the non-LoS and the computation of $\text{DL}_{gi}(K)$. $h^{(\max)}$ is given by:

$$h^{(\max)} = \max_{k \in \mathcal{K} \setminus \{g, i\}} \left\{ \frac{h_k - \min(h_g, h_i)}{\sum_{i=1}^k r_i} \right\} \quad (13)$$

where \setminus represents the set minus operator.

III. PROBLEM FORMULATION AND SOLUTION USING MILP

We provide a formulation for the trajectory planning in section III-A based on the previous description of the system model. Then, in section III-B, we define the multiple objectives for the UAV to minimize the travel distance and maximize the communication quality. Finally, the problem is reformulated and solved using the MILP.

A. Problem Formulation

We start by defining the constraints that organize the UAV behavior using $p_{ij}[t]$.

$$\sum_{j=1}^N p_{\gamma j}[t_{\gamma}] = 1 \quad (14)$$

$$p_{ij}[t].d_{ij} \leq \bar{V}.\Delta t, \quad \forall i, j \in \mathcal{N}, \quad \forall t \in \mathcal{T} \quad (15)$$

The constraint in (14) defines the UAV departure by imposing the starting location to γ and time to t_{γ} . The constraint in (15) assures that the traveled distance is limited by the drone velocity² \bar{V} and the slot duration Δt .

$$\sum_{i=1}^N \sum_{j=1}^N p_{ij}[t] \leq 1, \quad \forall t \in \mathcal{T} \quad (16)$$

²assumed constant over time in this study $v(t) = \bar{V}$, $\forall t \in \mathcal{T}$

The constraint in (16) limits the drone motion to one step per time slot. For example, given a time sample t , the UAV is allowed to move from one location i to another j , $\forall i, j \in \mathcal{N}$ or to stay at the same location i (in this case $p_{ii}[t] = 1$, $\forall i \in \mathcal{N}$).

$$\sum_{i=1}^N p_{il}[t] = \sum_{j=1}^N p_{lj}[t+1], \quad \forall l \in \mathcal{N} \setminus \{\delta\}, \quad \forall t \in \{1, \dots, T-1\} \quad (17)$$

The displacement of the UAV with respect to time is guaranteed using the set of flow equations in the constraint (17). For example, if the UAV is at the location l for instant t , it must mandatory move at the time instant $t+1$ to any location in \mathcal{N} (it can also hover at the same location).

$$\sum_{t=1}^T \sum_{i=1}^N p_{i\delta}[t] = 1 \quad (18)$$

The arrival at the destination is imposed by the location δ and can be achieved in any time slot from the \mathcal{T} set using (18).

$$\sum_{i=1}^N \sum_{j=1}^N p_{ij}[t] \text{PL}_j^{(\min)} \leq \xi, \quad \forall t \in \mathcal{T} \quad (19)$$

The constraint in (19) impels that the UAV must travel through spatial positions where the path loss satisfies a certain threshold ξ . $\text{PL}_j^{(\min)}$ is the minimum path loss between all the GBSs and the node j and is expressed by:

$$\text{PL}_j^{(\min)} = \min_{g \in \mathcal{G}} \left\{ \text{PL}_{jg} \right\} \quad (20)$$

B. Optimization via MILP

The goal is to design the UAV trajectory given the set of parameters and constraints explained in the previous formulation section. The UAV must travel from the departure position to the arrival position given a fixed time. The time mission is defined by the product of the time slots and the duration of each slot $T \cdot \Delta t$. The UAV must achieve the following: 1) minimum traveled distance to save power and minimize the time for mission execution; 2) maximum communication quality over the trajectory, by minimizing the threshold ξ for each traveling position $\mathbf{p}_j \forall j \in \mathcal{N}$ of the drone. Therefore, we have a multi-objective function to optimize in order to achieve the desired goal. The problem is a Mixed Integer Linear Programming (MILP) and defined by (\mathcal{P}):

$$(\mathcal{P}) : \min_{\substack{p_{ij}[t] \\ i, j \in \mathcal{N} \\ t \in \mathcal{T}}} \left\{ \omega_1 \left(\sum_{t=1}^T \sum_{i=1}^N \sum_{j=1}^N p_{ij}(t) d_{ij} \right) + \omega_2 \left(\xi \right) \right\} \quad (22)$$

s.t.

$$(14), (15), (16), (17), (18), (19)$$

$$p_{ij}[t] \in \mathbb{B} \quad (23)$$

$$\xi \in \mathbb{R}^+ \quad (24)$$

In (22), we use the scalarization method to assign the weights ω_1 and ω_2 for each objective. The weights are applied to control the tradeoff between two metrics; whereas, we can

allow enforcing priority either on minimizing the distance or minimizing the path loss threshold.

The solution to the problem (\mathcal{P}) is the optimal trajectory given by the vector \mathbf{s}^* and the scalar ξ^* where the elements of \mathbf{s}^* are defined by the set of values $p_{ij}^*[t]$ and given:

$$\mathcal{S} = \left\{ p_{ij}^*[t] \mid p_{ij}[t] = 1; \forall i, j \in \mathcal{N}, \forall t \in \mathcal{T}, \xi^* \right\}, \quad (25)$$

where ξ^* is the minimum (optimal) path loss value that satisfies the problem settings and outputs the minimum distance trajectory for the drone given by:

$$D = \sum_{t=1}^T \sum_{i=1}^N \sum_{j=1}^N p_{ij}^*(t) d_{ij} \quad (26)$$

We can use any off-the-shelf MILP solvers to provide the solution to problem (\mathcal{P}). One can cite CPLEX or the *intlinprog* function of Matlab. We should highlight that the MILP is an NP-hard problem to solve, yet such solvers having advanced techniques (different types of cuts, branch and bounds, and heuristics) can achieve solutions to a reasonable scaled problem in a reasonable time. However, we are developing a Dynamic Programming approach to solve this problem in a quasi-optimal way having a polynomial time of execution.

IV. SIMULATION RESULTS

In this section, we present numerical results to test and investigate the proposed approach for UAV trajectory and communication quality optimization in a geographical area located around the French and Spanish border called the Pyrénées mountains and is shown in "Fig. 3". As we can inspect, this terrain presents a complex topography with a lot of mountains of high elevations, the fact that complicates the electromagnetic wave propagation. The selected area is bounded using

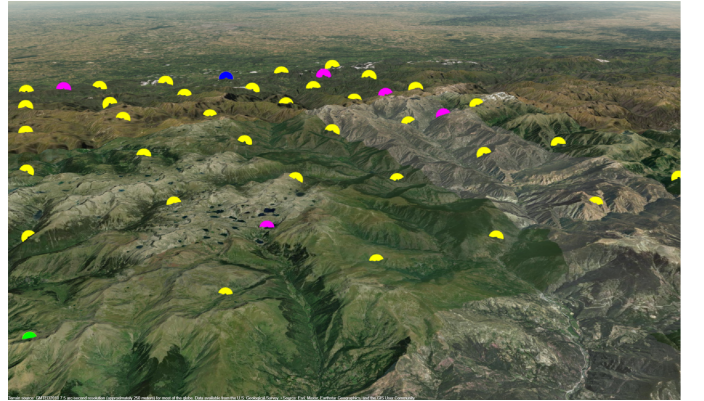


Fig. 3: Figure representing the 3D terrain visualization for the selected area near the Pyrénées. The positions of interest are represented using the colored circles. The possible navigation positions for UAV are in yellow \odot , the departure in green \odot and the arrival in blue \odot . The GBS positions are represented using the magenta circles \odot

two corner locations specified using the latitude, longitude, and elevation expressed in Decimal Degrees (DD) and meters.

The first and second corners are specified by the coordinates: $(42.46^\circ, 0.85^\circ, 860.8\text{m})$ and $(42.96^\circ, 1.35^\circ, 2246.5\text{m})$. The latitude and longitude are sampled using an equal step of 0.1° and we get in total $N = 36$ possible navigation positions for the UAV. The departure and arrival locations are fixed to $\gamma = 1$ and $\delta = 34$. The time slot of departure is specified by $t_\gamma = 1$. The mission time is divided into $T = 6$ slots of equal steps each $\Delta t = 500$ seconds. We have five GBSs ($G = 5$) distributed randomly in the terrain. We compute the path loss function $\text{PL}_{gi} \forall g \in \mathcal{G}, i \in \mathcal{N}$ expressed in (11) using the MKE where $K = 3$, the operator frequency is $f = 2.10^9$ Hz, $c = 3.10^8$ (m/s) and the excessive path loss $\eta_{\text{LoS}} = 0.1$ (dB). The simulation parameters are summarized in "Tab. I".

Parameters		Description
Δt	500 (s)	Duration of one time slot
N	36 positions	Total number of positions
T	6 slots	Total number of time slots
G	5 GBSs	Total number of GBSs
t_γ	1	Departure time slot
γ	1	Departure position
δ	34	Arrival position
V	31 (m/s)	UAV velocity position
K	3	Knife Edges #
f	2 (GHz)	GBS operating frequency
c	3.10^8 (m/s)	Speed of light
η_{LoS}	0.1 (dB)	Excessive path loss

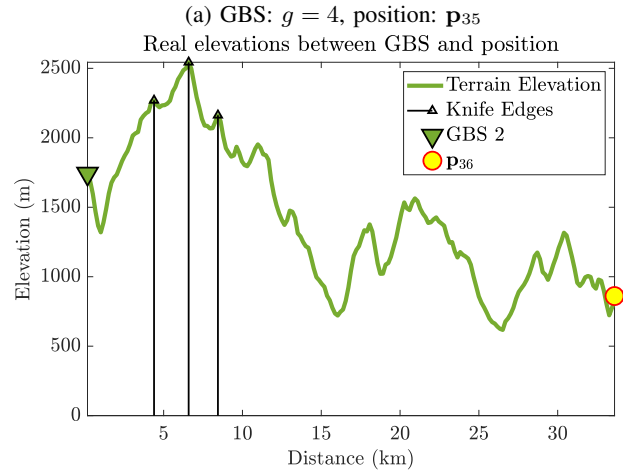
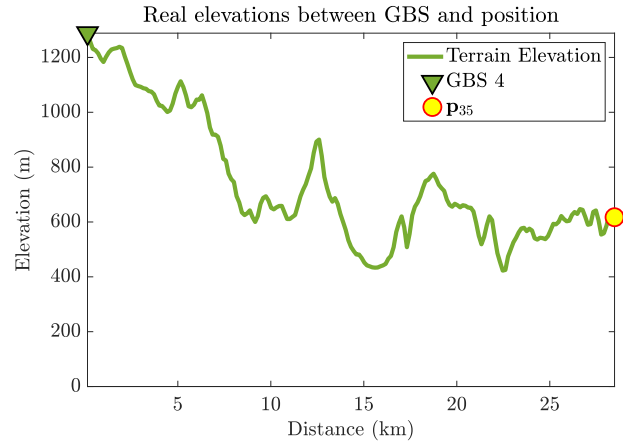
TABLE I: Table representing the simulation parameters

In "Fig. 4", we plot the elevation profiles to illustrate the terrain between a GBS and a navigation position. The difference of having a position in LoS and NLoS with respect to a GBS is depicted in "Fig. 4a" and "Fig. 4b" respectively. The path loss computation is done for the NLoS situations (i.e. "Fig. 4b") by accounting the diffraction and for the LoS situations (i.e. "Fig. 4a") by accounting the second part in (11). The path loss values are shown in "Fig. 5" for N positions and G base stations in different colors. The minimum path loss value $\text{PL}^{(\min)}$, at each position $\mathbf{p}_i \forall i \in \mathcal{N}$, for the five GBSs is plotted with blue thick line.

In this scenario, to regulate the tradeoff, the weights in equation (22) are selected as follows $\omega_2 \gg \omega_1$ to enforce the a priori on minimizing the threshold ξ of the path loss over the traveled trajectory to guarantee the "best" communication quality in the area. The solution to the problem (\mathcal{P}) is given by \mathbf{s}^* and $\xi^* = 102.04$ dB where:

$$\mathbf{s}^* = [p_{1,8}[1] \quad p_{8,9}[2] \quad p_{9,16}[3] \quad p_{16,22}[4] \quad p_{22,29}[5] \quad p_{29,34}[6]]^T.$$

The optimal distance trajectory is computed using (26) and we get $D = 74.504$ (Km). The optimal trajectory can be observed in the "Fig. 7" and "Fig. 6" for a two and three dimensional visualizations. Additional performance simulations in an extended version of this work will showcase contrasting outcomes with different weights in the objective function, parameter variations, and comparisons to alternative trajectory methods.



(b) GBS: $g = 2$, position: \mathbf{p}_{36}

Fig. 4: Figure representing the elevation in meters between a GBS g and a position \mathbf{p}_i .

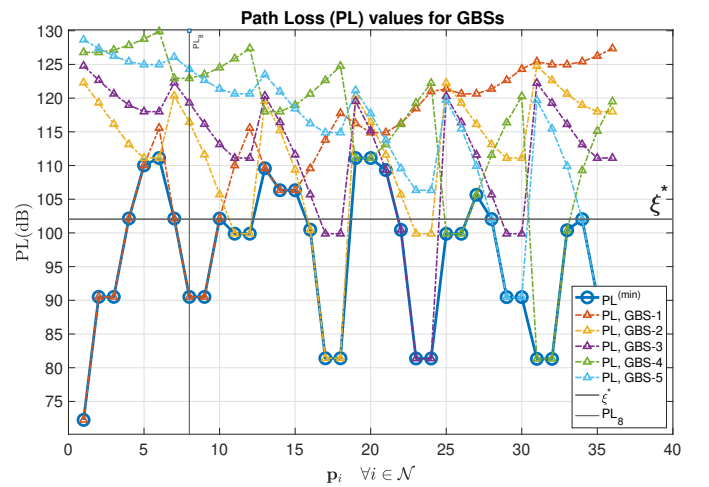


Fig. 5: Figure representing the path loss values for each GBS with a fixed color. The blue thick line represents $\text{PL}^{(\min)}$. The ξ^* is the optimal value obtained and plotted in a vertical line

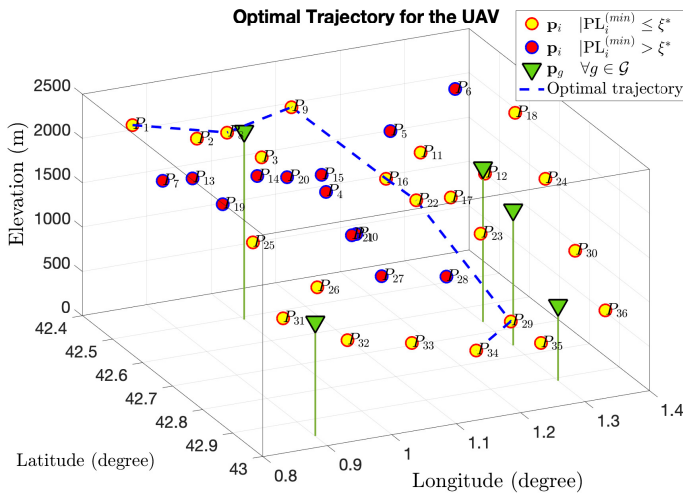


Fig. 6: Figure representing the UAV optimal trajectory in 3D visualization. The red circles \bullet represent the waypoints where the $PL_j^{(min)}$ is above the optimally achieved value ξ^* . The yellow circles \bullet represent the waypoints where the path loss is less or equal to ξ^* . The green triangles \blacktriangledown are the GBSs positions. The optimal found trajectory is in blue dashed line.

V. CONCLUSION

This paper presents a system model for UAV joint trajectory and communication quality optimization in complicated terrains such mountains and hill range where a complex propagation environment is encountered. The classical channel modeling in urban and rural zones can not be adopted in such situations where the NLoS aspect is extremely dominant. We propose to use the MKE diffraction phenomenon to retrieve a considerable wave energy (that may offer the link continuity) in such topographies to model the channel between the transmitter and the UAV. Then, we formulate the trajectory problem considering the communication quality by using the path loss between the GBSs and the UAV. We define the multi-objective cost to minimize the traveled distance and path loss for each trajectory waypoint and solve the problem using a MILP solver. Numerical investigations are conducted on a selected area of the French border using actual data terrains and randomly distributed GBSs with different elevations. The results reveal that the proposed approach provides the shortest trajectory and the minimum path loss over each waypoint between departure and arrival positions given a mission time. To this end, a "best feasible" communication with the shortest trajectory of a UAV using the diffraction in complicated topographies is achieved.

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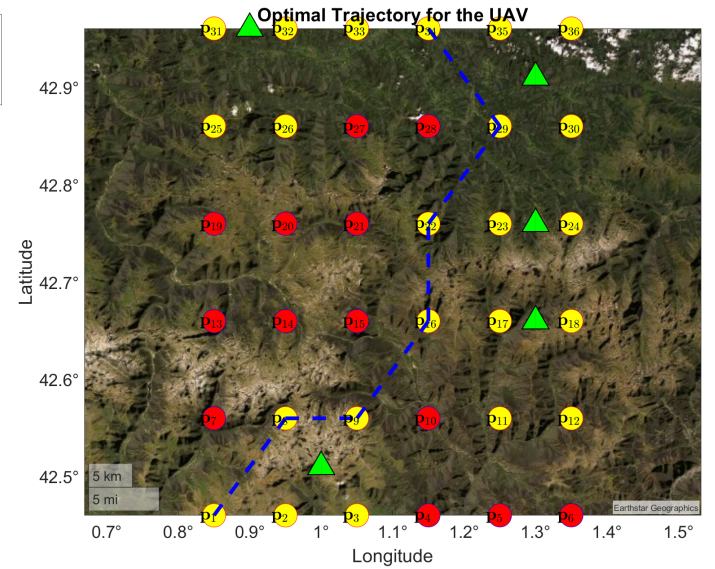


Fig. 7: Figure representing the UAV optimal trajectory in 2D visualization.

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