Numerical and Experimental Characterization of LoRa-based Helmet-to-UAV links on Flat Lands

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Abstract—The use of the LoRa communication protocol in a new generation of transceivers is attractive for search and rescue (SaR) procedures because they can operate in harsh environments covering vast areas while maintaining a low power consumption. The possibility of wearing helmets equipped with LoRa-radios and installing LoRa transceivers in unmanned aerial vehicles (UAVs) will accelerate the localization of the targets, probably unconscious. In this paper, the achievable communication ranges of such links are theoretically and experimentally evaluated by considering the possible positions of the helmet wearer (standing or lying) on a flat field, representing a simple SaR scenario. Simulations and experimental tests demonstrated that, for the standing position, the ground-bounce multi-path produces strong fluctuations of the received power versus the Tx-Rx distances. Such fluctuations can be kept confined within 100 m from the target by lowering the UAV altitude. Instead, for a more critical lying position, the received power profile is monotonic and nearly insensitive to the posture. For all the considered cases, the signal emitted by the body-worn transceiver can be exploited to localize the helmet wearer based on its strength, and it is theoretically detectable by the UAV radio up to 5 km on flat terrain.

Index Terms—Body-area IoT, LoRa, LPWAN, on-body radio, search and rescue, radio propagation, wearable antenna.

I. INTRODUCTION

The aim of search and rescue (SaR) operations is to localize a target person and then provide assistance. Such procedures are very common for both military and civilian purposes, particularly regarding the identification of first responders during fires, earthquakes and floods [1], [2] as well as in case of avalanches and to locate lost hikers [3]. Currently, ad-hoc civilian SaR systems are used in mountain environments and rely on radiofrequency devices: the avalanche beacons (also known as ARVs [4]) and the RECCO system [5]. However, the effectiveness of those technologies is hampered by the low ranges, which spans from about 60 m (ARVA) to about 120 m at most (RECCO). Moreover, both devices cannot transmit any critical data about the user’s health status.

TABLE I

EXAMPLES OF RELEVANT USE CASES OF LoRA.

| Ref. | Topic | Ref. | Topic |
|------|-------|------|-------|
| This work | Helmet-UAV off-body links for SaR | [13], [14] | Terrestrial links for mountain SaR |
| [8] | Localization and tracking | [15] | Emergency communications |
| [9] | Remote health monitoring | [16] | Extend the SMS coverage to unconnected areas |
| [10] | Human activity recognition | [17] | Industrial monitoring |
| [11] | UAV communications for swarm configurations | [18] | Wireless underground sensor networks |
| [12] | Recovery of incapacitated UAVs | [19], [20] | Smart cities |

Improvements could come from the internet of things (IoT) systems exploiting the recently developed low-power wide-area networks (LPWANs), such as LoRa, Sigfox and NB-IoT [6]. Thanks to their limited data rate, these networks can cover extended communication distances while maintaining very low power consumption [6]. They can thus enable connectivity even in the harshest environments.

LoRa is one of the most investigated LPWAN technologies, as it was proven to reach a 30 km communication range by transmitting 25 mW [7]. Wearable LoRa devices are currently under study for several applications ranging from tracking [8] to remote health monitoring [9]. Relevant use cases of LoRa are reported in Table I. LoRa was also proposed for SaR applications where the communication range and the power consumption are pivotal features. The authors recently proposed a LoRa-based IoT system for mountain SaR operations [14]. The system comprises body-worn LoRa radios and a range-based localization algorithm [21] exploiting received signal strength (RSS) measurements to localize the target when the GPS signal is absent. Thanks to the low energy consumption of the LoRa protocol, the radios can support the SaR operations for more than 5 hours and a half when they are fed with a typical battery of 1100 mAh capacity [14]. Meanwhile, the target can be localized even with a small number of measurements collected quickly by employing classical range-based localization algorithms that exploit the monotonic proportionality between the attenuation and the transmitter-receiver distance, as [21]–[24]. However, only terrestrial LoRa links have been considered so far, whereas, in SaR scenarios, the terrestrial operations are complex and slow. Therefore, LoRa-based SaR could greatly benefit from unmanned aerial vehicles (UAVs) searching the target from the sky. Indeed, by equipping a UAV with a LoRa receiver,
Most first responders and hikers wear a safety helmet during operations and outdoor activities (like skiing or canyoneering), so a possible placement of a LoRa wearable beacon is the helmet itself. Wearable helmet-mounted antennas were proposed for disaster prevention [23] and military forces [24]. The more common helmet antennas are dipoles [27], [28], patches [26], and loops [29]. Noticeably, as stated in Table I, a LoRa UAV-wearable device link [30] has never been neither characterized nor modeled. Moreover, all the helmet antennas proposed so far are designed to work when the user is vigilant and standing so that effects of the ground when the wearer is unconscious or injured have not been addressed. Instead, if an accident happens, the user is likely lying on the ground, eventually in the presence of snow, and the helmet-UAV link is expected to be greatly affected by the helmet wearer position.

This paper aims at evaluating the performance of radio-helmet-to-UAV links when both standing and lying users are involved. Such off-body links [31], [32] are analyzed for the purpose of collecting through a UAV the LoRa RSS coming from a radio-helmet wearer and activate a SaR procedure (the latter is outside of the scope of this paper).

The modeling and experimentation are focused on line-of-sight (LoS) scenarios in flat lands. However, despite the simple approximation, the model can describe several SaR events, for example, i) mountaineers in open environments hit by an avalanche, ii) lost hikers in some natural parks after fires, iii) injured soldiers in desert areas, iv) missing citizens and first responders after cataclysms (as earthquakes, tornadoes, tsunami) that destroy obstacles and create mostly flat and homogeneous zones. Within these conditions, the maximum LoRa communication ranges and the RSS stability versus the flight height and the UAV distance are here investigated. The propagation model accounts for several positions of the helmet wearer (both standing and lying), the ground-bounce multi-path and the LoRa transmission parameters (namely the variable sensitivity of the receiver). Furthermore, the basic model here presented can be extended to more complex environments by characterizing the radio propagation of the considered site, either through measurement campaigns [14], [33], [34] or by ray-tracing simulations [35], [36].

The paper is organized as follows. After the introduction of the most relevant symbols (section II), section III details the problem formulation exploiting the link budget and simplified modeling of the helmet transmitting antenna for some possible positions of a user with respect to the ground and the UAV receiver. A reliable gain for the helmet antenna, suitable to any condition, is derived for application to the link analysis in section IV through numerical simulations. An experimental campaign with a sensorized UAV and a helmet embedding a LoRa radio is described in section V and the measured data are compared, for corroboration, with the numerical results. Finally, in section VI findings are discussed, and conclusions are drawn.

### II. Symbols

The most relevant symbols used throughout the paper are here listed for the reader’s convenience in order of appearance.

- $G_T$: radiation gain of the transmitting antenna
- $G_R$: radiation gain of the receiving antenna
- $\varepsilon$: electric permittivity: $\varepsilon_0 \left[ \varepsilon_r + j \cdot \text{Im}\left(\varepsilon\right) \right]$ (permittivity of vacuum)
- $\sigma$: electrical conductivity
- $P_R$: power collected by the receiving antenna
- $H$: flying altitude of the UAV
- $h$: transmitter’s height from ground
- $t$: terrain condition
- $\tau_T$: power transfer coefficient of the transmitting antenna
- $\chi$: polarization loss factor
- $PL$: path loss
- $F$: path-gain factor
- $r$: ray-path
- $d_0$: reference distance of the log-distance path loss model
- $n$: path loss exponent
- $\lambda$: wavelength
- $\Gamma_T$: the module of the reflection coefficient of the transmitting antenna
- $SF$: spreading factor
- $pe^{j\varphi}$: Fresnel reflection coefficient
- $k_0$: propagation constant in the vacuum: $2\pi (\lambda)^{-1}$
- $\varphi$: incidence angle
- $\hat{\rho}_T$: polarization versor of the transmitting antenna
- $\hat{\rho}_R$: polarization versor of the receiving antenna

### III. Helmet-to-UAV Link

With reference to Fig. I the helmet-to-UAV link involves a LoRa transmitter (working in the $863 – 873$ MHz LoRa band [37]) connected to a helmet antenna having radiation gain $G_T$ and a UAV equipped with a receiving antenna of gain $G_R$. The user is assumed in four possible positions: standing, lying on the front, side-lying, lying on the back (Fig. I). Two reference boundary ground conditions are considered: a perfect electric conductor (PEC) ground (approximating a land covered by snow) and extremely dry terrain [i.e., rocks; permeability $\varepsilon = \varepsilon_0 (4.8 - 0.4j)$, electrical conductivity $\sigma = 10^{-4}$ S/m [38]].

The behavior of any real terrain is expected to be comprised between the aforementioned two extreme boundary conditions. The helmet-to-UAV link is hence described by the power $P_R$ collected by the receiver on the UAV according to the following link budget (all terms in dБ scale)

$$P_R (R, H, h, t) = P_T + G_T (R, H, h, t) + G_R (R, H, h) + \tau_T (h, t) + \chi (R, H, h, t) - PL (R, H, h) + F(R, H, h, t) \ ,$$

where $P_T$ is the transmitting power, $\chi$ is the polarization loss factor, $h$ is the transmitter height from the ground, $H$ is the flying altitude of the UAV, $R$ is the UAV’s ground distance from the target, and $t$ is the terrain condition (dry or
The log-distance $PL$ (path loss) expression is $PL(r) = PL(d_0) + 10 \cdot n \cdot \log_{10}(r/d_0)$, being $d_0$ a reference distance, $n$ the path loss exponent and $r$ the ray-path. Since LoS ground-to-air channels of low-altitude UAVs can be approximated by the free-space link [39], the conditions $d_0 = \lambda/4\pi$ and $n = 2$ are assumed. Being $\Gamma_T$ the module of the reflection coefficient of the transmitting antenna, $\Gamma_T = (1 - \Gamma_T^2)$ is the corresponding power transfer coefficient. The receiving antenna is instead considered perfectly matched to the receiver. The theoretical maximum communication distance is evaluated by imposing $P_R$ equal to the receiver’s sensitivity, which depends on the bandwidth and the spreading factor ($SF$) of the LoRa signal as in Table I. Based on [14] and [41], a signal bandwidth of 125 kHz and a variable $SF$ value are considered throughout the paper. Finally, the term $F$ is the path-gain factor that accounts for the multi-path in the case of a standing user through the flat-earth two-ray propagation model [39, 42]. With reference to the geometrical parameters in Fig. 1.

$$PL(r) = PL(d_0) + 10 \cdot n \cdot \log_{10}(r/d_0)$$

$$P_R = R,S\left[dBm\right]$$

**TABLE II**

| Spreading Factor | Sensitivity [dBm] |
|------------------|------------------|
| 12               | -136             |
| 11               | -133             |
| 10               | -132             |
| 9                | -129             |
| 8                | -126             |
| 7                | -123             |

where $k_0$ is the free-space propagation constant, $pe^{j\psi}$ is the Fresnel reflection coefficient, $\theta_2$ identifies the direction of the direct path, and the antennas’ gains are in linear scale. By assuming a smooth ground, then $\psi_1 = \psi_2 = \psi$. The Fresnel reflection coefficient for an electromagnetic wave polarized parallelly to the ground is evaluated from the permittivity of the land itself as [42]

$$\rho e^{j\psi} = \frac{\sin \psi - \sqrt{\varepsilon_0 - \cos^2 \psi}}{\sin \psi + \sqrt{\varepsilon_0 - \cos^2 \psi}}$$

For PEC reflecting surfaces, then $pe^{j\psi} = -1$. If the user is lying, the antenna is on the ground, the multi-path disappears, $F$ is dropped out from (1), and the ground effect is accounted for in the gain of the helmet antenna described in the next section.

The link budget in (1) is here parametrized regarding the user’s position (through the transmitter gain) and the features of the receiving antenna.

**A. Model of the Rx antenna**

The UAV is hereafter assumed to be equipped with a circularly polarized (CP) patch as in [43]. The gain $G_R$ (in linear scale) can be roughly approximated with an ellipsoid having rotational symmetry [44] whose elliptic section can be expressed in polar coordinates (w.r.t. Fig. 1).

$$G_R(\theta) = \frac{2a_z^2 a_z \sin \theta}{a_z^2 \cos^2 \theta + a_z^2 \sin^2 \theta}$$

The patch is assumed to be the pole and lie on the $(x, y)$ plane. The ellipse axes hence are

$$a_z = \frac{G_{R, max}}{2}$$

$$a_x = a_z \cot\left(\frac{BW_{z, x}}{2}\right),$$

where $\{G_{R, max}, BW_{z, x}\}$ are the maximum gain of the antenna and its half-power beamwidth, respectively.

**B. Model of the Tx antenna**

The choice of the reference helmet antenna could, in principle, consider both a linearly-polarized (LP) or a CP device as for the receiver onboard the UAV. A CP antenna would permit to minimize the interference due to the ground since the reflection would invert the polarization verse so that the reflected field is filtered out by the receiver antenna having opposite polarization. However, using a CP antenna
on the helmet too would introduce some drawbacks since the polarization of the helmet antenna could be seen as reversed by the receiver because of the unpredictable Tx-Rx mutual positions during the UAV flight and the actual posture of the user. Sharp polarization mismatches could occur hence preventing the establishment of the communication. For the sake of generality, the transmitting antenna is assumed to be a flat dipole (copper trace 35 μm thick) wrapped onto the top of the helmet (Fig. 3) according to two possible arrangements (w.r.t. the anatomical planes): along the median sagittal plane (hereafter *sagittal dipole*), and the coronal plane (*coronal dipole*). As shown next in section III-C, this arrangement guarantees a reliable polarization matching in most conditions.

The gain $G_T$ of the transmitting antenna is dependent on the working conditions. In particular, when the user is lying, the interaction with the ground is expected to disturb the radiation pattern strongly. To simplify the evaluation of the link budget in (1), the transmitting antenna is taken into account through an equivalent uniform gain pattern whose value is derived from statistical analyses involving the user’s possible positions. For this purpose, the radiation performances of all the combinations of antennas and positions are numerically evaluated utilizing the software CST Microwave Studio Suite 2018. The numerical model employed for the simulations includes:

- a homogeneous numerical phantom of a human head with average relative permittivity and conductivity $\varepsilon_r = 42.7$, $\sigma = 0.99$ S/m [45] respectively;
- a lossless foamed plastic ($\varepsilon_r = 1.5$ [46]) shell with the dimensions of a typical helmet for mountaineering (derived from the Vayu 2.0 model by Salewa, having perimeter length of 63 cm);
- ground modeled as a conducting plate.

The dipoles were preliminarily tuned at 868 MHz in the standing user case so that the reflection coefficient is $\Gamma_T \leq -10$ dB in the whole LoRa band. The proximity with the PEC ground in the case of a lying user produces a moderate impedance mismatch (Fig. 4), nevertheless preserving the same maximum value as before. If the terrain is dry, the reflection coefficients are less affected by the helmet position and are more similar to the standing user case.

By referring to the radiation gain patterns at the zenith (Fig. 5), it is clear that the two antenna layouts behave similarly for a standing user. In contrast, relevant differences are visible in the case of a lying user, with the maximum radiation occurring either along the zenith or the horizon depending on the position of the helmet.

The most appropriate antenna arrangement is the one maximizing the uniformity of the radiation pattern in the upper half-space in all the considered user configurations, especially in the lying ones. The complementary cumulative distribution function (CCDF) for $G_T > G_0$ in the whole half-space is used as a metric [Fig. 6(a)]. Accordingly, the coronal dipole outperforms the sagittal one. By considering, for instance, the

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**Fig. 3.** (a) Helmet and head numerical phantoms. The flat dipole (size in mm) along (b) the medial sagittal and (c) the coronal planes.

**Fig. 4.** Simulated reflection coefficients of the helmet antennas in Fig. 3 in four user positions over PEC terrain. The LoRa 863-873 MHz band is highlighted in grey.
Fig. 5. Simulated radiation gain of the helmet antennas (sagittal and coronal dipoles) over planes passing through the zenith. In the case of a lying user, a PEC ground is assumed. The dry terrain case returns the same patterns with an offset of $-2\,\text{dB}$.

**TABLE III**

| Standing user | Lying user |
|---------------|------------|
| Wet terrain   | $-4.5\,\text{dBi}$ | $-3.5\,\text{dBi}$ |
| Dry terrain   | $-6.5\,\text{dBi}$ |

threshold value of probability 75%, the corresponding lower bound gain $G_0 (CCDF = 75\%)$ of the coronal dipole is about 2 dB higher than the corresponding value of the sagittal dipole.

In conclusion, the coronal dipole is hereafter considered the transmitting antenna whose equivalent gain is $G_T = G_0 (CCDF = 75\%)$, keeping the different values for standing and lying cases and kind of terrain, as summarized in Table III.

![Image](image_url)

**Fig. 6.** Complementary cumulative distribution functions (a) $CCDF(G_0)$ for the sagittal and coronal dipoles by taking into account the data of all the three lying positions of the user on a PEC ground (Fig. 2), and (b) $CCDF(\chi_0)$ for the coronal dipole when considering both the standing and the lying postures.

C. Polarization Loss Factor

Like the antennas’ gains, the polarization loss factor heavily varies with the helmet wearer’s position and the terrain condition. The loss factor is evaluated from the polarization versors of the transmitter ($\hat{\rho}_T$) and the receiver ($\hat{\rho}_R$) as

$$\chi = |\hat{\rho}_T \cdot \hat{\rho}_R^*|^2$$

whereas the versor of the transmitting antenna is numerically evaluated when considering all the position-terrain combinations and all the possible observation angles [Fig. 6(b)]. From the simulations, $\chi \geq -3\,\text{dB}$ in 75% of the cases and, accordingly, the assumption $\chi = -3\,\text{dB}$ is considered for the next evaluation of the received power $P_R$.

IV. Link Evaluation

Following the above framework, the radio-helmet-to-UAV link is numerically evaluated to predict the maximum achievable communication range and analyze the two-ray interference through coverage maps. The communication range is expressed as the radio-helmet-UAV ground distance since it is a crucial parameter for most SaR operations. The user-UAV link must be as monotonic as possible to apply range-based location algorithms exploiting the RSS effectively.

The RSS is evaluated according to (1). The parameters of the receiving antenna to derive $G_R(\theta)$ are referred to the Keonn Advantenna-p11 ($BW_{z\xi} = 100^\circ$, $G_{R,max} = 3.2\,\text{dBi}$), which is then used for the experimentation described in the next section. The received power at the UAV side is evaluated for a variable flight altitude $5\,\text{m} \leq H \leq 120\,\text{m}$ of the UAV.

The corresponding maximum radio range $R_{max}$ wherein the received power $P_R$ equals the sensitivity of the receiver, is derived. The transmitter must moreover comply with the ERP (effective radiated power) regulation for LoRa systems. By $H = 120\,\text{m}$ is the highest altitude of a UAV that is compliant with EU regulations on civilian applications (open category).
enforcing the EU constraint \(\text{ERP} \leq 868\) MHz over the maximum LoRa irradiation (i.e., ERP = 14 dBm at 868 MHz), the maximum transmitter power to insert in (1) is \(P_T = 14\) dBm. All computations refer to an \(h = 1.7\) m tall user. Finally, from Fig. 4 \(\tau_T(h, t) \simeq -0.01\) dB. The values of the parameters employed in the numerical simulations are resumed in Table III and Table IV.

Table IV: Considered values for the numerical RSS evaluation.

| Parameter | Value | Parameter | Value |
|-----------|-------|-----------|-------|
| \(P_T\)   | 14 dBm| \(R\)     | [0; 10000] m |
| \(G_{R,max}\) | 2.3 dB | \(H\)     | [5; 120] m |
| \(BW_{eg}\) | 100 MHz| \(h\) (standing) | 1.7 m |
| \(\chi\)   | -3 dB | \(h\) (flying) | 0 m |
| \(f\)      | 868 MHz| \(\tau_T\) | -0.01 dB |

Although both the lying-user and the standing-user links are in LoS conditions, the evaluated RSS is rather different. Firstly, by considering the standing-user case, Fig. 7(a) shows the maximum estimated communication distances versus \(H\) for dry or wet terrains. The link range is mostly unaffected by the terrain’s wetness, which instead impacts the interference fringes, as shown next. The achievable \(R_{max}\) spans from about 3.8 km to 6.5 km, depending on the SF. For instance, by increasing SF from 7 to 12, the predicted \(R_{max}\) for \(H = 50\) m lengthens from 2 km to 3 km. Focused coverage maps for \(R \leq 500\) m, wherein the interference pattern is highly variable, are depicted in Fig. 7(b,c). The RSS is not monotonically related to the Tx-Rx distance, even in the ideal free-space case. The nulls in the RSS patterns are sharp due to the strong interference, especially for short horizontal distances. Regarding the ground’s condition, the wetter the terrain is, the stronger the reflected field is and, consequently, the more relevant the fluctuations are. An example of RSS profiles due to different terrain’s wetness is shown in Fig. 8. When comparing Fig. 8(a) with Fig. 8(b), it is evident that the fluctuations can be restricted to shorter distances \(R\) by lowering \(H\). In particular, for \(H = 15\) m, the interference fringes are restricted to \(R < 100\) m.

In the case of a lying user, the multi-path is absent so that the RSS decreases monotonically with the Tx-Rx distance (Fig. 9). Unlike the previous case, the wetness of the terrain has a significant impact on the maximum range, especially for high SF values. Indeed, if the wearer is lying on the ground, the on-helmet antenna’s gain improves with the terrain wetness of 2 dB (as in Tab. III), at most, leading to a 21% higher radio range. The maximum communication range is up to 9.5 km if the terrain is wet, and hence it is more extended than the corresponding distance in the case of a standing user.

V. Experimentation

The above numerical achievements are corroborated by preliminary experimentation with a UAV equipped with a LoRa receiver and a typical mountain helmet embedding a transmitter to reproduce the simulated scenarios. Both vertical and horizontal flights are performed to verify the model’s prediction.
Fig. 9. Theoretical coverage maps of the LoRa transmitting radio-helmet and the UAV receiver in the lying user case. (a) Maximum communication distances versus the UAV height when varying the $SF$ value and (b) RSS for $R \leq 500$ m (wet terrain).

Fig. 10. Radio-helmet prototype hosting a coronal dipole, (a) top view and (b) side view with the indication of the LoPy-4 board installed in the interior of the helmet.

The LoRa transmitting and receiving modules are Pycom LoPy-4 programmable boards (embedding the LoRa SX1276 transceiver; $P_T = 14$ dBm, bandwidth of 125 kHz, carrier frequency 868 MHz, coding rate 4/5 [14]). The spreading factor is set to $SF = 12$ to maximize the receiver sensitivity and characterize the link as far as possible.

The transmitting antenna is a commercial dipole (by Pycom company [49]) fixed on a Vayu 2.0 helmet for mountaineering along the coronal plane (Fig. 10). The helmet is worn by a 1.7 m tall volunteer as in the simulations.

The input parameter of the helmet-mounted dipole is measured by a portable Vector Network Analyzer (MS2024A by Anritsu) when the volunteer is standing and lying over dry and wet terrains. Overall, despite some frequency shift between standing and fallen positions w.r.t. the nominal LoRa band, as predicted by the simulations (Fig. 4), the obtained reflection coefficient (Fig. 11) is always $\Gamma_T < 11$ dB at the useful frequencies, and it is well comparable with the simulated $\tau_T$ value in Table IV. The maximum observed downward frequency shift is about 55 MHz over all the conditions, so the helmet antenna must thus ensure a frequency bandwidth of at least 65 MHz to cover the whole UHF LoRa band regardless of the wearer posture.

The UAV is a DJI Phantom 3 Pro hosting a 137 mm × 137 mm CP patch (Advantenna-p11 Keonn as before). The battery pack and the LoRa receiver are fixed at the landing gear of the UAV (Fig. 12).

The RSS measurements are performed during a period of consecutive sunny days over an uncultivated field near Colle Romito [Ardea, Lazio, Italy; Fig. 13(a)]. The field is flat [Fig.
and covered by bushes. Thus, the test field can be considered dry ground. In the experiments, the UAV is driven at 1 m/s approximate speed along both horizontal trajectories at fixed altitudes and vertical trajectories at a fixed radial distance from the user. The RSS in the dBm scale is estimated from the RSSI (received signal strength indicator) and from the SNR (signal-to-noise ratio) that are returned by the receiver, as \[ P_R = RSSI - 10 \log_{10} \left( 1 + \frac{1}{SNR} \right) + c_0, \] where \( P_R \) is in dBm scale, the RSSI is in dB scale, the SNR is in linear scale, and \( c_0 \) (dBm scale) is a constant parameter obtained from a single-point calibration through the Anritsu MS2711A spectrum analyzer.

In the first test, the UAV takes off at a distance \( R = 500 \text{ m} \) from the volunteer and then flies up vertically up to \( H = 120 \text{ m} \) [Fig. 13(c)]. In the second test, the UAV flies horizontally at two fixed altitudes \( H = \{50 \text{ m}, 15 \text{ m} \} \) for distances \( 1 \text{ m} \leq R \leq 2700 \text{ m} \) [Fig. 13(d)]. During the flights, 1921 data packets are received overall.

The measured RSS profiles are reported in Fig. 14 and Fig. 15 and compared with the simulated ones for vertical and horizontal flights, respectively. Interestingly, the RSS is rather insensitive to the lying user’s particular position, and the modeling through a numerically evaluated equivalent gain is proven to be effective.

Overall, in spite of some differences, the measurements corroborate the phenomena derived by the numerical model in section IV (Fig. 7 and Fig. 9), even in the presence of the significant multi-path in the standing configuration. In detail, simulations overestimate the RSS of just 2 dB on the vertical and horizontal paths shown in Fig. 14 and Fig. 15(a,b,d). Regarding Fig. 15(c), there are some differences with the simulations at the end of the profile, where the model underestimates the RSS. The measured profile follows the flat-earth two-ray model for \( R \leq 700 \text{ m} \) but, afterwards, it shows an intermediate behavior between the two-ray and the single-ray propagation. In this condition, the incident rays intercept the ground at grazing angles (\( \phi \leq 1.4^\circ \)) so that slight surface irregularities are no longer negligible [42]. Moreover, the combined effect of the absorption by the low vegetation, scattering, and the earth elevation [Fig. 13(b)] can attenuate further the reflected field. The result is a weaker interference and, consequently, a lengthening of the link range, benefiting the target identification from long distances.

The Tx-Rx distance slightly affects also the time delay between the transmission and the reception of the packets. In the performed flights, the measured delay ranges between 820 ms (at the shortest helmet-UAV mutual distance) up to 1022 ms (upper bound distance) and is comparable with the values reported in [50]. By considering the typical packet transmission rate (roughly 1 packet every 3 s), the above delays will not cause any loss of the received packet sequence. Accordingly, the observed packet delivery ratio (PDR) in the experiments is of the order of 95% and nearly constant in all the cases. In more complex environments with non-flat grounds, the soft degradation of the LoRa signals will lead to reduced radio ranges with the corresponding decrease of the PDR [7, 14]. Concerning the implications on localization, the time delay could slightly raise the localization errors, especially if the target is moving. In SaR operations, however, the transmitter is mostly stationary since the wearer could be fallen or at most slowly moving within a confined area. The corresponding error in estimating the position of the target is therefore expected to be modest. Furthermore, the UAV will generally get closer and closer to the target during SaR procedures so that the time delay reduces, the PDR increases, and the estimation of the target position is progressively refined.

It is worth specifying that, due to hardware constraints and law regulations, the above experimental tests did not allow us to appreciate the complete communication range corresponding to the last received packet. For this purpose, the UAV should have flown up to a much longer horizontal distance \( R > 2700 \text{ m} \), thus exiting from the test area and overflying various obstacles (houses, roads, woods). Anyway, ...
in past experiments [13], we placed a LoRa radio over an 85-
m-high overpass while the other radio was kept inside a car that was driven away from the overpass. This arrangement, comparable with the helmet-UAV system, achieved communications up to 8.4 km, in reasonable agreement with the numerical estimations.

VI. DISCUSSION AND CONCLUSION

The helmet-to-UAV communication over flat lands based on the LoRa protocol has been numerically characterized and corroborated by a preliminary experimental campaign. The UAV is theoretically capable of collecting the helmet signal up to 5 km in a flat scenario even in the worst case (standing user, perfectly flat and wet terrain), and up to 9.5 km in case of wet terrain and lying user when the UAV flies at an altitude of 120 m. The RSS in the case of a lying user is robust concerning the position of the helmet on the ground, and it monotonically decreases with the Tx-Rx distance. Instead, the RSS with a standing user (e.g., a lost hiker wandering on a snowy land) experiences fluctuations that are sharper the wetter the terrain, due to the ground-bounce multi-path, especially near to the helmet’s wearer.

The basic model extension to a more complex radio propagation environment, including non-LoS links, can be quickly drawn if an equivalent log-distance PL model is available. For example, the authors recently modeled the LoRa propagation in snowy mountain fields, even when the transmitter is buried [14]. Burying the transmitter under 1 m of snow adds an entry loss of about 60 dB, which can be accounted for in the transmitter’s equivalent gain. Instead, the retrieved log-distance parameters for a transmitter placed on the snow were $n = 3.17$ and $PL(d_0 = 1 \text{ m}) = 56.7 \text{ dB}$, and these values are still approximately valid in the case of a lying user in a snowy plain. Hence, the path loss model and the eventual path-gain factor must be inserted appropriately in the proposed link budget.

It is worth considering that the communication could be more challenging or even forbidden in harsher conditions that excessively reduce the equivalent antenna gain, as, for instance, when the helmet is buried under more than 1 m of wet snow or deeply submerged by water (e.g., fallen into a river). In other cases, particular configurations of obstacles may highly raise the multi-path and the shadowing, as we observed when the target was on the bottom of a canyon while the UAV was flying outside it [51].

Finally, considering the model’s application to SaR operations, the lying user case is the most interesting because the user could be unconscious and even partially covered and, consequently, not detectable by a camera. The helmet wearer can be rescued through classic range-based localization algorithms like those mentioned in section I. Instead, in the case of a standing user, the interference fringes make applying the above localization methods more challenging [52]. Spatial fluctuations can be mitigated by lowering the UAV’s flying altitude. For instance, the RSS oscillations are confined between 100 m far from the target for an altitude $H = 15 \text{ m}$. The fluctuations can also be reduced by placing the wearable antenna near the ground (e.g., on a boot). In any case, thanks to the local confinement of RSS fluctuations, the UAV can roughly estimate the target position from longer distances. Then, the UAV can approach the estimated location and, when the signal begins fluctuating, it could use the support of optical or thermal cameras to reach the user, who is standing and, likely, conscious. Hence, while the high-RSS fringes are produced by the reflection from the flat ground when the user is standing, the eventual low-RSS fringes are generated by the multi-path from non-flat terrains and will be observed for longer distances. Furthermore, the dynamic refinement of the position estimation while approaching the target allows also to contrast the packet’s loss caused by the harsh environment. Regardless of the target’s posture, the UAV could move along non-linear trajectories to speed up the search, as proposed in [53], [54], by dynamically accounting for the signal variations and the topology of the area. A swarm of multiple coordinated UAVs [55], [56] could also be deployed to provide data from different angles and distances to mitigate the multi-path effect.

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