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Improving the radio signal intensity loss model between the drone and the base station

Roman Zaivyi*
Postgraduate Student
Lviv Polytechnic National University
79013, 12 Stepan Bandera Str., Lviv, Ukraine
https://orcid.org/0009-0003-4096-4111

Volodymyr Pavlysh
PhD in Technical Sciences, Associate Professor
Lviv Polytechnic National University
79013, 12 Stepan Bandera Str., Lviv, Ukraine
https://orcid.org/0009-0004-3996-5923

Abstract. The purpose of the study was to develop a radio signal propagation model that considers the drone's flight altitude and the specifics of the ground-to-air channel to improve the accuracy of signal loss estimation. The study used comparative analysis of classical models, calculation of signal losses at different altitudes and distances, estimation of the effect of line-of-sight and birefringence propagation, and development and verification of an improved exponential model depending on the height of the drone. It was determined that these models do not account for the substantial influence of the drone's flight altitude and the increased probability of a line of sight between the drone and the base station, which leads to an overestimation of the predicted signal loss by tens of decibels. Based on the analysis, an improved analytical model was proposed, in which signal losses are defined as the sum of losses in free space and the height-dependent additional term. This additional term is described by an exponential function that decreases with increasing drone altitude and reflects a gradual transition from indirect visibility conditions to line-of-sight conditions. In addition, the model introduced distance correction, taking into account the actual geometry of the ground-to-air channel. Calculations performed for the frequencies of 868 MHz and 1,800 MHz showed that the improved model is in good agreement with experimental observations and provides results close to the free space model at significant altitudes. Comparison with the Hata models confirmed that the new model reduces the forecast error in urban conditions to tens of decibels. Considering the flight altitude and gradually moving from indirect to direct visibility greatly increases the accuracy of predicting signal loss for unmanned aerial vehicles. The practical importance of the study lies in the fact that the proposed model enables a more accurate prediction of radio signal losses in the ground-to-air channel, which is the basis for designing reliable communication systems with unmanned aerial vehicles

Keywords: radio communication; altitude; direct visibility; exponential correction; urban environment; analytical model

INTRODUCTION

Unmanned aerial vehicles are increasingly being used in the civil and military fields for surveillance, cargo delivery, and data collection. Stable radio communication between the device and the base station is critical to ensure reliable control of drones and information transmission. Traditional radio signal propagation models

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*Corresponding author

developed for ground-based cellular networks, such as the Okumura, Hata, and COST-231 Hata models, are based on statistics for transmitters and receivers located close to the ground and account for the effects of reflections, diffraction, and shielding by buildings. However, when applying these models to unmanned aerial vehicles, there are substantial limitations: drones can be located at an altitude of tens of meters or higher, which significantly increases the probability of line-of-sight, reduces the impact of ground interference, and changes the nature of signal attenuation. As a result, classic ground-based models often overestimate signal losses, especially in urban environments.

In the field of accurate signal loss prediction for ground-to-air scenarios under study, the problem of considering the drone's altitude and line-of-sight effects remains. O.V. Troyanskiy & P.O. Kandieiev (2025) showed that classical ground-based models overestimated signal loss at high altitudes due to ignoring the line of sight (LoS). It was necessary to address the altitude of the drone to accurately predict the signal strength. N. Moraitis *et al*. (2023) noted that drone amplification reduced the multipath propagation effect and reduced average signal loss. It was proposed to account for the exponential reduction of additional losses with increasing height to adapt the model. F. Fuschini *et al*. (2022) demonstrated that considering the LoS between the drone and the base station improved the accuracy of signal strength prediction. It is proven that models that disregarded height significantly overestimated losses in line-of-sight conditions. O.Yu. Malyi *et al*. (2024) pointed out that at short distances, classical models often overestimated losses, while the two-beam approach accurately reflected interference effects. It was determined that bearing the effect of reflection from the ground in mind was crucial for low drone flights. N. Ranchagoda *et al*. (2021) emphasised that the type of terrain and density of buildings drastically affected the characteristics of the ground-to-air channel. It was stated that corrections for urban and open areas were necessary to improve the accuracy of the model.

A. Chornyi *et al*. (2025) demonstrated that an exponential decrease in additional losses with increasing altitude reflects the transition from indirect to direct visibility. Experimental observations confirmed that this relationship was in good agreement for different heights. H.-S. Shin *et al*. (2024) showed that geometric correction of the distance between the drone and the base station improved the accuracy of modelling at small horizontal distances. It was recommended to use the adjusted distance in formulas for a more accurate estimate of signal loss. S.K. Alavipanah *et al*. (2022) proved that taking the average height of buildings in urban areas into account allowed adjusting the shading effect. Without this amendment, the models significantly overestimated losses in dense buildings. Z. Xiao *et al*. (2025) established that changes in signal frequency significantly affected losses and should have been considered in the simulation. High frequencies were found to be more sensitive to interference and multipath propagation. Q. Zhu *et al*. (2021) showed that altitude-dependent parameters allow the model to be adapted for various environments, including urban, suburban, and open areas. It is emphasised that this approach provided more reliable forecasting and improved the efficiency of drone control systems. These studies have shown that increasing the drone reduces multipath attenuation, considering the LoS and altitude improves simulation accuracy, and geometric and exponential corrections allow models to be adapted for different types of terrain. However, there is a need to develop a generalised model that simultaneously takes into account flight altitude, the impact of reflections from the ground, and adapts to different environments to accurately predict signal strength.

The study aimed to develop a signal propagation model that accounts for the drone's flight altitude, ground-to-air channel geometry, and environmental influences, providing a more accurate assessment of signal losses and improving the reliability of unmanned control and data transmission systems. The objectives of the study were to review existing approaches to modelling signal propagation in the ground-to-air channel, consider the influence of drone flight altitude and environmental features on signal characteristics, and evaluate the accuracy of classical and improved signal loss models and their effectiveness for unmanned data transmission systems.

MATERIALS AND METHODS

The study examined methods for estimating radio signal loss to ensure reliable communication between a base station and an unmanned aerial vehicle (UAV). The fundamental Free Space Path Loss (FSPL) model was analysed, which describes ideal conditions for signal propagation without interference (Al-Hourani *et al.*, 2014) (1):

$$PL_{FS(d)} = 32.44 + 20\, log^{10}(d) + 20\, log^{10}(f), \quad (1)$$

where d – the distance between the transmitter and receiver, km; f – the signal frequency, MHz.

When developing the improved model, the FSPL value was used as the lower limit of signal loss, 91.5 dB at a distance of 0.5 km at 1,800 MHz. Empirical ground-based models were also considered, in particular, the Okumura model, which is based on experimental data and considers average signal losses depending on distance and terrain features (Gupta, 2013) (2):

$$L^{50}(d,f) = L_{FS(d,f)} + A_{\mu(d,f)} - G_{ht} - G_{hr} - G_{env}, \quad (2)$$

where $L_{FS\,(d,\,f)}$ – loss of free space; $A_{\mu\,(d,\,f)}$ – average additional losses (deviations from free space) according to measurement data for distance and frequencies f; G_{ht} and G_{hr} – coefficients (wins) due to the height of the transmitting and receiving antennas, respectively; G_{env} – coefficient considers the type of terrain (urban, suburban, open).

A model of M. Hata (1980) was examined as an analytical approximation of the Okumura model, which provides explicit formulas for calculating average losses in urban and suburban conditions (3):

$$L_{Hata}(d) = 69.55 + 26.16\ log_{10}(f) - 13.82\ log_{10}(h_b) - a(h_m) + (44.9 - 6.55\ log_{10}(h_b))\ log_{10}(d), \quad (3)$$

where f – frequency, MHz (from 150 to 1,500 MHz); h_b – base station antenna height, m (from 30 to 200 m); h_m – mobile receiver antenna height, m (from 1 to 10 m); d – distance, km (1-20 km).

The COST-231 Hata model was examined as a modification of Hata for high frequencies and densely built-up large cities with additional correction factors (European Commission: Directorate-General…, 1999) (4):

$$L_{COST231}(d) = 46.3 + 33.9\ log_{10}(f) - 13.82\ log_{10}(h_b) - a(h_m) + (44.9 - 6.55\ log_{10}(h_b))\ log_{10}(d) + C, \quad (4)$$

where all values are in the same units as in (3), and C – an additional coefficient for large cities: $C = 3$ dB for the metropolitan area and $C = 0$ for medium-sized cities.

During the next stage, the paper systematised the factors that affect signal losses in the air-ground channel. Key aspects were highlighted: the height of the drone's flight, the presence of a LoS between the transmitter and receiver, the nature of multipath propagation, and the effect of reflection from the Earth's surface. For each of these factors, it was discussed how it changes the signal intensity and why classical ground-based models do not take these effects into account or do so insufficiently. Special attention was paid to the dependence of losses on altitude, which determines the probability of a LoS and reduces the impact of interference and multipath. The theoretical basis of the study was the recommendations of ITU-R, where the FSPL model was used as a baseline scenario: P.525 defined the method for calculating free losses, P.528 described ground-to-air radio lines, and P.1411 – short-distance systems in urban and suburban settings (Uko *et al.*, 2024).

Based on the analysis, the concept of an improved model was proposed. The main idea was to combine the classic free space model with an additional term that considers excessive signal loss associated with the drone's environment and altitude. This term was defined as an exponential function of altitude, which allows the model to smoothly transition from ground-based Non-Line-of-Sight (NLoS) conditions to line-of-sight conditions as the vehicle's height increases. Thus, the model becomes able to correctly describe the channel over a wide range of heights, without resorting to various empirical corrections for each specific scenario. Calculations were performed in two typical scenarios using comparative analysis to evaluate the behaviour of the models, which allowed comparing the results of classical models and the proposed improved model for different drone heights, distances, and signal frequencies. In the first scenario, the frequency $f = 1{,}800$ MHz was used, and the base station height was = 30 M, and horizontal distances ranged from 0.5 km to 5 km; calculations were performed for FSPL, equation (1), Hata model for the city (formula (3), $h_m = 1.5$ m), Hata models for open terrain with appropriate correction and improved model (Formula 7). In the second scenario, the frequency $f = 868$ MHz with similar parameters was used to compare the effect of frequency on signal loss.

In addition, the work considered the geometric aspects of signal propagation, particularly the use of an effective distance between the base station and the drone, including the flight altitude. This allows for adequately describing the signal intensity even at short distances or at a drone height drastically higher than the height of the base station antenna. The inclusion of average effects of ground reflections and possible interference phenomena, which are characteristic of two-beam models, was also discussed with the aim of improving the accuracy of modelling in real conditions. The final stage of the work was the formulation of the analytical dependence of signal losses on the horizontal distance and height of the drone, which includes parameters that can be interpreted physically and adjusted to different environments: urban areas, suburbs, open areas, or woodlands. This approach allows creating a unified model that covers different scenarios for using UAVs without having to switch between several classic models.

RESULTS

Overview and characteristics of known radio signal propagation models

The most basic model of signal attenuation in free space, FSPL describes the conditions of an ideal LoS without interference. It was based on the Fris equation applied to the far field of an antenna (Al-Hourani *et al.*, 2014). According to this model, the power received by the receiver decreases inversely proportional to the square of the distance d between the transmitter and receiver and the square of the frequency (or directly proportional to the square of the wavelength). In logarithmic terms (in decibels), losses in free space are written as (1). Formula (1) is based on the assumption that isotropic antennas are used and that there is no reflection or absorption of the signal. The FSPL model is used in the ITU-R recommendations as a baseline scenario for line-of-sight signal loss (Uko *et al.*, 2024). In these documents, the FSPL is considered as a reference value that determines the minimum possible level of power loss under ideal conditions. In real-world conditions, in particular, when providing communication with UAVs, this model has limitations related to the altitude orientation of the antenna. It does not address the variable altitude of the drone, the presence of obstacles in urban or forest environments, the influence of the angle of inclination of the signal trajectory, and dynamic environmental factors such as the movement of objects or weather conditions. Due to the influence of interference, multipath propagation, and other factors, signal loss in real conditions increases (Isabona *et al.*, 2023). In further development of the improved model, the FSPL values will be used as the lower limit of signal loss, i.e., as the most optimistic scenario.

One of the first empirical models for ground-based radio communication was the Okumura model, developed based on large-scale measurements in the Tokyo area (Gupta, 2013). This model does not have a simple analytical dependency since it is based on graphs and reference tables. It defines the median signal strength (or loss) as the sum of losses in free space and empirical correction components. In general, the average signal loss according to the Okumura model can be represented as (2). Value A_μ and *G*-coefficients are determined from empirical curves. The Okumura model covers frequencies from about 100 MHz to 1,920 MHz and distances from 1 to 100 km. It accounts for different types of terrain (densely built-up urban, suburban, open rural), introducing appropriate amendments. Although the Okumura model is quite accurate (error ~10-14 DB) for conditions similar to those in which measurements were made, its disadvantage is the lack of a simple formula – the need to use graphs reduces the convenience of practical application.

A model of M. Hata (1980) was developed as an analytical approximation of the experimental Okumura model. It is known as the "Okumuri-Hata model" and has become the standard for calculating losses in terrestrial cellular networks. In contrast to Okumura's original model, Hata presented empirical dependencies in the form of easy-to-use formulas describing average signal losses. For urban development conditions (small/medium city), this model looks like (3). Function $a(h_m)$ – correction for the height of the mobile receiver, depending on the size of the city. For medium/small cities: $a(h_m) = (1.1\ log_{10} f - 0.7)\ h_m - (1.56\ log_{10} f - 0.8)$, and for a large city, formula $a(h_m)$ other (quadratic dependence). Thus, (3) determines the average signal loss in urban settings. For other types of terrain, additional corrections are introduced: for suburban areas, the value (3) is reduced by the $2\,[log_{10}(f/28)]^2 + 5.4$ factor, and for open rural areas – factor $4.78\,[log_{10}(f)]^2 - 18.33\ log_{10}(f) + 40.94$ (these negative values reduce losses compared to the urban environment). The Hata model actually translates Okumura curves into a convenient analytical form and covers the frequency range of 150-1,500 MHz and distances up to 20 km. The average error of the model is about 6 dB, which is considered an acceptable level for engineering calculations of the coating. Its limitations are similar to the Okumura model: it is correct only within the parameters obtained during measurements, and does not consider random signal fluctuations, in particular, fading or shadow attenuation. Therewith, due to its simplicity and compliance with practical data, Formula (2) has become widely used in network planning (Djomadji *et al.*, 2023).

For use at higher frequencies (up to 2 GHz) and in conditions of dense urban development, a modification of the Hata model was created as part of the Action 231 of COST-231 project in 1990s (European Commission: Directorate-General..., 1999). The COST-231 Hata model retains the structure of Formula (3), but includes an additional correction term and expands the operating frequency range. For urban areas, it is presented in the form of (4). Formula (4) is valid for frequencies from 1,500 MHz to 2,000 MHz. Thus, the COST-231 Hata model considers the tendency for losses to increase at higher frequencies by partially adjusting the frequency term (compared to (3), the coefficients at $log_{10}(f)$ and the constant values are changed) and introduces a correction C for the densest urban development. Within its application range, this model provides precision similar to the original Hata model.

Practical applicability and limitations of the considered signal propagation models

The classical models considered are based on a terrestrial communication scenario, where the base station is located on a mast or building (h_b up to ~200 m), and the receiver is at human or vehicle level (h_m up to ~10 m). They empirically consider the impact of urban development through fixed corrections, but do not reflect changes in the nature of signal propagation when the receiver is substantially raised above the average level of buildings. The free space model (1) describes ideal conditions, while the Okumura-Hata models (3-4) provide averaged losses for typical urban conditions without LoS, accounting for multiple reflections and diffraction from terrain and buildings. Therefore, when using these models for drones that can fly tens of meters or higher, it is necessary to consider their limitations.

One of the key limitations is the receiver height (Tataria *et al.*, 2021). Okumura Hata models were designed for $h_m \leqslant 10$ m. For drones, the height of the receiving antenna can be intensely higher – from 50-100 m for small models to hundreds of meters for high-altitude vehicles. Extrapolation of Hata formulas to such heights has not been experimentally confirmed and may give inaccurate results. In particular, in the Hata model, the term $a(h_m)$ for large h_m stops growing (for $h_m > 10$ m, it is actually stabilised), i.e., raising the antenna above 10 m is disregarded. In fact, raising the drone reduces the impact of interference on the ground, which should reduce signal loss. Therefore, without additional adjustments, the Hata model may overestimate the loss estimate for drones at high altitudes.

Another important aspect is the availability of LoS (Waqas *et al.*, 2024). In urban settings, direct visibility over long distances is usually absent for terrestrial subscribers – the signal mainly reaches the receiver through reflection and diffraction. These are the conditions that the Hata and COST-231 models consider. Drones flying above roofs are much more likely to establish a LoS connection to the base station. In LoS mode, the signal loss approaches the free space model, where the attenuation index is $n \approx 2$. Therefore, classical empirical models focused on NLoS overestimate losses in the case of LoS. This is confirmed by field observations: as the height of the drone increases, the share of direct signal increases, and additional losses decrease. For example, when the receiver is raised from 10 m to 40 m, the average fading value (log-normal shadow stagnation) decreases exponentially from about 14 dB to 3 dB, which indicates a substantial improvement in propagation conditions. Classic models are also limited at short distances (ElSayed & Mohamed, 2022). In particular, the Hata model is formally applied for $D \geqslant 1$ km. For drones, the range is much shorter – for example, during takeoff, landing, or hovering directly over a base station, when d can be hundreds of meters or less. In such cases, the classical model is extrapolated beyond the original data and may produce unreliable results. On the contrary, the free space model correctly describes the situation even for minimal d, considering the transition to the near zone of the antenna, if necessary. Thus, at short distances, empirical models often overestimate losses, since they disregard the presence of a LoS and the reduced number of obstacles.

Special attention should be paid to the influence of the Earth's surface and reflections (Zhao *et al.*, 2025). In the ground-to-air scenario, signal propagation is characterised by reflection from the ground. A drone located at a certain altitude simultaneously receives a direct signal and a signal reflected from the surface of the ground or water. The superposition of these two waves on receivers can cause interference effects: at some distances, the signal can be amplified or weakened, as described by the two-beam model. For a ground receiver, the reflected signal is usually partially shielded by surrounding objects, while for a drone, this restriction is absent. The classic Hata and Okumura models disregard the explicitly two-beam nature of the channel. Because of this, at certain distances, the actual signal losses may exceed the values predicted by the free space model due to partial destructive interference of the direct and reflected signals. This is especially noticeable when the drone flies at a low altitude over an open area or water surface, forming so-called beam web zones, where the signal level changes with distance. Thus, classic models need to be adapted for drone scenarios. It is necessary to consider the increase in efficiency due to height, which reduces losses due to the presence of LoS, along with the effects of the birefringence of the signal.

The improved model should take into account the height of the drone as one of the parameters that affect losses. At $h \to 0$ (drone on the ground), the model must coincide with the classic ground model (for example, a Hata for a suitable environment), and at a large h, it must approach the loss of free space. The model should consider the possible influence of the reflected beam from the Earth – for this purpose, it is desirable to reflect an interference increase in losses at some distances, or at least account for the average effect of reflections (for example, an increase in the effective indicator of the degree of attenuation over long distances). The model should retain its usability – preferably an analytical formula with a small number of parameters that can be interpreted. In the two-beam model, there is a so-called fracture distance d_b, after which, the reflected and direct rays begin to interfere significantly, and the effective attenuation law changes from $1/d^2$ to approximately $1/d^4$. When the transmitter height is h_b and the height of the receiver h (drone), this distance is estimated as:

$$d_b \approx \frac{4\pi h_b\, h}{\lambda}, \tag{5}$$

where λ – wavelength. For example, for a base station $h_b = 30$ m, drone $h = 50$ m, and frequency f 2GHz ($\lambda \approx 0.15$ m) is obtained $d_b \approx 0.19$ km, that is, about 190 m. At distances less than d_b signal losses ~ both in free space and in large ones-additionally increase due to interference with reflection (by tens of dB after several kilometres). In real-world conditions, sharp interference dips are somewhat smoothed out due to surface irregularities, angle changes, etc., so this effect was considered on average as a smooth increase in losses with distance.

Based on the free space model (1), a term that considers excessive signal losses (in addition to FSPL) due to environmental factors can be added to it – mainly shielding and multipath. This additional term is denoted as $\Delta L\,(h)$. It should depend on the height of the drone h so that $\Delta L \to 0$ at high h (when the drone is high and nothing significantly interferes with the signal, except for free space), and ΔL peaked at h close to zero (when the drone is at ground level and the conditions correspond to the ground NLoS case). The simplest choice is an exponential dependence, which has the property of asymptotically approaching zero:

$$\Delta L(h) = A exp(-\frac{h}{h_0}), \tag{6}$$

where A – the excess loss coefficient at $h = 0$ (i.e., the difference between ground-based NLoS losses and free space), and h_0 – characteristic "effective height", at which additional losses fall e times. The parameter A reflects the influence of the environment: it is smaller for open areas and larger for densely built-up areas. Typical estimates can be as follows: $A \approx 30\ dB$, $h_0 \approx 20\ m$ for urban conditions; $A \approx 10 - 15\ dB$, $h_0 \approx 5 - 10\ m$ for open areas. These values are consistent with the analysis of the Hata model: for example, for a city at $h_m = 1.5\ m$ (about 0), the Hata model produced 30-40 DB more losses than the FSPL. With an increase of h up to tens of meters, the exponent (6) decreases sharply, which corresponds to the transition to conditions close to LoS (De Beelde *et al.*, 2022).

Reflection from the ground can be considered due to the effective distance d', which is equal to the length of a straight line between the base and the drone. Since the drone is at an altitude of h, geometrically $d' = \sqrt{d^2 + h^2}$, where d – horizontal distance (projection on the ground). For large horizontal distances at low altitudes, the difference between d' and d minor, but for small ones, it improves accuracy (for example, if the drone hangs high almost above the base, d it can go to 0, whereas $d' = h$ – this is the correct distance for FSPL). Thus, d' is substituted instead of d in Formula (1). Combining these considerations, the improved signal loss model can be represented as a function of the horizontal distance d and the height of the drone h:

$$PL_{Drone}(d,h) = 32.44 +$$
$$+ 20\,log_{10}\left(\sqrt{d^2+h^2}\right) + 20\,log_{10}(f) + Aexp(-\frac{h}{h_0}). \quad (7)$$

Formula (6) is given in dB and is valid for d in km, h in m, f in MHz (just like formulas (1-4)). The first two terms (up to "+") correspond to the loss of free space at a distance d' (i.e., FSPL between the base and the drone). The last term adds excess losses ΔL, which depend on the height. At $h = 0$ this term is equal to A (for example, ~30 dB in a city, which makes PL_{Drone} close to the values of the Hata model). For large cases $h \gg h_0$ the term tends to 0, and $PL_{Drone} \rightarrow FSPL$, as required for full line-of-sight conditions. Thus, (4) smoothly interpolates between the ground-based empirical model and the free space model as a function of the height of the device.

Coefficient A characterises the maximum possible additional losses due to the environment. Its value is related to the average effect of buildings, trees, and other obstacles on the ground level. Parameter h_0 can be interpreted as "effective obstacle height". If the drone rises to approximately a height of h_0, most interference ceases to significantly affect propagation, and losses are dramatically reduced. For the city h_0, the order of tens of meters correlates with the average height of buildings (for example, the average height of a building in a certain area can be ~15 m – if the drone is higher, most buildings no longer shade it) (Mirzabeigi *et al.*, 2025). For open areas h_0 is low, as it is enough to climb a few meters to provide almost LoS above the terrain.

Formula (7) gives the average signal loss. Statistical fluctuations (shadow attenuation, multipath feeding) can be additionally considered. These data show that as the drone's height increases, the RMS deviation of random signal level fluctuations decreases. This can be considered by introducing a height-dependent standard deviation in the model (for example, as $\sigma(h) = \sigma_0 \, exp(-{}^{h}/_{H})$). At the stage of the average model, they are limited to a deterministic estimate (7), while practical calculations of the power reserve involve the inclusion of statistical margins.

Comparative analysis of the accuracy and reliability of various propagation models

2 scenarios were considered to show the differences between the known classical models and the proposed improved model (7), followed by the calculation of signal losses. The first scenario concerns frequency $f = 1{,}800$ MHz, which is typical for cellular communication, the second – the frequency $f = 868$ MHz used to control drones (Table 1).

Table 1. Example of calculating signal losses based on different models ($f = 1{,}800$ MHz, $h_b = 30$ m)

Model	a	b	c	d
Distance, km	FSPL (dB)	Hata (city) (dB)	Hata (open) (dB)	Advanced model (6) (dB)
0.5	91.5	123.6	91.7	94.0
1.0	97.5	134.3	102.3	100.0
2.0	103.6	144.9	112.9	106.0
3.0	107.1	151.1	119.1	109.6
4.0	109.6	155.5	123.5	112.0
5.0	111.5	158.9	126.9	114.0

Source: compiled by the authors

The Hata model was analysed separately for open terrain and cities due to various empirical corrections, while the FSPL and improved model consider the impact of the environment on an average basis, so the division by terrain type was not applied. Calculating signal losses for a frequency of 1,800 MHz and a base station height of 30 m shows that different models predict different levels of attenuation depending on the distance. The FSPL gives the lowest loss values that are adequate for line-of-sight conditions without interference, while the urban Hata model seriously overestimates losses due to considering buildings and other obstacles in the city. The open Hata model assumes intermediate values close to FSPL over short distances, but with a greater increase in losses over long distances. The improved model, based on (6), shows more balanced results, correctly accounting for terrain and urban development, and provides a compromise between the conservative assessment of Hata and the optimistic FSPL. This shows the importance of choosing a model based on the environment and specific forecast accuracy requirements (Table 2).

Table 2. Example of calculating signal losses based on different models (f = 1,800 MHz, h_b = 30 m)

Model	a	b	c	d
Distance, km	FSPL (dB)	Hata (city) (dB)	Hata (open) (dB)	Advanced model (dB)
0.5	85.2	115.4	87.0	87.7
1.0	91.2	126.0	97.6	93.7
2.0	97.2	136.6	108.2	99.7
3.0	100.8	142.8	114.4	103.2
4.0	103.3	147.2	118.8	105.7

Source: compiled by the authors

The calculation of signal losses for a frequency of 868 MHz and a base station height of 30 m shows that the models differ in the attenuation estimate depending on the distance. The FSPL shows the lowest losses because it only accounts for the direct signal path without interference, while the urban Hata model overestimates losses due to the impact of development, especially over long distances. The open Hata model predicts losses slightly higher than the FSPL, but significantly lower than the urban Hata model, reflecting conditions of weak or no obstructive development. The improved model offers intermediate values, more realistically estimating losses in different environments, and provides a balance between a conservative Hata estimate and an optimistic FSPL, making it suitable for practical wireless network planning. The main models for calculating signal losses based on various efficiency and applicability criteria are compared (Table 3).

Table 3. Model comparison

Model	a	b	c	d
Criterion	FSPL	Hata (city)	Hata (open)	Improved model (7)
Accuracy for LoS	good	overvalued	Moderate	high
Consideration of the height of the drone flight	no	partially (via h_m)	partially	yes (via h)
Smooth transition between conditions	no	no	no	yes
Relevance for the air-ground channel	limited	unadapted	partially	high
Implementation complexity	low	average	average	moderate
Proximity to FSPL at high h	-	-	-	secured

Source: compiled by the authors

As can be seen from the comparison, the FSPL model is easy to use and accurate enough for LoS conditions, but it does not consider the height of the drone and the complexity of the environment. The urban model of the Hata greatly overestimates losses in urban conditions and is not adapted to air-ground channels. The open Hata model shows moderate accuracy and partially considers the height, but does not provide a smooth transition between different conditions. The advanced model (7) stands out for its high accuracy for LoS, realistic drone altitude accounting, smooth transition between conditions, and proximity to FSPL at high altitudes, making it most suitable for modern applications in wireless networks with drones or other aerial platforms. A graph of the dependence of signal loss on distance for several models (Fig. 1) is presented to evaluate the behaviour of models at different distances. The FSPL curve shows the theoretical minimum losses in the case of LoS, the Hata curve for the city shows typical losses in dense buildings (NLoS), and the Hata curve for open terrain illustrates an intermediate option with minimal interference.

A similar comparison for a different frequency allows estimating the effect of frequency on signal loss (Fig. 2).

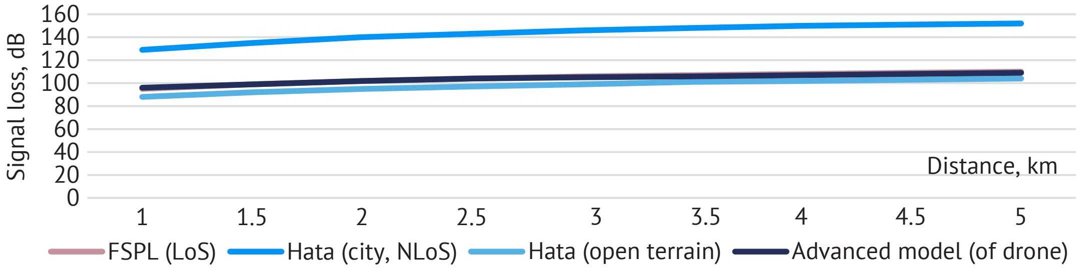

Figure 1. Comparison of signal loss models

Notes: FSPL (direct visibility); Hata model for the city (dense development, typical NLoS); Hata model for open terrain; advanced model (7). Frequency 1.8 GHz, h_b = 30 m, h_m = 1.5 m
Source: compiled by the authors

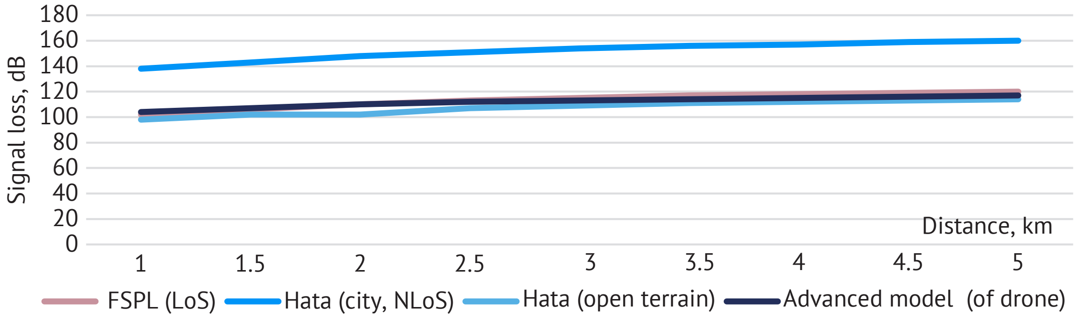

Figure 2. Comparison of signal loss models

Notes: FSPL (direct visibility); Hata model for the city (dense development, typical NLoS); Hata model for open terrain; advanced model (7). Frequency 868 MHz, $h_b = 30$ m, $h_m = 1.5$ m
Source: compiled by the authors

Analysis of calculations for both frequencies (1,800 MHz and 868 MHz) demonstrates a stable advantage of the improved model (7) over classical approaches. It provides less deviation from theoretical losses in LoS conditions compared to Hata models, especially in urban scenarios where the latter significantly overestimate values. In addition, model (7) adapts to changes in frequency and altitude, ensuring correct interpolation between open environment and line-of-sight conditions. This makes it suitable for cellular networks and LoRaWAN, IoT alike, along with other systems using unmanned platforms.

The proposed formula (7) for the improved model actually describes a family of curves parameterised by height h. Its main property is the ability to interpolate between classical signal propagation modes. For small altitudes of h, it coincides with the results of the Hata model (with the correct choice of parameter A), and for large h – asymptotically approaches FSPL. This is convenient for networks with drones, where one device can move between dense buildings and high altitudes above the city: there is no need to switch between different models, just substitute the current altitude in (7).

The difference between the improved model is that it explicitly considers the coupling geometry and displays height-dependent shading. A typical scenario is considered: a drone at an altitude of $h = 50$ m above the city, the distance to the base station is 5 km. Let the model parameters be: $a = 30$ dB, $h_0 = 20$ m. The following results were obtained:

$$(FSPL\,(5\ km) = 111 dB);$$

$$\Delta L(50) = 30exp\left(-\frac{50}{20}\right) \approx 30e^{-2.5} \approx 2.5\ dB;$$

$$(PL_{Drone} \approx 111.5 + 2.5 = 114\ dB).$$

For comparison, using the Hata (city) model for the same conditions, ≈ 159 DB was obtained. The difference is about 45 dB – that is, the classical model seriously overestimates losses in LoS conditions. If the drone drops to $h = 5$ m:

$$(\Delta L\,(5) \approx 30e^{-2.5} \approx 26\ dB);$$

$$(PL_{Drone} \approx 111.5 + 26 = 137.5\ dB).$$

The obtained value approaches the level of the model for open terrain (≈ 126.9 DB), but slightly exceeds it, which is quite logical given the influence of partial shading. Thus, by adjusting the parameters A and h_0, it is possible to accurately adapt the model to urban, suburban, forest, or mountain conditions – unlike Hata models, which have fixed empirical parameters. The approach laid down in formula (7) is consistent with the trends of modern channel models. For example, T.T. Oladimeji *et al.* (2024) proposed a modified Close-In model, in which the attenuation index depends on the height by the formula: $n\,(h) = 2.6h^{-0.53} + 2$, and the additional losses decrease linearly with increasing h. If the exponential function from model (7) is decomposed into a Taylor series, its approximation to a linear relationship at low altitudes can be shown. This means that model (7) has a similar behaviour, but at the same time, a simpler structure and a clear physical meaning of parameters.

DISCUSSION

As a result of the calculations, it was found that the improved signal loss model for the ground-to-air scenario showed significantly more accurate results compared to the classic Hata and cost-231 Hata models. For a drone at an altitude of 50 m above urban buildings, the calculated signal loss according to the proposed model was about 114 dB, while the Hata model for the city gave a value of about 159 DB. This difference of more than 40 dB confirmed that classical ground-based models greatly overestimate losses in LoS conditions, especially over long distances. This problem was also investigated by M.K. Elmezughi *et al.* (2022), where the results confirmed that in LoS conditions, signal losses for classical models, such as the free space model, are usually estimated by the simple inverse square law of distance. Advanced models take additional factors into account, such as atmospheric influence, refraction, and diffraction, which enable a more accurate prediction of losses over long distances. The comparison shows that classical models underestimate signal loss on high climbs or long transmission routes, while improved models provide a more realistic estimate.

A study by X. Huang *et al.* (2024) also indicated that increasing altitude affects signal attenuation due to atmospheric rarefaction and increasing distance to the receiver. Improved models allow paying attention to this effect and predicting changes in the quality of communication in real time. Therefore, for safe and efficient operation of drones at high altitudes, it is important to use accurate signal loss models that reflect real-world conditions. Notably, the accuracy of predicting signal loss directly affects the route planning and power consumption of drones. Underestimating losses in classical models can lead to unpredictable communication disruptions and reduced mission efficiency. Therefore, the implementation of advanced models is crucial to ensure the reliability of data transmission in complex environments.

Analysis of the dependence of signal losses on altitude showed that the exponential correction $\Delta L\ (h)$ effectively considered the gain from lifting the drone antenna. When the height was reduced to 5 m, the additional losses increased to 26 dB, which was close to the results for open terrain according to the Hata model. This indicated an adequate interpolation between NLoS conditions on Earth and near-full line-of-sight conditions at high altitudes, which allowed correct estimation of signal losses for various flight scenarios. I. Bennageh *et al.* (2024) concluded that an increase in the drone's flight altitude directly affects additional signal losses as the distance to the receiver increases and atmospheric conditions change. Exponential correction allows accounting for nonlinear loss growth with height and improves the accuracy of coupling modelling. This is especially important for high-flying drones, where classic models may underestimate the actual signal attenuation. B.S. Shawel *et al.* (2024) established that interpolation between ground-based NLoS and aerial LoS conditions allows creating a flexible model that considers different signal transmission scenarios. For UAVs, this technique allows predicting changes in the quality of communication during the transition from a dense urbanised zone to an open space. The use of interpolation approaches provides more reliable route planning and optimisation of data transmission parameters. These results support the above study, as they demonstrate a clear dependence of additional signal losses on the drone's flight altitude. The introduction of an exponential correction allows a more accurate prediction of signal attenuation at high altitudes. Therefore, taking these effects into account is crucial to ensure stable communication and efficient operation of the UAV.

A comparison of the results for two frequencies – 1,800 MHz and 868 MHz – showed that the proposed model remained stable and consistent with the physical patterns of radio signal propagation. Signal losses decreased as the frequency decreased, which was in line with expectations, while distance-dependent trends remained the same. This confirmed the versatility of the model for applications in both cellular communications and low-frequency drone control systems, such as LoRaWAN or IoT. The paper of P. Ramamoorthy *et al.* (2023) deserves special attention, showing that the stability and consistency of the model for different frequencies of the cellular and IoT spectrum ensure its versatility and practical applicability in many scenarios. A reliable model should correctly describe signal losses for both high-frequency and low-frequency bands, considering different permeability due to interference and atmospheric effects. This allows creating predictable and consistent forecasts for different types of wireless networks, which is especially important for integrated communication systems.

In turn, R. Robles-Enciso *et al.* (2024) concluded that a comparison of signal loss behaviour shows that high-frequency signals experience greater losses in dense media due to their greater sensitivity to interference. Low-frequency bands show better permeability and lower losses over the same distances, making them suitable for large-coverage IoT applications. This comparison allows optimal selection of frequency bands depending on environmental conditions and communication stability requirements. These data were consistent with the theses given in the previous section, as they confirmed the consistency of the model for different frequency ranges. The model demonstrated stable behaviour for both cellular bands and the IoT spectrum, which highlights its versatility. This allows it to be used to predict signal loss in various network scenarios without the need for significant adaptation.

An important result was the confirmation of the effect of the beam reflected from the ground on signal loss. The use of a geometrically correct distance $d' = \sqrt{(d^2 + h^2)}$ allowed considering the effect of birefringence, especially at short distances and at low altitudes. This gave the model additional physical correctness and explained the differences between real measurements and classical ground-based models that ignore reflections from the surface. F.K. Banaseka *et al.* (2021) also conducted a study, the results of which confirmed that taking into account the two-beam propagation and reflection of the signal from the ground allows for more accurate modelling of real-world communication conditions for UAVs. This approach addressed both the direct signal and the reflected signal from the Earth's surface, which is especially important at low and medium flight altitudes. Due to this, it is possible to predict the effects of interference and signal fluctuations that affect the stability of communication.

S. Wang *et al.* (2023) also determined that the influence of geometrically correct distance on the accuracy of estimating UAV signal losses is critical, since disregarding the real propagation trajectory can lead to major errors. Using a precise geometric distance allows for more correct consideration of phase changes and signal attenuation on the way to the receiver. This increases the reliability of forecasts and the efficiency of route planning for the safe operation of drones.

Comparing the data obtained in the course of research, it can be concluded that considering birefringence significantly increases the accuracy of signal loss modelling. Interference effects from the reflected signal can drastically change the reception level, especially at low and medium altitudes. Therefore, the inclusion of this factor is necessary to create realistic and reliable forecasts of UAV operation. Compared to the Hata and cost-231 Hata models, the improved model showed a smoother transition between signal propagation modes, which made it suitable for scenarios with dynamic changes in drone height. This allowed avoiding sudden transitions in calculations and provided a more realistic assessment of coverage, especially in conditions of dense urban development or when flying over open areas.

D.K. Nishad *et al.* (2025) concluded that a smooth transition between signal propagation modes for dynamic drone altitudes allows the model to correctly react to changes in conditions from LoS to partially blocked trajectories. This is especially important when manoeuvring drones in difficult landscapes or when changing the altitude of flight, when rapid changes in the environment can lead to sharp fluctuations in signal quality. This approach ensures continuity of forecasts and reduces the risk of loss of communication during flight. D. Marek *et al.* (2024) found that optimising the reliability of radio communication and drone control in various environments can improve mission performance. The use of adaptive signal propagation models helps predict potential loss zones and adjust the route or power of the transmitter in advance. This ensures stable control of the drone and reduces the likelihood of communication interruptions in difficult conditions.

When analysing the results of the study, it was determined that a smooth transition between signal propagation modes significantly increases the accuracy of forecasts for dynamic flight altitudes of the drone. Sudden changes in environmental conditions without adapting to these changes can lead to unpredictable fluctuations in the quality of communication. Therefore, the integration of adaptive models is identified as a key factor for ensuring continuous and reliable control of UAVs. Thus, the results obtained indicated the practical feasibility of using the proposed model for planning and optimising communication channels with unmanned aerial vehicles. It allowed correct consideration of flight altitude, communication geometry, and environmental influences, providing more reliable estimates of signal loss. This created prerequisites for more accurate design of drone control systems and improved radio communication stability under various operating conditions.

CONCLUSIONS

The proposed improved model demonstrates high adaptability to various signal propagation conditions and effectively considers the influence of the drone's flight altitude on radio signal losses. By exponentially reducing additional losses with increasing altitude (from 14 dB at 10 m to 3 dB at 40 m), the model smoothly transitions from ground – based conditions to the law of free space (FSPL ≈ 91.5 dB at 0.5 km at 1,800 MHz), which allows one formula to cover a wide range of scenarios-from shaded low flights among urban buildings to fully open tracks with direct visibility. The model parameters have a physical justification: for example, for urban conditions, excess losses at zero altitude are about 30 dB, and the effective height at which they decrease is about 20 m; for open terrain, the corresponding values are 10-15 DB and 5-10 m. This formulation provided high accuracy in predicting signal losses. For urban conditions, the use of the proposed model can seriously reduce the systematic error compared to the classic Hata model: if the Hata model overestimates the loss by 30-40 DB for receivers at a height of about 1.5 m, then the improved model reduces this error to tens of decibels, while the average error of the Hata model itself is about 6 dB. This result is critical when designing air-ground communication networks. The model is effective for estimating the coverage area, calculating the balance of the communication line at different altitudes and frequencies, and analysing the quality of the channel depending on the flight of the drone. It is compatible with existing radio planning tools and is easily integrated into the software due to an additional altitude parameter. Future studies should include field measurements in various settings – urban, suburban, and rural – to clarify model parameters and possibly introduce additional participants. It is also promising to account for the dynamics of the channel when the drone is moving, use machine learning methods to adapt parameters in real time, and expand the model to high-frequency ranges, considering atmospheric influences and rain. Thus, the proposed model is a universal and flexible tool for estimating signal losses in modern UAV communication networks.

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Вдосконалення моделі втрати інтенсивності радіосигналу між дроном та базовою станцією

Роман Зайвий

Аспірант
Національний університет «Львівська політехніка»
79013, вул. Степана Бандери, 12, м. Львів, Україна
https://orcid.org/0009-0003-4096-4111

Володимир Павлиш

Кандидат технічних наук, доцент
Національний університет «Львівська політехніка»
79013, вул. Степана Бандери, 12, м. Львів, Україна
https://orcid.org/0009-0004-3996-5923

Анотація. Мета дослідження полягала у розробці моделі поширення радіосигналу, що враховує висоту польоту дрона та специфіку каналу «земля-повітря» для підвищення точності оцінки втрат сигналу. У дослідженні було використано порівняльний аналіз класичних моделей, розрахунок втрат сигналу на різних висотах і відстанях, оцінку ефекту прямої видимості та двопроменевого поширення, а також розробку та перевірку вдосконаленої експоненційної моделі залежно від висоти дрона. Встановлено, що ці моделі не враховують значного впливу висоти польоту дрона та збільшеної ймовірності наявності прямої видимості між дроном і базовою станцією, що призводить до завищення прогнозованих втрат сигналу на десятки децибел. На основі проведеного аналізу було запропоновано вдосконалену аналітичну модель, у якій втрати сигналу визначаються як сума втрат у вільному просторі та висотно-залежного додаткового члена. Цей додатковий член описано експоненційною функцією, що зменшується зі зростанням висоти польоту дрона та відображає поступовий перехід від умов непрямої видимості до умов прямої видимості. Крім того, у модель введено корекцію відстані з урахуванням реальної геометрії каналу «земля-повітря». Проведені розрахунки для частот 868 МГц і 1 800 МГц показали, що вдосконалена модель добре узгоджується з експериментальними спостереженнями й забезпечує результати, наближені до моделі вільного простору на значних висотах. Порівняння з моделями Хата підтвердило, що нова модель зменшує похибку прогнозу у міських умовах до десятків децибел. Врахування висоти польоту та поступовий перехід від непрямої до прямої видимості суттєво підвищують точність прогнозування втрат сигналу для безпілотних літальних апаратів. Практичне значення дослідження полягає у тому, що запропонована модель дозволяє точніше прогнозувати втрати радіосигналу в каналі «земля-повітря», що є основою для проєктування надійних систем зв'язку з безпілотними літальними апаратами

Ключові слова: радіозв'язок; висота польоту; пряма видимість; експоненційна поправка; міське середовище; аналітична модель