Wireless Communication for Flying Cars

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Abstract

The existing ground-based transportation systems suffer from various challenges, mainly the high cost of infrastructure development, limited land space, and the growing urban population. Therefore, the automotive and aviation industries are collaborating to develop flying cars, also known as electric vertical takeoff and landing aircrafts (eVTOLs). These eVTOLs will enable reliable and rapid urban and suburban transportation. Safe operation of eVTOLs will require well-developed wireless communication networks. However, existing communication technologies need advancement to provide services to flying cars. We report various potential solutions that are feasible for communication among the eVTOLs and with the ground. These possibilities include on-ground three-dimensional cellular networks, tethered balloons, high altitude platforms, and satellites.

Flying promises a boundless form of freedom that has always been a dream of human society. The aviation and automobile industries have undergone enormous development to fulfill this ambition by introducing the electric vertical takeoff and landing vehicles (eVTOLs). The network of eVTOLs will likely have low cost compared to the substantial infrastructure based ground transportation systems such as roads, bridges, rail tracks, and tunnels [1–3]. These eVTOLs will enable "on demand" mobility in the near future for intra- and inter-city transportation, improving the connectivity between the city centers and the airports in metropolitan areas [4]. Recently, there has been a growing interest in developing these eVTOLs where more than a dozen companies are working passionately to bring the eVTOLs to reality. Some of the on-going projects on eVTOLs include Uber Air VTOL Taxi [5], Airbus Vahana [6], Kitty Hawk Cora [7], Toyota SkyDrive [8], Terrafugia [9], and Aeromobil [10] (Figure. 1). The eVTOLs technology faces many challenges at the moment, such as certification from the regulation authorities, efficient batteries for long-range transportation, interference to the

Figure 1: Some on-going projects on eVTOLs technology for urban air mobility.

existing air traffic control system, development of the communication system, lack of safety considerations, high vehicle noise, and requirement of the vertical ports [11–13]. All these challenges are open research problems where few studies have focused on the sustainability, power, and energy requirement of eVTOLs [14]. However, the existing works lack to present the role of wireless communication technologies for the eVTOLs. Nevertheless, AT&T and Uber started a joint venture for providing 4G and 5G connectivity to their eVTOLs [15]. Nonetheless, this project is still in its earliest stages and may become one of the use cases of 5G in the near future. Hence looking at the importance of wireless networks for eVTOLs, we report various possible solutions for connectivity to provide both safety and autonomous operation.

To address the issue of communication in flying cars, we need to briefly look at the technologies used by the ground intelligent transportation systems (ITS). For instance, dedicated short-range communication (DSRC) that operates at 5.9 GHz, is adopted in many parts of the world for safety applications in vehicular networks [16]. Although DSRC is a well-established technology, it is short-range, has a low data rate, high latency, and suffers from interference in the dense urban environment. Due to the low reliability and considerable delay of DSRC, it cannot support autonomous driving [17]. On the contrary, cellular technologies dedicated to vehicular communications such as Long term evolution for vehicle (LTE-V) have long transmission range, low latency, and higher data rate [18]. LTE-V is fourth-generation (4G) technology that can support high-speed autonomous driving. LTE-V operates in two modes: (1) direct vehicle to vehicle communication without involving the cellular infrastructure and (2) vehicle to infrastructure communication where the vehicles route their data through the cellular network.

Figure 2: Potential connectivity solutions for eVTOLs.

Among the six levels of autonomy defined by the society of automotive engineers (SAE) from 0 (full control with driver) to 5 (fully autonomous), the existing LTE-V system can enable automation level 2, which is partial automation [19]. Nevertheless, the indispensable attributes of fifth-generation (5G) technology, such as high capacity, flexibility, extremely low-latency, and shorter wavelengths, can lead the path to fully autonomous, connected vehicles [20]. Also, 5G technology, along with the software-defined networking and network virtualization, can make it remarkably favorable for autonomous cars [21].

All these communications technologies for connected vehicles on the ground may fail or need significant modifications to enable connectivity for flying cars since they do not have enough aerial coverage. The altitude of eVTOLs when cruising is around 300 meters that will require new airborne networks or modifications to the terrestrial cellular networks to provide communication, safety, and reliability for these eVTOLs. This motivates us to investigate the potential technologies that can provide aerial connectivity for the eVTOLs.

Hence, we report various possible solutions that can enable connectivity in the eVTOLs network. We design the link between the eVTOL and the base station (BS), where the BSs can be either on the ground or airborne (Figure 2). On the ground, we have cellular BSs, whereas, the airborne BSs can be tethered balloons (TBs), high-altitude platforms (HAPs), or satellites. As a part of the analysis, we consider achievable capacity, signal to noise ratio, and received power as key performance indicators. Our report first focuses on designing the link between an eVTOL and a three-dimensional cellular BS regarding the received power. Then, we discuss the link between a TB and eVTOL for varying distances maximum of up to 20 kilometers. Afterward, we analyze the communication link between a HAP and eVTOL in terms of the achievable capacity at various frequencies. Finally, we design the link between the satellites and the eVTOL concerning the operating frequency and altitude of the satellites. Further details are available in methods and results sections.

Results

The flight profile of eVTOL consists of takeoff hover, climbing, cruising, descending, and landing. Different types of eVTOLs have distinct flight profiles with varying speeds of cruising and takeoff/landing style. The conventional flight profile for eVTOLs is shown in Figure 3. The eVTOLs can communicate using conventional on-ground networks during takeoff, climbing, descending, and landing. However, a significant part of the eVTOL flight profile consists of a cruising phase where the traditional on-ground communication networks fail. Therefore, our primary results consider the potential solutions for designing the communication link in the cruising stage. Note that the key input parameters for the results are given in Table 1.

Figure 3: Flight plan of an eVTOL in a metropolitan area.

Table 1: Channel model parameters.

Parameter	Notation	Value	Unit	Source
Frequency	f	24 – 28	GHz	[22]
Transmission power	P_t	46	dBm	[23]
Bandwidth	B	400	MHz	[24]
Atmospheric loss	A_t	0.001	dB/km	[25]
Small scale fading	s	2.02	dB	[23]
Additional loss	A_f	0.5	dB	[23]
Noise temperature	T	290	K	[23]
Boltzmann constant	k	1.3803×10^{-23}	$\text{m}^2 \text{kg s}^{-2} \text{K}^{-1}$	Universal constant
Distance	d	1 – 20	km	Chosen input
Channel capacity	C	–	Gbps	Calculated

Connectivity using Cellular Networks

One of the potential technologies that can enable connectivity for the eV-TOLs is the ground-based cellular networks. Since the on-ground BSs are at lower height compared to the cruising altitude of the eVTOLs, the BS-to-eVTOL link will consist of both LoS and NLoS components. Here, the NLoS component arises due to obstacles such as high-rise buildings. Hence, we calculate the received power for both the LoS and NLoS components of a BS-to-eVTOL link. To illustrate this, we consider an eVTOL flying at a cruising height (330 m), communicating with the ground BS. Note that here we consider a modified ground BS that has a three-dimensional coverage, enabling aerial connectivity. We consider the eVTOL at three different projection distances from the BS, i.e., 0.5, 1, and 1.5 km, respectively. Figure 4 shows that as the projection distance between the eVTOL and BS increases (black and blue color represents the highest and lowest projection distances, respectively), the received power reduces. As previously mentioned, this is due to the inverse relationship between the path length and the received power. Furthermore, Figure 4 plots the received power at the eVOTL for both LoS and NLoS paths at different frequencies. It is clear from Figure 4 that the obstacles in the environment certainly reduce the received power, for instance, at 20 GHz of frequency and path length of 1 km, the received power for LoS and NLoS components are -97 and -200 dBs, respectively. Moreover, Figure 4 verifies that the path loss increases at higher operating frequencies due to greater attenuation.

Figure 4: Received power with respect to operating frequency and distance.

Connectivity using Tethered Balloons

Figure 5 shows the relationship between the achievable capacity (Gbps) as a function of the distance (in kilometers) for the communication link between the eVTOL and a tethered balloon. The received power at the eVTOL significantly depends on the frequency used by the TBs. Assuming the fifth-generation (5G) wireless communication transceiver on the TBs, the operating frequency can be either in the long term evolution (LTE) band (600 MHz to 6 GHz) or in the millimeter-wave band (24-86 GHz) [22]. Hence, we use two candidate frequencies for the TBs, i.e., 24 and 28 GHz, that are identified by the ITU. The bandwidth is equal to 400 MHz for the (24-86 GHz) as per the ITU specifications. Intuitively, the power of the wireless signals is inversely proportional to the square of the distance. In this context, the path length plays a significant role in the path loss of the propagating signal, for instance, Figure 5 shows that the TB-to-eVTOL links operating at 24 GHz and with the path length of 4 km and 12 km can achieve 3.7 and 2.5 Gbps, respectively. Besides the distance between the TB and eVTOL, operating frequency is another critical parameter; for example, the results in Figure 5 suggests that higher frequency leads to better channel capacity. To elaborate further, Fig. 5 shows that for a fixed path length of 8 km, 24 and 28 GHz frequencies achieve 3 and 3.2 Gbps of capacity, respectively.

Figure 5: Capacity vs. operating frequency for TB-to-eVTOL link

Connectivity using High-Altitude Platforms

High-altitude platforms (HAPs) have better coverage compared to the TBs due to their greater altitude. A network of HAPs needs to be employed to enable communication services for the entire eVTOLs network in a large coverage area. The HAPs can have inter-platform communication links (IPCL), that can be employed either by using millimeter-waves or free-space optical communication. For example, in [26], Miura *et al.* demonstrates that a network of 16 HAPs can cover the entire country of Japan. Besides other channel losses that we considered for the TBs-to-eVTOL link, it is important to model the effect of the elevation angle in the case of HAP-to-eVTOL links. This is due to the higher altitude of HAPs compared to the TB where the elevation angle between the HAP and the eVTOL can play a major role in the achievable capacity. To elaborate further, we consider a HAP at 20 km of height, communicating with the eVTOL. Here we show the impact of the elevation angle and operating frequency on the capacity. Figure 6 illustrates that the capacity of the HAP-to-eVTOL is maximum when the eVTOL is below the center point of the HAP, however, when the elevation angle increases or decreases from 90 degrees, the capacity reduces. This is mainly due to the longer path lengths at lower elevation angles and vice versa. Also, Figure 6 tells us that higher frequencies achieve better capacity, for instance, at 90 degrees of elevation angle, capacities of 0.51 and 0.39 Gbps can be achieved using 28 and 24 GHz of frequencies, respectively.

Figure 6: Capacity vs. elevation angle for the HAP-to-eVTOL Link

Connectivity using Satellite Networks

Unlike TBs and HAPs, the altitude of satellites is much higher, starting from a few hundreds of kilometers (LEO) to thousand of kilometers (GEO). Due to the higher altitude of the satellites, the path length is far greater than in the case of TBs and HAPs. Besides the longer path length, there are additional losses that affect the satellite-to-eVTOL link, such as atmospheric, antenna misalignment, and polarization losses. Moreover, the altitude of the satellite and elevation angle between the satellite and eVTOL also plays a vital role in designing the satellite-to-eVTOL link.

Table 2: Parameters of the calculating the energy-per-bit to noise spectral density for satellite-to-eVTOL link.

Parameter	Values	Parameter	Values
Transmitted power	15 dBm	Satellite antenna gain	0 dBi
eVTOL antenna gain	12 dBi	Noise temperature	1160 K
Data rate	2.4 kbps	Beam-width	2.9°
Pointing error	0.5°	Pointing loss	0.35 dB
Polarization loss	1 dB	Atmospheric loss	2.5 dB

Figure 7: Path length calculation of the satellite-to-eVTOL link regarding the altitude of the satellite and elevation angle.

Figure 7 illustrates this phenomenon where we calculate the path length between the satellites at different altitudes (200, 500, and 1000 km) and the eVTOL. When the satellite is just above the eVTOL, i.e., at 90 degrees of elevation angle, the path length is minimum. However, when the satellite moves towards the horizon, the path length of the satellite-to-eVTOL link significantly grows. For example, in the case of a satellite at 1000 km, the path length is 1000 km (minimum) at 90 degrees; however, it reaches around 2500 km at 20 and 160 degrees. When the elevation angle is smaller than 10 degrees and larger than 170 degrees, the visibility between the satellite and eVTOL vanishes. Figure 8 plots the effect of elevation angle, operating frequency, and altitude of the satellite on the path loss of the satellite-to-eVTOL link. We use 1260 MHz and 1090 MHz frequencies in L-band for the satellite-to-eVTOL link with three different altitudes (1000, 500, and

Figure 8: Path loss for the satellite-to-eVTOL link in LEO for different frequencies, altitudes, and elevation angles.

Figure 9: Energy-per-bit to noise spectral density for the satellite-to-eVTOL link at different frequencies, altitudes, and elevation angles.

200 km) of the satellites and variable elevation angle. Table 2 specifies the parameters used for the results in this section. Figure 8 suggests that the path loss is minimum at 90 degrees of elevation angle due to minimum path length; for example at operating frequency of 1260 MHz and altitude of 100 km, the path loss at 90 degree is 97 dB whereas, at the horizon points (10 or 170 degrees), it reaches to around 103 dB. Additionally, the path loss increases at higher operating frequencies; for example, at a fixed elevation angle of 90 degrees and 1000 km altitude, the path loss for 1260 MHz is 97 dB while for 1090 MHz, it is 95 dB, which is 2 dB less. Moreover, the path loss increases as the altitude of the satellites increases due to the longer path length.

Furthermore, we calculate the energy-per-bit to noise spectral density for the satellite-to-eVTOL link in Figure 9, concerning the altitude of the satellites, elevation angle, and operating frequency. From Figure 9, we can see that the signal quality at the eVTOL depends heavily on the elevation angle, satellite altitude, and operating frequency. As the satellite altitude or operating frequency increases, the signal quality degrades. This is mainly because of the longer path length in case of higher satellite altitude and more signal attenuation at higher frequencies. Also, as mentioned earlier, elevation angles towards the horizon can lead to lower signal quality. For example, at a fixed operating frequency of 1260 MHz and satellite altitude of 200 km, 90 degrees of elevation angle leads to 18 dB while 20 degrees can attain 10 dB only, which is 80% less.

Discussions

We present various wireless communication solutions for the flying cars. From our assessment, following key insights can be drawn.

First, the existing cellular communication systems do not guarantee seamless aerial coverage and are mainly optimized for the on-ground users [29]. For instance, the antennas at the base stations (BSs) are tilted towards the ground to generate high antenna gain in that direction, reducing coverage for the aerial users. Therefore, the on-ground base stations will require significant modifications to provide communication to the eVTOLs. Establishing the ground-to-eVTOL communication links is quite different and challenging compared to the conventional cellular systems supporting ground communications due to different channel characteristics and height of the eVTOL. One solution to this problem is to equip the ground BSs with extra antennas pointing towards the air, thus improving the aerial coverage. Specifically, the three-dimensional massive multiple-input and multiple-output (3D MIMO) technology in 5G can provide aerial coverage for the eVTOLs.

Second, tethered balloons have been widely used in the past for meteorological studies, surveillance, and enabling communications for disaster-

affected regions. These TBs require lightweight, and ultra-strong tethers support the aerial platform. The tethers can provide both communication and power capabilities for the TBs. The TBs typically operate at the altitude of 200 – 440 m that makes it a suitable candidate for providing connectivity to the eVTOLs flying at around 300 m of altitude. There are various types of TBs, depending on their structure and deployment. The famous among them is the Helikite that is oblate-spheroid in shape and filled with Helium. Helikites can operate in harsh weather and can support high altitudes due to their robust aerodynamic structure. Figure 2 shows the system model consisting for TBs connected to the ground using tether, acting as aerial base stations for the eVTOLs.

Third, high-altitude platforms is another alternative to support aerial communication for the eVTOLs. Unlike TBs, the HAPs operates at higher altitudes in the stratosphere, thus providing wider coverage [27]. Current deployments of the HAPs focus only on extending the ground-coverage of existing cellular systems, especially in rural areas. HAPs overcomes the shortcomings of both satellite and terrestrial communication networks, such as small coverage area, high propagation delay, incremental deployment, and low maintenance cost. The HAPs can be classified into two major categories depending on the underlying physical principle for lifting of the airborne vehicle. First are the aerostatic HAPs (lighter than air) that uses buoyancy for floating in the air, second are the aerodynamic HAPs (heavier than air) that utilizes the dynamic forces in air for stability. In terms of communications, International Telecommunication Union (ITU) has recently identified 24.25-27.5 GHz and 38-39.5 GHz band of frequencies for HAPs [28].

Lastly, satellite communications can provide the safety of eVTOLs by enabling the connectivity between the satellites and the eVTOLs. Generally, the ground station controller uses C-band (4-8 GHz) to communicate with the satellite [30]. In contrast, the eVTOL can communicate with the satellite using L-band (1-2 GHz) to enable safety communications, such as flight-plan and weather updates. Besides, the satellite networks can facilitate providing the real-time position information of the eVTOLs, including speed, direction, and altitude. The satellites report this information to the ground station controller to continuously track eVTOLs. Additionally, the satellite networks provide global coverage compared to TBs, HAPs, and cellular networks, and therefore, they can also support voice communications in case of a critical scenario when the other solutions are out of range for the eVTOLs. Nevertheless, recent developments in small satellite communication systems such as SpaceX [31], OneWeb [32], Telesat LEO [33], and Kuiper [34] that are operating in the low-earth-orbit (LEO) can enable broadband services for the on-board passengers in the eVTOLs.

Methods

The key parameters for designing the link between the eVTOL and various types of BSs are defined in Table I and II. We consider achievable capacity, signal to noise ratio, and received power as key performance indicators for various link designs.

Cellular BS-to-eVTOL link design

Consider a terrestrial cellular network BS with additional antennas pointing towards the sky for aerial coverage as shown in Figure 2. Let the height of the BS is h_b and the antenna's beamwidth is θ_b . The distance between the eVTOL and the ground BS can be calculated as

$$d_{eb} = \sqrt{r^2 + (h_e - h_b)^2}, \quad (1)$$

where r is the eVTOL-to-BS projection distance on ground and h_e is the height of the eVTOL. Considering an urban scenario, both LoS and NLoS components exists for the wireless channel between the eVTOL and ground BS. In this regard, the path loss can be expressed as

$$\text{PL}_{ebx} = A_x d_{eb}^{-\alpha_x} = A_x (r^2 + (h_e - h_b)^2)^{\frac{-\alpha_x}{2}}, \quad (2)$$

where $x = L$ and $x = N$ for LoS and NLoS components, respectively. Consequently, A_L and A_N are constants representing the path losses at $d = 1$ and α is the path loss exponent. Unlike the TBs and HAPs, eVTOL-to-BS link suffers from small scale fading with the channel gains of Ω_L and Ω_N for LoS and NLoS components, respectively. This small scale fading can be well modeled by the Nakagami-m distribution with the following probability density function

$$f_{\Omega_x}(\omega) = \frac{m_x^{m_x} \omega^{m_x-1}}{\Gamma(m_x)} \exp(-m_x \omega); \quad x \in \{L, N\}, \quad (3)$$

where m_L and m_N are the integers representing the fading parameters for LoS and NLoS components, respectively. Based on (2) and (3), the received power at the eVTOL for both LoS and NLoS components is given as

$$P_r = \begin{cases} P_t G_t G_r \text{PL}_{ebL} \Omega_L; & \text{for LoS} \\ P_t G_t G_r \text{PL}_{ebN} \Omega_N; & \text{for NLoS} \end{cases}, \quad (4)$$

where G_t and G_r are the antenna's gain for the BS and eVTOL, respectively. Now, the signal to noise ratio is calculated as, $\gamma_c = P_r[\text{dBm}] - N_{0c}[\text{dBm}]$, where N_{0c} is the noise power.

TB-to-eVTOL link design

The communication link between TBs and eVTOLs can be modeled by taking into account the large scale fading and small scale fading. The large scale fading mainly occur due to the free space path loss (FSPL) and the atmospheric attenuation. As such:

$$\text{FSPL} = \left(\frac{c}{4\pi df} \right)^2, \quad (5)$$

where c is the speed of light, d is the distance between the TB and the eVTOL, and f is the operating frequency. Since the TBs to eVTOL link will consists of a pre-dominantly line of sight (LoS) path, the multipath effect can be modeled by using the Rician distribution. The fading amplitude r at time instant i is expressed as

$$r_i = \sqrt{(x_i + \rho)^2 + y_i^2}, \quad (6)$$

where x_i and y_i are the zero mean Gaussian random processes with variance σ^2 . The ratio of the dominant LoS path and scattered non-line of sight (NLoS) path is expressed in terms of the Rice factor K as follows

$$K = \frac{\rho^2}{2\sigma^2}. \quad (7)$$

In best case scenario with a clear dominant LoS path, $K = \infty$ whereas in worst case with no LoS path, $K = 0$, leading to the Rayleigh fading. As we have mentioned that the TBs to eVTOL link will consists of a strong LoS path due to non existance of obstacles in the atmosphere, hence the channel will follow Rician distribution, given as

$$p(r) = \frac{r}{\sigma^2} \exp\left(\frac{-r^2 - \rho^2}{2\sigma^2}\right) I_0\left[\frac{r\rho}{\sigma^2}\right], \quad (8)$$

where $I_0[\cdot]$ is the zero-order modified Bessel function. In addition to the multipath fading, Doppler frequency shift is also important to model for the TBs to eVTOL link. The mobility between the TBs and eVTOLs introduces the Doppler shift in the carrier frequency f_c . The maximum Doppler shift is determined as

$$f_s = \frac{vf_c}{c}, \quad (9)$$

where v is the speed of eVTOL. If the eVTOL is directly moving towards the TB, then the resulting Doppler shift is positive however when the eVTOL is moving away from the TBs, the Doppler shift is negative. Based on these relevant effects, the channel model described by the received power at eVTOL from the TB is expressed as

$$P_r[\text{dBm}] = P_t[\text{dBm}] - \text{FSPL}[\text{dB}] - s[\text{dB}] - A_l[\text{dB}] - A_f[\text{dB}], \quad (10)$$

where P_t is the transmitting power of the TBs, s is the small scale fading loss, A_l is the atmospheric loss, and A_f is the additional losses due to feeder link and Doppler shift. The achievable capacity using the Shannon formula can be written as

$$C = B \log_2(1 + \gamma), \quad (11)$$

where B is the available bandwidth and $\gamma = P_r[\text{dBm}] - N_0[\text{dBm}]$, is the signal to noise ratio (SNR) of the received signal at the eVTOL. $N_0 = kTB$, is the noise power where k is the Boltzmann constant and T is the noise temperature.

HAP-to-eVTOL link design

Figure 2 shows the architecture for a network of HAPs in the stratosphere, providing connectivity to the eVTOLs. Consider that the HAP is at altitude A having coverage with radius R at the eVTOLs height. Then for the eVTOL at any point P in R , the elevation angle to the HAP is defined as

$$\theta = \tan^{-1} \left(\frac{A}{r} \right), \quad (12)$$

where $r = CP$, C is the point below the HAP, i.e., $\theta = 90^\circ$. For maximum coverage area, i.e., R , the minimum value of θ is

$$\theta_{\min} = \tan^{-1} \left(\frac{A}{R} \right). \quad (13)$$

The path loss by the eVTOL at point P as a function of θ and frequency is given as

$$\text{PL} = 20 \log_{10} \left(\frac{A}{\sin \theta} \right) + 20 \log(f) + 92.35[\text{dB}]. \quad (14)$$

The atmospheric loss for the HAP-to-eVTOL link at point A is given as

$$\text{PL}_a = \frac{A_n(f)}{\sin \theta}, \quad (15)$$

where $A_n(f)$ is the atmospheric loss at the nadir point. Note that (15) is true only for the frequencies between 1 GHz to 350 GHz. Based on these losses the received power at the eVTOL is given as

$$\begin{aligned} P_r[\text{dBm}] &= P_t[\text{dBm}] + G_t[\text{dB}] + G_r[\text{dB}] - \text{PL}[\text{dB}] \\ &\quad - \text{PL}_a[\text{dB}] - s(\theta)[\text{dB}] - A_f[\text{dB}], \end{aligned} \quad (16)$$

where P_t is the transmission power of the HAP, G_t is the antenna gain of the HAP, G_r is the antenna gain of the eVTOL, s is the small scale fading loss, and A_f represents other losses, including feeder loss and Doppler shift.

Satellite-to-eVTOL link design

The energy-per-bit to noise spectral density for a satellite-to-eVTOL link mainly depends on the link budget that can be expressed as [35]

$$\frac{E_b}{N_o} = \frac{P_t G_t G_r}{L k T R_b}, \quad (17)$$

where P_t represents the transmitted power, G_t and G_r are the satellite and eVTOL antenna gains, respectively. T represents the system temperature noise, k is the Boltzmann constant, R_b stands for the target data rate, and L is the total loss. The total loss consists of the following losses when the signal propagates from the satellite to the eVTOL:

- The Free-space path loss, L_p , that increases inversely with the square of the distance propagated.
- The atmospheric loss, L_a , due to absorption and scattering of the propagating signal by the environment, for example, signal attenuation caused by rainfall.
- The polarization loss, L_{pol} , that occurs due to the improper alignment of the eVTOL antenna with the signal polarization, causing polarization mismatch.
- The antenna misalignment loss, L_{aml} , due to the difficulty of steering correctly to the eVTOL antenna.

Based on these losses, the total loss L_t can be expressed as

$$L_t = L_p L_a L_{pol} L_{aml}. \quad (18)$$

Besides these losses, the elevation angle between the satellite and eVTOL is also an important parameter. When the satellite is above the eVTOL, i.e., the elevation angle is 90 degrees, then the path loss is minimum whereas above and below 90 degrees can lead to higher path loss. This is mainly due to the path length between the satellite and the eVTOL.

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Author Contributions

Prof. Mohamed-Slim Alouini and Prof. Tareq Al-Naffouri conceived the work and suggested the outline of the paper. Dr. Nasir Saeed carried out the investigations and wrote the paper.

Competing Interests

The authors declare no competing interests.

Data and Materials Availability

All data associated with this study are present in the paper.

Figures

(a) Uber Air (Photo courtesy of Uber)

(b) Airbus Vahana (Photo courtesy of Airbus)

(c) Kitty Hawk Cora (Photo courtesy of Kitty Hawk)

(d) SkyDrive (Photo courtesy of Toyota)

(e) TerraFugia (Photo courtesy of TerraFugia)

(f) Aeromobil (Photo courtesy of Aeromobil)

Figure 1

Some on-going projects on eVTOLs technology for urban air mobility.

Figure 2

Potential connectivity solutions for eVTOLs.

Figure 3: Flight plan of an eVTOL in a metropolitan area.

Figure 3

Flight plan of an eVTOL in a metropolitan area.

Figure 4

Received power with respect to operating frequency and distance.

Figure 5

Capacity vs. operating frequency for TB-to-eVTOL link

Figure 6

Capacity vs. elevation angle for the HAP-to-eVTOL Link

Figure 7

Path length calculation of the satellite-to-eVTOL link regarding the altitude of the satellite and elevation angle.

Figure 8

Path loss for the satellite-to-eVTOL link in LEO for different frequencies, altitudes, and elevation angles.

Figure 9

Energy-per-bit to noise spectral density for the satellite-to-eVTOL link at different frequencies, altitudes, and elevation angles.