Technological Trends and Key Communication Enablers for eVTOLs
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Abstract—The world is looking for a new exciting form of transportation that will cut our travel times considerably. In 2021, the time has come for flying cars to become the new transportation system of this century. Electric vertical take-off and landing (eVTOL) vehicles, which are a type of flying cars, are predicted to be used for passenger and package transportation in dense cities. In order to fly safely and reliably, wireless communications for eVTOLs must be developed with stringent eVTOL communication requirements. Indeed, their communication needs to be ultra-reliable, secure with ultra-high data rate and low latency to fulfill various tasks such as autonomous driving, sharing a massive amount of data in a short amount of time, and high-level communication security. In this paper, we propose major key communication enablers for eVTOLs ranging from the architecture, air-interface, networking, frequencies, security, and computing. To show the relevance and the impact of one of the key enablers, we carried out comparative simulations to show the superiority compared to the current technology. We compared the usage of an air-based communication infrastructure with a tower mast in a realistic scenario involving eVTOLs, delivery drones, pedestrians, and vehicles.

Index Terms—Flying cars, eVTOL, flying taxi, NTFP, UAV, HAP, LEO, RIS, NOMA, RSMA, SDN, NFV, RAN slicing, RF, mmWave, FSO, VLC, blockchain, quantum computing, edge computing, cloud computing, fog computing, digital twin.

I. INTRODUCTION

Since the invention of automobiles, humans have always dreamed of building flying cars, which at that time, were more of a science fiction fantasy and The Jetsons trademark than a reality. Today, flying cars are no longer fiction, but rather an obvious next step for a better future. They are expected to alleviate urban congestion, reduce travel time, and offer a sustainable solution for travel.

Although the name “flying car” is used often to describe a flying vehicle, it is, in reality, an umbrella term. Indeed, flying cars are categorized depending on their take off/landing mode: horizontal, vertical, or hybrid. Horizontal take off/landing flying cars fly like airplanes where they need long runways and are difficult to deploy in dense urban cities. On the other hand, vertical take-off/landing cars can take off from almost anywhere and can be deployed in cities easily. Hybrid take off/landing cars can either take off horizontally and land vertically, or the opposite. Flying cars can also be categorized depending on their energy source, the most popular are hydrocarbon and electricity. The type of flying cars that have attracted the most attention are electric vertical take-off and landing (eVTOL) vehicles.

Fig. 1: CityAirbus eVTOLs [1].

The eVTOL vehicle is a type of flying car that is powered by electricity and can take off and land vertically. It is predicted they will be heavily used to transport packages and passengers in the upcoming decade. This will ease the increasing pressure on ground transportation and utilize the underused near-ground air space. They are more environmentally friendly, and require less travel time than traditional ground transportation. Companies are racing to design and implement eVTOLs such as the CityAirbus four-seat eVTOL made by Airbus [1]. However, this comes with many hurdles, such as finding a sustainable energy source, passing certifications and regulations, and connecting to wireless networks.

Even though communication is of utmost importance for eVTOLs, at the time of writing this paper, there are only a limited number of works that deal with eVTOLs from the communication aspect. In [2], the authors presented a general survey about flying cars systems, where they gave a detailed categorization of flying cars and their challenges. The authors in [3] are the first to tackle the wireless communication aspect of eVTOLs. They proposed several alternatives for cellular networks such as tethered balloons, high-altitude platforms (HAPs), and satellites. In this paper, we propose and speculate on what can be the major key communication enablers for eVTOLs ranging from the architecture, air-interface, networking, frequencies, security, and computing.

The rest of this paper is organized as follows. In section [4] we present the main requirements for communications in eVTOLs. In section [5] the key enablers for communications in eVTOLs are described. In section [6] we carry out simulations to compare one key enabler with the current technology for eVTOL communications. Finally, we conclude this paper in section [7].
II. eVTOL Communication Requirements

Connecting eVTOLs to communication networks and among themselves is crucial. Indeed, the communication needs to be ultra-reliable, secure with high data rate and low latency. Additionally, passengers should enjoy a stable connection to voice and data networks with a satisfactory Quality of Service (QoS). Another aspect that makes the reliability and robustness of eVTOL communications extremely important is the autonomy. In fact, researchers and industrialists have made progress towards making autonomous vehicles a reality. Hence, eVTOLs are aimed to have partial then full autonomy which require a stable and reliable connection to the network with minimum delay and high data rate. Hence, eVTOL communications have to be reliable, to achieve high data rates with low latency, and to be secure.

A. Reliable Communications

Ensuring reliable communications between eVTOLs and communication networks will be challenging, either significant changes must be made to existing systems, or new systems must be designed. For example, using existing cellular networks without adjustment is infeasible, since the antennas are designed in such a way to propagate towards the ground. Also, line-of-sight (LOS) of cellular towers in urban areas will be blocked due to high buildings. Therefore, new architectures have to be adopted such as aerial-based platforms and new network technology must be used.

B. High Data Rate with Low Latency Communications

Since eVTOLs have to exchange massive data in an extremely short amount of time, they must transmit an ultra-high data rate with low latency. This is because eVTOLs fly at very high speeds (300 km/h) and they can be partially or fully autonomous. Hence, they deal and react in real-time to any critical occurrence. In fact, eVTOLs need to constantly share their position, receive other eVTOL positions, and other flying platforms such as UAVs. They also need to be constantly informed about the air traffic status, weather conditions, and any unexpected events. To that end, new air interfaces should be used to allow the required data rate and latency for eVTOLs. Additionally, different frequency bands must be explored and used for eVTOLs.

C. Secure Communications

One of the main focuses when designing eVTOLs is safety and security. Since eVTOLs will most likely be flying in urban cities and over pedestrians, they must be safe for both people on the ground and for passengers. Hence, secure communications must be implemented. Furthermore, secure communications are vital to prevent eVTOLs from being hacked or jammed. Indeed, it will be disastrous if malicious hackers could take the control of one or several eVTOLs and the damage that results can be fatal for pedestrians, eVTOLs, passengers, and also buildings. To this end, different technologies can be used to guarantee the communication security.
such as blockchain, machine learning security algorithms and quantum computing.

### III. Key Communication Enablers

#### A. Architecture

For a long time, almost all wireless communication base stations were ground based. This worked relatively well when most users were on the ground. However, with flying cars and platforms getting close to deployment, the need for more favorably placed base stations is critical. In this section, we study different architectures that make use of aerial platforms to supply eVTOLs with communications.

1) **Unmanned Aerial Vehicles (UAVs) & High Altitude Platforms (HAPs):** UAVs are small unmanned vehicles that are usually deployed in groups and distributed around an area to maximize coverage, they fly at altitudes around 150 m \[^4\]. UAVs are cheaper to deploy than cellular towers and they provide larger coverage due to their altitude. UAVs can be deployed easily, and they can be reprogrammed to other locations quickly and precisely. They can be used to connect eVTOLs during take-off, landing, and low altitude flights. UAVs can maneuver to provide a constant LOS connection to eVTOLs. On the other hand, HAPs are platforms that fly in the stratosphere around 20 km \[^5\], at this height, HAPs have a large coverage area, and they can connect with eVTOLs using LOS signals. Examples for HAPs are blimps, which are lighter-than-air vehicles that use a buoyant gas to fly, and solar-powered planes that fly against the wind. HAPs can stay in the air for long periods of time which allows reliable connections to eVTOLs \[^6\].

2) **Networked Tethered Flying Platforms (NTFPs):** NTFPs are flying platforms that are connected to the ground via a tether. The tether provides power and data to the platforms, allowing them to stay in the air for long periods of time, to have an increase in backhaul capacity, and increased security in comparison to UAVs/HAPs. There are many types of NTFPs, such as tethered UAVs, tethered balloons, tethered blimps, and tethered Helikites \[^6\]. These types fly at various altitudes, ranging from 150 m to 5 km. Low altitude NTFPs can offer low latency communications while high altitude NTFPs provide high coverage. NTFPs can provide eVTOLs with a reliable connection throughout take-off, cruising, and landing. Using NTFPs still comes with a few challenges. For example, tethered HAPs require multiple kilometers of tethers making it heavy, hence the materials used need to be lightweight. In section IV, we compare the use of NTFPs and cellular towers for communication in eVTOLs.

3) **Low Earth Orbit (LEO) Satellites:** LEO satellites are satellites that orbit relatively close to earth, from around 160 km to 1000 km \[^7\]. Due to their high altitude, LEO satellites have global coverage, which allows connecting eVTOLs during inter-city trips. LEO satellites can be deployed in great numbers to form a dense network that can offer continuous connectivity to eVTOLs with high reliability. Furthermore, LEO satellites can provide accurate position, speed, and altitude of the eVTOLs. Using LEO satellites will help in meeting the increasing connectivity demand in the skies.

#### B. Air Interface

Traditional multiple access schemes, such as frequency division multiple access (FDMA), time division multiple access (TDMA), and code division multiple access (CDMA), offered fairly good performance in terms of throughput. However, with future generations of wireless communications and the new technologies that will utilize them, superior performance is expected. For example, eVTOLs require very low delay for enhanced safety while flying, as well as high throughput for data rate heavy applications like tactile communications and brain-vehicle interfacing \[^8\]. This section studies new and promising multiple access schemes.

1) **Non-orthogonal multiple access (NOMA):** NOMA is a multiple access scheme that allows users to send simultaneously on the same frequency, at the same time, with the same code, but using different power levels \[^9\]. Decoding is done at each user by successive interference cancellation (SIC), where the unwanted part is decoded then removed from the signal. Users with low channel gain in NOMA are assigned more power, while users with high channel gain are assigned less power. Since users do not need to wait for their time or frequency slots to transmit information, NOMA can serve more users with lower latency. Hence, NOMA can improve communications for eVTOLs in dense urban areas, and it can help satisfy latency demands.
Moreover, NOMA can be used for eVTOLs according to two types of priority rankings, channel priority ranking and QoS priority ranking. When considering the channel priority ranking, eVTOLs with weaker channel gains will have more power allocated to them and inversely. This will guarantee a fairness among eVTOLs. However, when considering the QoS priority ranking, eVTOLs will be ranked according to their needs in terms of QoS. For instance, an eVTOL requiring urgent transmission will have more power allocated compared to an eVTOL with less important transmission. The authors in [10] proposed a cooperative NOMA scheme that lets users with better channel conditions to the base station (BS) decode and relay messages for other users that have a poor connection to the BS. This scheme might be a promising solution to enable reliable communications between eVTOLs.

2) Rate-splitting multiple access (RSMA): RSMA is a new multiple access framework that, similar to NOMA, users can send simultaneously on the same resources. The difference is that in RSMA, part of the interference is decoded and the other part is treated as noise. RSMA is a scheme midway between traditional multiple access schemes and NOMA, where traditional schemes fully treat the interference as noise, and NOMA fully decodes the interference. RSMA allows for another degree of freedom to improve spectral efficiency and data rate.

3) Reflective Intelligent Surfaces (RISs): For a long time, enhancements in wireless communications were mostly applied in the transmitter and the receiver, while the channel was given. Recently, RISs gained popularity as a way to alter the channel to enhance the performance of wireless communications [11]. RISs are a low-cost passive reflective surface that works by changing the phase and/or amplitude of the signal, in a way that improves the signal power in the receiver’s direction. RISs are promising as a key enabler for communications in eVTOLs, they can be installed on the walls of buildings in urban cities to improve signals during take-off and landing, and provide a strong link around the corner where LOS is not available. Additionally, RISs can be installed on the rooftops of buildings to strengthen signals coming from aerial platforms or satellites.

C. Networking

To achieve a reliable, flexible, and automated network management, a suitable networking algorithm must be chosen.

1) Software defined networking (SDN): Achieving desired qualities of eVTOL networks like flexibility and programmability using traditional networks is hard, since traditional networks functionalities’ are implemented using dedicated hardware that requires manual configuration. SDN uses software to control and intelligently reconfigure the network, it does this by separating the data plane from the control plane. The data plane consists of simple forwarding devices, while the control plane does all the computations in a centralized node which then distributes commands to the forwarding devices. With this architecture, SDN enables a flexible and programmable communication network for eVTOLs, and allows for easy scalability of the network. It will allow for simpler and cheaper equipment to be installed in eVTOLs, lowering the cost, and it will enable the eVTOLs network to be upgraded easily without hardware replacements. It is a promising solution that is used extensively today in data centers [12].

2) Network function virtualization (NFV): NFV allows software functions to be applied in virtual machines contained in servers, thus separating network services from hardware and lowering the cost of operation [13]. It is a recent network architecture that was introduced by the industry to reduce the cost of operating and implementing new technologies, since deploying new functionalities required installing new hardware. NFV is a promising network architecture for eVTOL communications, where new functionalities can be integrated using software, thus allowing scalable and cost-effective eVTOL networks. As mentioned earlier, eVTOL networks will require strong security and will need to execute complex functions, NFV allows for these functions to be executed virtually.

3) RAN Slicing: Slicing a RAN network means dividing the network infrastructure into multiple logical and virtual networks each for a different use-case. Hence, the eVTOL network will be separated into virtual networks depending on the application. For instance, a slice is used for internet connection for eVTOL passengers, another slice is used to transport safety information between eVTOLs and their respective control towers, and another slice can be used to share location information among eVTOLs [14]. That way, the eVTOL network is sliced according to the requirements of each application. Consequently, the right amount of resources is allocated to each slice. Additionally, separating the network into slices can mitigate the attacks on the network by limiting the cyber attack on a single slice and leaving the other slices unharmed. In that case, the level of security of each slice will be different, for example, communication between an eVTOL and their assigned control tower will have ultra-high security...
and robustness compared to a non-critical slice that is used to provide infotainment for eVTOL passengers. This will be cost-effective since high security mechanisms come with a high cost.

D. Spectrum

The operating frequencies must be chosen wisely. The frequency spectrum is diverse, some parts are highly congested because of their favorable characteristics, and other parts are underutilized because of the challenges they present.

1) Radio frequency (RF): RF is the frequency range from around 20 kHz to around 30 GHz. It is the most used part of the spectrum for wireless communications because of its favorable characteristics. It is congested and vulnerable to attacks since the signals propagate radially, however, these challenges can be overcome by advanced applications of waveforms, encryption, and coding. RF signals travel relatively far and can penetrate walls and go around obstacles, which makes them helpful for eVTOLs in congested urban areas, where LOS to the base station is not always available. They are also suitable for long distance trips. Furthermore, RF signals are not affected greatly by adverse weather conditions.

2) Millimeter wave (mmWave): mmWave communications uses the frequency range from around 30 GHz to around 300 GHz. It has been researched heavily the past decade. It offers a much bigger bandwidth than RF and has potential for very high data rates, enabling the use of data rate heavy applications for eVTOLs. Furthermore, mmWave signals have very short wavelengths, which makes small antennas possible, reducing the size of circuits on eVTOLs and allowing for a large number of antennas to improve capacity and range. Using mmWave comes with challenges, frequencies this high tend to attenuate quickly. Furthermore, mmWave communications are affected by atmospheric absorption like rain and snow. However, solutions are proposed to counteract these limitations, like massive multiple-input multiple-output (MIMO) and beamforming [15].

3) Free space optics (FSO)/Visible light communications (VLC): FSO communications uses the frequency range 187 THz to 370 THz. This part of the spectrum is unlicensed and underutilized, it also has practically unlimited bandwidth, allowing for very high data rates. FSO communications need a LOS path between transmitters and receivers, which makes them a suitable solution for connecting eVTOLs during flight. eVTOLs can benefit from FSO communications by having an unobstructed LOS to a UAV/HAP or a LEO satellite. VLC uses visible light to communicate, it is the frequency range from 430 THz to 790 THz. Similar to FSO, it has potential for very high data rates, and needs a LOS path between communicating devices. VLC can be implemented by using the eVTOL headlights and taillights, lights can also be installed on buildings and on rooftops to have a LOS path. Furthermore, VLC communications is highly secure since an attacker would need to intercept the light directly to receive the signal.

E. Security

To prevent a hijacking or jamming attack in the eVTOL traffic control networks, and to protect the privacy of passengers’ data, strong state-of-the-art security applications must be implemented.

1) Blockchain: Blockchain is a decentralized and distributed technology that is made up of blocks, the blocks are connected to each other in a cryptographic link [16]. It enables very secure device-to-device communication, where each device validates the information sent by the sender using a key. Blockchain can be implemented in a distributive manner in eVTOL networks, where nodes can be eVTOLs, control towers, pedestrian mobile devices, and ground vehicles. Decentralization in blockchain security prevents a single point of failure, which means a single compromised node will not have an impact on the rest of the network.

2) Machine Learning (ML): ML is a really active field of research, where it’s been implemented in almost every technology including security. ML relies on experience and acquired data to build an analytical model and identify patterns. ML can be implemented to secure communications, where the ML algorithm can detect anomalies, misuses, or intrusions from potential attackers, using data from recorded attacks in the past. Authors in [17] listed ML algorithms and their uses to achieve secure communications in 6G vehicular networks. For example, neural networks can be used for misuse detection, support vector machines for malicious attacks detection, and Bayes learning for mobility and anomaly detection. Hence, ML can be used to secure eVTOL communications by detecting when an attack happens, or by detecting suspicious behavior, and quickly adjusting the network to protect against them.

3) Quantum Computing: Quantum computing is the study of exploiting the quantum mechanics characteristics to do extremely fast computations. Quantum computers can solve certain problems 3 million times faster than a classical computer [18]. Quantum computers can offer extremely strong security by using the innate quantum entanglement property of particles, which virtually cannot be hacked [19]. It works when the quantum state of two particles become entangled together, then their quantum states will be dependent on each other, moreover, a device wishing to communicate securely to another device will send the entangled particle to it using quantum key distribution (QKD). An attacker that wishes to obtain the key must be physically present at the device. This method, and the fact that quantum computers are based on true randomness, will allow eVTOLs to have secure communications.

F. Computing Paradigm

As technology progresses and more complex algorithms are invented, and with the exponential increase of the number of
communication devices and network sizes, the need for high computational power became crucial. This prompted research into innovative computing paradigms that help resource-limited devices in computations. In this section we study technologies that enable eVTOLs to have access to strong computing power, without the need for expensive on-board hardware.

1) Cloud computing/Fog computing: Cloud computing offers computational resources to devices, often deployed on the internet. The devices send their data to the cloud where the required computations are done. Then, if needed, results are disseminated back. Cloud computing could help eVTOL networks run complex algorithms that require a lot of computing resources, such as route planning and weather analysis. Furthermore, cloud computing could contain quantum computers that might be used for security in eVTOL networks. Similar to cloud computing, fog computing provides computational resources, however closer to the end-devices which means less latency and less bandwidth usage on the network. In eVTOL networks, cloud computing can be used for computation heavy and delay-tolerant applications, like weather reporting, and fog computing can be used for applications that are delay intolerant, like route planning and traffic simulation.

2) Digital Twin: A digital twin is a virtual real-time copy of a physical entity, which can be used to synchronize with and keep track of the real-world entity [20]. In a multi-device network, devices send their data to the digital twin, then it can build a virtual world where every device is synchronized with others. The digital twin can then simulate the world and send back its decisions. Digital twins are a good computing technology for eVTOL communications, where a complete overview of the eVTOLs is needed for safety and route planning. A digital twin can be built that mirrors the real-world network of eVTOLs, all synchronized in real time, then simulations can be run to return answers back to the eVTOLs about best routes and to warn about possible congestions. A cloud-based digital twin for vehicle communications was proposed in [21].

3) Mobile edge computing (MEC): Instead of off-loading computations to a center that might be far away which introduces delay, MEC technology have distributed computing servers at the edge of the network, in close proximity to communication devices [22]. MEC servers are generally designed to be placed at cellular BSs [23]. However, authors in [24] proposed using UAVs as MEC servers, which is a suitable design for eVTOLs. MEC offers high reliability to eVTOL networks, since many mobile units can be deployed in the vicinity of eVTOLs, and there is less possibility of a network issue that prevents access to them.

In this section, we show the improvement of the performance when using an NTFP-based communication infrastructure and a traditional tower to connect eVTOLs. We simulate a real-life scenario composed of delivery drones since they will be ubiquitous during the next decades along with eVTOLs. The simulation also involves vehicular communications and mobile communications from pedestrians. The area of the simulation is set to be 1 km$^2$, which corresponds to the tenth of downtown Los Angeles area.

The eVTOLs fly at an altitude of 300 m and are distributed according to a two-dimensional (2D) binomial point process with intensity $\lambda_{eV}=10$ eVTOLs; the UAVs fly at 100 m and are distributed according to a 2D homogeneous Poisson point process (HPPP) with intensity $\lambda_{UAV} = 5 \times 10^{-5}$ UAV/m$^2$. Pedestrians and ground vehicles are distributed according to a one-dimensional (1D) HPPP with intensity $\lambda_p = 1 \times 10^{-3}$ pedestrian/m$^2$ [25]. The NTFP is a tethered blimp flying at an altitude of 500 m, and the cellular tower mast is 50 m high. We refer to downlink as the connection from NTFP/tower mast to eVTOL, and uplink to the connection from eVTOL to NTFP/tower mast.

Fig. 6: Computing Paradigm for eVTOLs.

Fig. 7: Outage probability as a function of spectral efficiency.
Figures 7 to 10 show the outage probability of eVTOL transmissions. We see from Fig. 7 that by using NTFPs, a better performance is achieved in comparison with tower masts for eVTOL communications, whether it is for uplink or downlink transmission. The gap in performance is more significant for the uplink transmission. This is due to the fact that pedestrians, vehicles, and the delivery drones are closer to the tower mast than to the NTFP. Hence, the interference is stronger at the tower mast. This shows a clear advantage of an NTFP-based solution that mitigates the effect of ground interference.

Figure 8 and 9 show the outage probability as a function of the pedestrian/vehicle intensity and the UAV intensity, respectively. The outage probability increases with increasing intensity in the tower mast architecture, but the increase is minimal in the NTFP case. This is because the interfering devices are closer to the tower mast than the NTFP. We can clearly notice that NTFPs are more suitable than tower masts for eVTOLs while coexisting with pedestrians and delivery UAVs. In fact, there is a significant gap in the performance, which makes NTFPs a better candidate for eVTOL communications.

In Fig. 10 the outage probability for downlink and uplink is drawn against the number of eVTOLs flying, the outage probability increases with increasing number of eVTOLs. However, the outage probability is greater when using tower masts than NTFPs. This is because the interfering eVTOLs are all close to the receiving eVTOL, and are far from the tower mast and NTFP.

V. CONCLUSION

In this paper, the key enablers for communications in eVTOLs were proposed and discussed. Key enablers were proposed for eVTOL communication architecture, air interface, networking, spectrum, security, and computing paradigm. Furthermore, the key drivers for eVTOL communications were discussed, mainly the predicted development of autonomous vehicles, unreliable current cellular networks, and the importance of safety and security for eVTOLs. Finally, a simulation comparing between two communication architectures was done, where it was shown that NTFPs offer better performance than cellular towers.

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