Urban Air Mobility: Vision, Challenges and Opportunities

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***Abstract*—Urban Air Mobility (UAM) involving piloted or autonomous aerial vehicles, is envisioned as emerging disruptive technology for next-generation transportation addressing mobility challenges in congested cities. This paradigm may include aircrafts ranging from small unmanned aerial vehicles (UAVs) or drones, to aircrafts with passenger carrying capacity, such as personal air vehicles (PAVs). This paper highlights the UAM vision and brings out the underlying fundamental research challenges and opportunities from computing, networking, and service perspectives for sustainable design and implementation of this promising technology providing an innovative infrastructure for urban mobility. Important research questions include, but are not limited to, real-time autonomous scheduling, dynamic route planning, aerial-to-ground and inter-vehicle communications, airspace traffic management, on-demand air mobility, resource management, quality of service and quality of experience, sensing (edge) analytics and machine learning for trustworthy decision making, optimization of operational services, and socio-economic impacts of UAM infrastructure on sustainability.**

***Index Terms*—Urban air mobility, vertical take-off and landing vehicles, space-air-ground integrated networks.**

I. Introduction

With the ubiquity of the Internet, wireless mobile communications, smart sensors (including smartphones), internet of things (IoT) and pervasive technologies, citizens from diverse demographic regions around the world have access to vast opportunities than ever. Such development has been instrumental for better quality of life, increased job employments, and marketability of essential commodities and services in daily life, thus resulting in unprecedented economic growth to the society at large [1]. However, significant challenges are posed for sustainable development and maintenance of proper infrastructures that ensure smooth and reliable operations and services catering to the growing needs of modern lifestyles. To this end, a key challenge is to provide sustainable mobility and transportation solutions, particularly in urban areas.

Increased urbanization and shift to urban lifestyles bring forth a unique set of fundamental challenges and opportunities in computing and networking research. Some of the basic needs are the availability of affordable and sustainable housing and the development of a stable, manageable, safe and efficient transportation network to aid the movement of the resident and commuter population. With the urban sprawl of a city, the existing transportation capabilities are often saturated or insufficient to support the increased load on mobility needs [2]. This calls for innovation in alternative modes of transport that will not only enhance existing transportation capacity in congested urban areas but also provide economically feasible solutions and services with reliable operations. Focusing on *urban air mobility* (UAM) as an emerging technology to help realize such a vision, this paper attempts to highlight some of the underlying research challenges and opportunities from the networking and computing perspectives.

The contributions of this paper are summarized as follows. First, we describe various types of aircrafts envisioned for urban air mobility. Next, we discuss the infrastructure and operations for managing the airspace and air-traffic in UAM networks. This is followed by challenges and opportunities in the underlying communications, networking, and on-board computations (edge analytics) on UAM. We then discuss ways to minimize adverse environmental impacts on sustainable design and usage of UAM technology. Different services including on-demand air mobility are also presented. Security and privacy issues are highlighted for safe operations of this new mode of transport. Finally, we outline the socio-economic and policy impacts, and conclude the paper.

II. UAM Aircrafts and Autonomy

The UAM scenario may encompass vehicles ranging from small unmanned aerial vehicles (UAVs) or drones, to personal air vehicles (PAVs) with larger payload capacity and more robust autonomous capabilities [2]. Autonomous capabilities and features developed for terrestrial vehicles are discussed as to their applicability to the airspace. Challenges and opportunities in developing novel methods of object detection and collision avoidance are also briefly discussed.

A wide variety of commercial aircrafts exists today with varying payloads. This works well for the aviation industry where flight schedules, routes and demands are quite well defined, determining the allocation of aircrafts for operations. However the lack of specific schedules in the anticipated UAM market to pre-determine the type of flights to be undertaken leads to the 'on-demand' nature of flight scheduling, where the popularity of flights and/or resulting congestion might change frequently over short intervals (days or weeks), making vertical take-off and landing (VTOL) and short take-off and landing (STOL) vehicles the main contenders for the UAM market (see Figure 1 for illustration).

Fig. 1. From top: PAV (Volocopter), STOL (Just Aircraft), VTOL (Joby Aviation)

A recent surge has been noted on research and development of VTOL (eVTOL) vehicles involving major companies like Airbus, Volocopter, and Terrafugia. Different types of vehicles that can potentially be used in UAM are described in [3]. Vehicles with VTOL capabilities include City Airbus and ALIA-250, a joint effort by Blade and Beta [4], which conducted the first test flight in February 2023 in New York City. The general consensus is that initially the UAM market will be dominated by piloted aircrafts, eventually leading to fully autonomous vehicles with collision avoidance and real-time route maintenance as the top priority.

Collision avoidance by terrestrial autonomous vehicles are based on object detection algorithms relying mostly on vision-based techniques, such as YOLOv2 used in self-driving cars with the help of monocular cameras and LiDAR sensors [5]. Monocular cameras provide shape and texture information for identifying elements that are important to observe while driving on road, but will be absent in UAM flight scenarios. It is also known that object detection capabilities are heavily dependent on the resolution of the camera and ambient conditions, and the model does not perform well during night time nor rainy conditions. Moreover, YOLOv2 have limitations in adverse weather conditions and reduced visibility [6].

Therefore, reliance on other modalities than only vision must be a fundamental design consideration for autonomous UAM flights, leading to better perception of the environment. This implies redesign of sensors and algorithms for air taxi (PAV) operations. While other modalities like seismic and acoustic signature (e.g., vibration and noise) can be used for object detection in terrestrial vehicles [7], [8], the aeroacoustic signature [9] can be considered for sensing operation in UAM. Accurate weather predictions are also extremely important for safe operations [10] of UAM.

From computing viewpoint, creation of reliable datasets is important for accurate object detection and tracking in airspace. Existing datasets are mostly based on classifying objects (humans, lane markings) encountered in ground transportation. Datasets with elements encountered in the air like other vehicles, birds, and clouds are essential. For example, identifying clouds as obstacles by air taxis will require considerable training of machine learning models as clouds are not easily distinguishable from the sky background.

III. UAM Infrastructure and Operations

This section presents the infrastructure design aspects for UAM traffic network, which depends on the types of aircrafts and their take-off and landing capabilities. Key positioning of the take-off and landing areas and localization of passengers and vehicles are essential for smooth and convenient access to the UAM airspace to fully realize the benefits of this new transportation paradigm [2]. Two most common terms used in the literature are Vertiports and Vertistops, catering to VTOL aircrafts effective in congested urban areas. Vertiports have much larger capacity to handle multiple UAM vehicles, analogous to the existing airports, whereas Veristops are similar to single helipads, catering only to one aircraft at a time.

The design and construction of Vertistops and Vertiports will not not only depend on the precise locations for passenger on-and-off boarding, but also how the UAM vehicle airspace is designed and managed. Since most air taxis are expected to be VTOL enabled, the landing units can be built as docking stations with multiple ports stacked on top of one another, for better utilization of vertical space. The design will also depend on the altitude of the airspace in which the UAM vehicle will operate. The capacity of each station depends on the nature of UAM flights, requiring efficient allocation and management of the airspace (resource), discussed next.

IV. UAM Airspace and Traffic Management

A critical issue in developing UAM ecosystem is efficient utilization of available airspace. This section discusses if some of the traditional methods for airspace and air-traffic management are applicable to UAM scenario. An important challenge is how to choose efficient routes in real-time from an origin to a destination given such constraints as airspace sector capacity, adverse weather, traffic congestion, or blockage of some routes. Efficiently solving this multi-objective problem will help design optimal scheduling and routing algorithms.

The first step towards operating a UAM fleet is to efficiently allocate suitable airspace. One approach is to segregate the available airspace into different regions (sectors) for different types of aerial vehicles. Since air taxis are typically expected to fly at a lower altitude than conventional airlines or drones, efficient planning of limited airspace is crucial. The Federal Aviation Authority (FAA) is developing Unmanned Aircraft System Traffic Management (UTM), while EUROCONTROL is developing U-Space [2], [11]–[13]. The U-Space Concept of Operations (ConOps) divides the airspace into three types X, Y, and Z based on the services offered and the entry/access requirements. Type X does not provide conflict resolution and the remote pilot has full responsibility of flight operation. Type Y supports only pre-flight or offline conflict resolution by coordinating flight plans ahead of time. Type Z offers both pre-flight and in-flight conflict resolution using the position and motion of other aircrafts.

In addition to planning and allocation of airspace, efficient path planning of air taxis from source to destination depends on a variety of factors that are often dynamic in nature. In traditional air traffic controller (ATC) concept, for safety every flight is manually monitored by air traffic personnel for run-time operations, such as re-routing due to weather, elevation adjustment, or emergency actions [14]. If UAM is realized with autonomous (or piloted) air taxis, safe flight operations and minimum separation between air taxis can be assured by employing techniques proposed for UAVs in [14], where the entire usable airspace is divided into sectors, similar to cellular wireless communication networks. This will help reduce the current load of air traffic personnel as the expected volume of flights in the UAM scenario will be much more, making it impossible to manually handle all run-time flight requests.

This model can further be extended to include additional parameters like the closure of certain sectors (e.g., due to high priority passengers passing or flight route reservation for air ambulance), as in ground transportation. Likewise, in the aerial mode of transport, there will be designated *skyways* similar to roads, for proper monitoring and surveillance of the airspace, thereby decreasing accidents due to uncertainty related to the unplanned and unrestricted air vehicle paths.

V. UAM Communications and Networking

When the UAM airspace becomes sufficiently crowded with vehicles, they will not only serve as a new mode of passenger mobility or cargo transport, but also as access points or relays to aid in better integration and adoption of space-air-ground integrated networks (SAGIN), as illustrated in Figure 2.

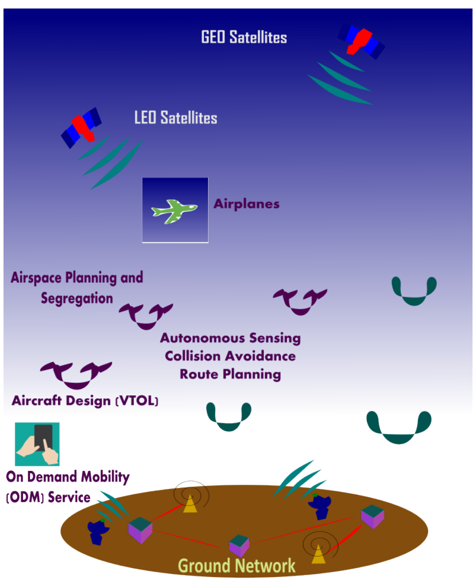

Fig. 2. UAM as part of space-air-ground integrated network (SAGIN)

Demanded by the volume of UAM users and data generated by them, cellular wireless communications are expected to dominate UAM operations, spawning new research ranging from adaptation of 5G/6G signals for aeronautical use [15], to securing such communications [16]. Aerial vehicles will act as servers or communication relays, thereby reducing the shadow effects of buildings [17]–[19]. Similar to UAVs, air vehicles may also act as sensor data collectors from the ground [20].

As regard to 5G networking, one may explore if peer-to-peer communication is effective between the air taxis. Another question is: how to optimize the minimum separation distance between these aerial vehicles for efficient communications yet guaranteeing safe operations? For smooth traffic movement within the airspace, the UAM paradigm of commuter transport offers the opportunity of utilizing different layers within the same airspace. They can be used as parallel routes for transport at varying altitudes ensuring safe transition of air vehicles from one layer to the other. The mobility management aims to develop novel techniques for efficiently switching tracks within the same layer or across layers in the airspace, analogous to horizontal/vertical hand-offs in wireless networks [21], [22]. For autonomous vehicles, sensors and IoT will detect obstacles and other elements in upper and lower strata of 3D airspace.

With the advent of any new technology like UAM, there is tremendous opportunity for interdisciplinary collaborations across research community and industry with a goal to provide affordable and robust solutions with improved customer experience. As autonomous air taxis continue daily commutes, the model will learn over time. Vehicles belonging to different service providers can collaborate and share data for improving the model and refinement of the technology. This is where federated learning (one kind of distributed machine learning) can be useful to preserve privacy of customer's sensitive data. Thus, individually trained models from different companies could be aggregated to create a more robust model, offering better value to the customers without compromising their data.

Similar to static roadside units (RSUs) in autonomous terrestrial vehicular networks, the UAM scenario will support air taxi to ATC infrastructure (V2I) communications and air taxi to air taxi (V2V) communications. Such networked environment is vulnerable to failures and malicious attacks (see Section IX for details). Due to the heterogeneous nature of 5G networks, fair allocation and efficient reuse of resources (wireless bandwidth) will play important roles [23], [24].

VI. Onboard Computation – Edge Analytics

Similar to IoT, UAV and vehicular networks, how much onboard computation and edge analytics are feasible in UAM vehicles with limited resources (energy, bandwidth) for real-time scheduling and route planning [25]? For a comprehensive survey on edge computing driven IoT, see [26].

Computation offloading using federated learning (FL) is used in [27] to jointly optimize latency and energy consumption in vehicular edge computing. A similar approach can be used in UAM where autonomous vehicles requiring huge computations while minimizing both latency and energy. Like RSUs on roads, the UAVs supporting inter-air taxi communications will act as edge computers, thereby reducing energy consumption of air taxis. The objective is not only to perform computations but also aggregate the models of air taxis belonging to different service providers to generate a more robust model. The updated aggregate model can later be dispatched to all air-taxis coming in proximity of the edge units at pre-scheduled times essentially performing an update of the model on-board the vehicle. Following [28], an important research problem is to apply distributed learning to connected vehicles to acquire data at scale.

Furthermore, the UAVs acting as substitutes for RSUs in the aerial domain can potentially be used to mitigate important information about the current state of the airspace they are placed in (see Fig. 3). In case of a skyway closure due to reasons mentioned in Section IV, this information can be sent from a central server like ATC to all the UAVs relaying the information to the air taxis as and when they pass by the units. It can also be directly transmitted to the vehicles through services like GPS, but the inclusion of supporting UAVs adds fault tolerance in potentially critical situations (see Figure 3).

Edge analytics not only improves computation efficiency but also flight path planning for a trip. Besides sector constraints mentioned earlier, data offloading and uploading to and from the UAV edge units require energy. Hence the flight path can be optimized not only in terms of shortest path measured in the number of sectors, but also considering energy required for edge computation at various *waypoints* [25]. Due to the dynamic nature of communication (as vehicles are mobile), data offloading to a computing cloud can employ deep reinforcement learning and deep meta Q-learning in such a large scale mobile edge computing scenario [29], [30].

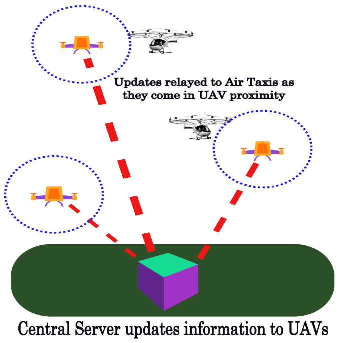

Fig. 3. UAVs acting as relays to pass on important updates from the central server (Computing Cloud) on ground

To improve positioning or localization accuracy of air taxis in UAM, range-free localization algorithms can be employed by using UAVs as mobile anchors [31], which relay information received from air taxis passing by them to the ground units for better tracking. Thus, even if GPS does not function properly due to reasons like bad weather, a direct beacon from the air taxi sent to UAV as mobile anchor can be relayed to the ground stations keeping track of vehicle movements in the airspace. In [32], we developed methods for reducing localization errors in some range-based algorithms that can prove to be useful for UAM vehicle localization and relative positioning with respect to other vehicles during flight. Approaches similar to federated learning for collaborative positioning of internet of vehicles [33], and localization methods for IoT using compartmental model [34] can be explored for air taxis.

VII. Sustainable Design of UAM

This section discusses how to reduce adverse environmental threat and ecological footprint of specific technologies (e.g., propulsion systems, efficient batteries) in UAM design and usage. Electric air taxis will significantly reduce harmful emissions compared to combustion-based commercial aircrafts. Although most of the UAM aircrafts are expected to be of eVTOL types, the power requirements are expected to be much higher than ground vehicles due also to the energy required to hover at a particular place. Therefore, an active research area is to develop more energy efficient power sources (batteries) at reduced costs. The industry standard has mostly been lithium-ion batteries for electric vehicles. Recently, the JAC Group in China unveiled the world's first sodium-ion battery powered car, the Hua Xianzi meaning 'Flower Fairy' [35].

For eVTOLs, efficient route planning must not only depend on conventional power sources (batteries), but also consider alternate energy (e.g., solar) given the vehicles will be in the air most of the time. To compute an optimal path from source to destination, factors like weather and sector blockage can be considered, in addition to the number of hops and time.

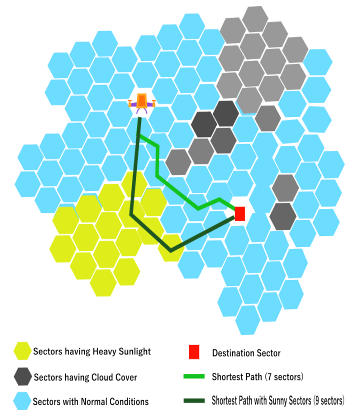

Fig. 4. Calculating optimal path to the destination to maximize solar charging and minimize distance: shortest path takes 7 sector hops, increasing to 9 using sectors with sunlight while charging the VTOL aircraft at the same time.

Assuming sunlight is a factor, under good weather in all sectors and no saturation in any of the sectors, the multi-objective optimization goal will be to cover maximum sectors with proper sunlight while selecting the shortest path. To this end, dynamic route planning algorithm proposed in [14] for UAVs can be suitably adapted. This approach will allow the air vehicle to be charged en route, and reduce the frequency of electric charging. thus saving power (see Fig. 4 for illustration). Additionally, distributed V2V charge sharing as in electric vehicles can also be potentially exploited [36].

VIII. UAM Services - On Demand Mobility

This section summarizes pros and cons of different services to be offered for UAM along with the computing and networking issues. Similar to ride-share services like Uber for ground transportation, the UAM service will be available in future through various platforms. On demand mobility (ODM) can offer shorter travel times with increased carrying capacity. Existing ride-share services mostly follow the transportation network companies (TNC) model [2], which may not be suitable for UAM scenario initially, as it will require an abundance of eVTOL aircraft owners and qualified pilots.

The concept of transportation service providers (TSPs) will offer a more convenient solution by involving companies providing air taxi services with a fleet of aircrafts and certified pilots. This approach is scalable with autonomous aircrafts, ultimately bringing down the service cost and making them widely accessible. The timeline for realizing this vision depends on socio-economic factors (see Section X) and the pace of research addressing domain-specific challenges.

To make ODM a viable and useful concept to the users, proper integration of aerial services with existing ground transport networks is needed, involving efficient planning of sky routes in tandem with ground vehicular routes, thereby optimizing the source to destination transit. Thus, UAM must be viewed as an alternate mode of transport and a complementary service provider toward overall solution for urban mobility. While ODM may lead to a decrease in car ownership due to cost and journey time, major automobile manufacturers are likely to eventually provide air mobility solutions, leading to novel pricing and revenue models.

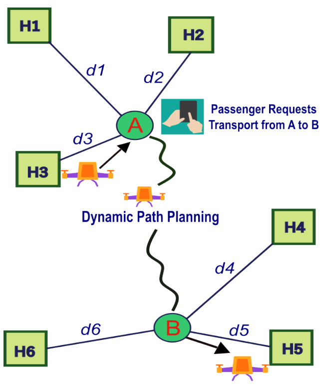

Fig. 5. Air taxi deployed from hub H3 as distance d3=min(d1,d2,d3). After dropping customer at B, the vehicle proceeds to hub H5 for docking as d5=min(d4,d5,d6)

To support ODM needs of users, the aerial vehicles must be on standby at strategically placed hubs. The hub nearest to the customer requesting a ride can deploy an aircraft to minimize the waiting time. In Fig. 5, the hubs H3 and H5 and the optimal flight path between A and B must be selected prior to the deployment of air taxi. Due to environment dynamics (wind or rain) and other factors, the path planning algorithm will be dynamic, employing similar approaches to [10], [14].

Machine learning methods can be applied to increase service provider's revenue by allocating variable number of vehicles to the hubs based on local demands during the day. A model for allocating vehicles to the hubs will learn over time which hub locations need to serve more customers at specific times of the day, and accordingly divert fleets on standby mode. Such an action and reward scenario can be formulated as reinforcement learning, in which the state of the intelligent agent can be modeled with location and time of the day, while an action will be to reach a certain hub at a given time of the day. The destination hub location and time will constitute the resulting (*terminating*) state having a utility (e.g., the number of flight requests received). The utility value will change over time, and the agent will identify the hubs (*states*) with maximum utility.

IX. Security and Privacy Issues

Security is extremely important for communications, networking, and computing in UAM services. A malicious agent can launch manipulation-based attacks by gaining control of communication channels [37], sensors [38] or other critical components of airborne vehicles, and injecting false data to impede proper functioning of flight operations. Malicious agents can cause further damage by sharing sensitive information to unauthorized entities, thus posing severe privacy concerns for UAM customers as well as service providers.

Analogous to authentication and secure V2V communications in the Internet of vehicles [39], [40], developing secure UAM communication protocols will lead to safe and reliable smart air transportation. Recent advances in securing autonomous terrestrial vehicles using collaborative AI and Blockchain techniques [41] can potentially be deployed to improve the security of unmanned personal aerial vehicles.

There also exist possibilities of location trailing attacks by tracking customer flight paths and potentially creating profiles based on the places visited frequently and other personal data. This can eventually lead to targeted attacks, implying the communication channels and UAM applications providing on-demand mobility services must be robust enough to handle such intrusions. This is particularly important during early stages of UAM deployment when the aircrafts may not be fully autonomous. If a pilot is compromised or has malicious intent, proper tracking will ensure safety and apprehend rogue individuals upon landing. The UAM service apps may have an option for passengers to hit a panic button that will transfer the vehicle control to a remote operator for smooth landing at a secured location. High standards of security is instrumental for wider acceptance and market penetration of UAM applications.

X. Socio-Economic and Policy Impacts

Although UAM is a promising technology for air mobility, full realization of this vision will depend on various socio-economic factors. At the social front, the most challenging hurdle to overcome is the acceptance by the customers. Riding on an autonomous air vehicle (without human pilot) is a major concern for many. There exist some studies on customers' willingness to avail air taxi services [42]–[44]. Safety is revealed as the most important factor for which proper policies must be in place to harness the full potential of this technology.

With gradual progress of UAM services, the technology can become a popular alternative to current mobility solutions in busy urban areas. From economic viewpoint, there is a huge business potential. Intelligent algorithms can help improve revenue generation under UAM transport scenarios, in presence of uncertainty. For example, the selection of optimal sites for passenger pick-up based on aerial vehicle's payload capacity, can be formulated as a Knapsack problem.

Computing technology can further aid in easier adoption of this paradigm by reducing privacy concerns like blocking in-flight passengers from viewing people's homes when flying over urban settings using augmented reality in aircraft windows. Trustworthy and explainable AI will also have a positive impact on UAM services.

XI. Conclusion

Moving into a new era of urban air mobility integrated with satellite, ground and UAV networks presents a plethora of unique challenges and opportunities in terms of new technological innovation and computing and communications research. This paper provides a snapshot of key research issues that must be tackled at the design and operational phases towards the realization of UAM technology. Important research topics include autonomous aircraft design and infrastructure development, real-time scheduling and dynamic route planning, aerial-to-ground and inter-vehicle communications, airspace traffic management and on-demand air mobility, resource management, quality of service and quality of experience, edge (sensing) analytics and machine learning for trustworthy decision making, optimization of services offered, socio-economic and policy impacts of UAM technology on environmental sustainability and user acceptance.

References

[1] J. Hjort and C. Sacchetto, "Can internet access lead to improved economic outcome?," *https://blogs.worldbank.org/digital-development/can-internet-access-lead-improved-economic-outcomes*, 2022.

[2] J. Pons-Prats, T. Živojinović, and J. Kuljanin, "On the understanding of the current status of urban air mobility development and its future prospects: Commuting in a flying vehicle as a new paradigm," *Transportation Research Part E: Logistics and Transportation Review*, vol. 166, p. 102868, 2022.

[3] S. Gupta, M. Ghonge, and P. Jawandhiya, "Review of Unmanned Aircraft System (UAS)," *International Journal of Advanced Research in Computer Engineering and Tech.*, vol. 9, pp. 1646–1658, 04 2013.

[4] C. Alcock, "Beta & Blade Air Mobility demonstrate ALIA-250 eVTOL aircraft in NY area," *futureflight.aero/news-article/2023-02-14/beta-and-blade-air-mobility-demonstrate-alia-250-evtol-aircraft-new-york*, 2023.

[5] H.-H. Jebamikyous and R. Kashef, "Autonomous vehicles perception (AVP) using deep learning: Modeling, assessment, and challenges," *IEEE Access*, vol. 10, pp. 10523–10535, 2022.

[6] M. Gluhaković, M. Herceg, M. Popovic, and J. Kovačević, "Vehicle detection in the autonomous vehicle environment for potential collision warning," in *Zooming Innovation in Consumer Technologies Conference (ZINC)*, pp. 178–183, 2020.

[7] D. Roy, Y. Li, T. Jian, P. Tian, K. Roy Chowdhury, and S. Ioannidis, "Multi-modality sensing and data fusion for multi-vehicle detection," *IEEE Transactions on Multimedia*, pp. 1–1, 2022.

[8] A. Nooralahiyan, H. Kirby, and D. McKeown, "Vehicle classification by acoustic signature," *Mathematical and Computer Modelling*, vol. 27, no. 9, pp. 205–214, 1998.

[9] J. H. Stephenson, "Acoustic signature measurements and modelling of sUAS vehicles," *U.S. Army Combat Capabilities Development Command, Aviation and Missile Center, MS 461, Hampton, VA, USA 23681*.

[10] F. B. Sorbelli, F. Coro, S. K. Das, and C. M. Pinotti, "Energy-efficient delivery of goods with drones in varying wind conditions," *IEEE Trans. Intelligent Transportation Systems*, vol. 22, no. 9, pp. 6048–6060, 2021.

[11] FAA, "Concepts of operations, foundational principles, roles and responsibilities, scenarios and operational threads, Unmanned Aircraft Systems (UAS) Traffic Management (UTM) concept of operations, v2. 0," 2020.

[12] C. Barrado, M. Boyero, L. Brucculeri, G. Ferrara, A. Hately, P. Hullah, D. Martin-Marrero, E. Pastor, A. P. Rushton, and A. Volkert, "U-space concept of operations: A key enabler for opening airspace to emerging low-altitude operations," *Aerospace*, vol. 7, no. 3, p. 24, 2020.

[13] Single European Sky ATM Research 3 Joint Undertaking, *U-space : blueprint*. EU Publications Office, 2017.

[14] S. Vaidhun, Z. Guo, J. Bian, H. Xiong, and S. K. Das, "Dynamic path planning for unmanned aerial vehicles under deadline and sector capacity constraints," *IEEE Transactions on Emerging Topics in Computational Intelligence*, vol. 6, no. 4, pp. 839–851, 2022.

[15] L. Ma and C. Zhang, "5G waveforms design for aeronautical communications," in *IEEE/AIAA Digital Avionics Systems Conf.*, pp. 1–7, 2016.

[16] B. Li, Z. Fei, Y. Zhang, and M. Guizani, "Secure uav communication networks over 5G," *IEEE Wireless Communications*, vol. 26, no. 5, pp. 114–120, 2019.

[17] N. Hosseini, H. Jamal, J. Haque, T. Magesacher, and D. W. Matolak, "UAV command and control, navigation and surveillance: A review of potential 5G and satellite systems," in *IEEE Aerospace Conference*, pp. 1–10, 2019.

[18] R. Gopal and N. BenAmmar, "Framework for unifying 5g and next generation satellite communications," *IEEE Network*, vol. 32, no. 5, pp. 16–24, 2018.

[19] E. W. Frew and T. X. Brown, "Airborne communication networks for small unmanned aircraft systems," *Proceedings of the IEEE*, vol. 96, no. 12, pp. 2008–2027, 2008.

[20] W. Xu, T. Xiao, J. Zhang, W. Liang, Z. Xu, X. Liu, X. Jia, and S. K. Das, "Minimizing the deployment cost of UAVs for delay-sensitive data collection in iot networks," *IEEE/ACM Transactions on Networking*, vol. 30, no. 2, pp. 812–825, 2022.

[21] S. K. Das, "Mobility management – a personal perspective," *Computer Communications*, vol. 131, pp. 26–31, 2018.

[22] A. Misra, A. Roy, and S. K. Das, "Information-theory based optimal location management schemes for integrated multi-system wireless networks," *IEEE Trans. Networking*, vol. 16, no. 3, pp. 525–538, 2008.

[23] A. Pratap, R. Misra, and S. K. Das, "Maximizing fairness for resource allocation in heterogeneous 5G networks," *IEEE Transactions on Mobile Computing*, vol. 20, no. 2, pp. 603–619, 2021.

[24] A. Pratap and S. K. Das, "Stable matching based resource allocation for service provider's revenue maximization in 5G networks," *IEEE Trans. on Mobile Computing*, vol. 21, no. 11, pp. 4094–4110, 2022.

[25] A. Khochare, Y. Simmhan, F. B. Sorbelli, and S. K. Das, "Heuristic algorithms for co-scheduling of edge analytics and routes for UAV fleet missions," in *IEEE INFOCOM*, 2021. (Extended version to appear in IEEE/ACM Transactions on Networking, 2023).

[26] K. Kong, J. Tan, J. Huang, G. Chen, S. Wang, X. Jin, P. Zeng, M. K. Khan, and S. K. Das, "Edge-computing-driven internet of things: A survey," *ACM Comput. Surveys*, vol. 55, no. 8, pp. 174:1–174:41, 2023.

[27] S. S. Shinde, A. Bozorgchenani, D. Tarchi, and Q. Ni, "On the design of federated learning in latency and energy constrained computation offloading operations in vehicular edge computing systems," *IEEE Transactions on Vehicular Tech.*, vol. 71, no. 2, pp. 2041–2057, 2022.

[28] A. Qayyum, M. Usama, J. Qadir, and A. Al-Fuqaha, "Securing connected autonomous vehicles: Challenges posed by adversarial machine learning and the way forward," *IEEE Communications Surveys Tutorials*, vol. 22, no. 2, pp. 998–1026, 2020.

[29] Z. Hu, J. Niu, T. Ren, B. Dai, Q. Li, M. Xu, and S. K. Das, "An efficient online computation offloading approach for large-scale mobile edge computing via deep reinforcement learning," *IEEE Transactions on Services Computing*, vol. 15, no. 2, pp. 669–683, 2022.

[30] N. Sharma, A. Ghosh, R. Misra, , and S. K. Das, "Deep meta q-learning based multi-task offloading in edge-cloud systems," *IEEE Transactions on Mobile Computing, to appear*, 2023.

[31] F. B. Sorbelli, S. K. Das, C. M. Pinotti, and G. Rigoni, "A comprehensive analysis of range-free localization algorithms with mobile anchors at different altitudes," *Pervasive and Mobile Computing*, vol. 73, 2021.

[32] F. B. Sorbelli, C. M. Pinotti, S. Silvestri, and S. K. Das, "Measurement errors in range-based localization algorithms for UAVs: Analysis and experimentation," *IEEE Transactions on Mobile Computing*, vol. 21, no. 4, pp. 1291–1304, 2022.

[33] X. Kong, H. Gao, G. Shen, G. Duan, and S. K. Das, "FedVCP: A federated learning based cooperative positioning scheme for social internet of vehicles," *IEEE Transactions on Computational Social Systems*, vol. 9, no. 1, pp. 197–206, 2022.

[34] S. Kumar and S. K. Das, "Target detection and localization methods using compartmental model for internet of things," *IEEE Transactions on Mobile Computing*, vol. 19, no. 9, pp. 2234–2249, 2020.

[35] "The JAC Hua Xianzi is the world's first sodium-ion battery vehicle," *timeslive.co.za/motoring/news/2023-03-07-the-jac-hua-xianzi-is-the-worlds-first-sodium-ion-battery-vehicle/*, 2023.

[36] P. Chatterjee, P. Majumder, A. Debnath, and S. K. Das, "Distributed decision making for V2V charge sharing in intelligent transportation systems," in *IEEE SECON*, pp. 506–514, 2022.

[37] M. Tiloca, D. De Guglielmo, G. Dini, G. Anastasi, and S. K. Das, "Jammy: A distributed and self-adaptive solution against selective jamming attack in tdma wsns," *IEEE Transactions on Dependable and Secure Computing*, vol. 14, no. 4, pp. 392–405, 2017.

[38] J.-W. Ho, M. Wright, and S. K. Das, "Zonetrust: Fast zone-based node compromise detection and revocation in wireless sensor networks using sequential hypothesis testing," *IEEE Transactions on Dependable and Secure Computing*, vol. 9, no. 4, pp. 494–511, 2012.

[39] H. Vasudev, V. Deshpande, D. Das, and S. K. Das, "A lightweight mutual authentication protocol for V2V communication in Internet of vehicles," *IEEE Trans. Vehicular Technology*, vol. 69, no. 6, pp. 6709–6717, 2020.

[40] T. Limbasiya, D. Das, and S. K. Das, "MComIoV: Secure and energy-efficient message communication protocols for Internet of vehicles," *IEEE/ACM Trans. on Networking*, vol. 29, no. 3, pp. 1349–1361, 2021.

[41] G. Bendiab, A. Hameurlaine, G. Germanos, N. Kolokotronis, and S. Shiaeles, "Autonomous vehicles security: Challenges and solutions using blockchain and artificial intelligence," *IEEE Transactions on Intelligent Transportation Systems*, vol. 24, no. 4, pp. 3614–3637, 2023.

[42] H. Eißfeldt, V. Vogelpohl, M. Stolz, A. Papenfuß, M. Biella, J. Belz, and D. Kügler, "The acceptance of civil drones in germany," *CEAS Aeronautical journal*, vol. 11, no. 3, pp. 665–676, 2020.

[43] P. Yedavalli and J. Mooberry, "An assessment of public perception of urban air mobility (uam)," *Tech Report, Airbus*, pp. 1–28, 2019.

[44] P. Planing, Y. Pinar, *et al.*, "Acceptance of air taxis-a field study during the first flight of an air taxi in a european city," tech. rep., Center for Open Science, available online at osf.io/rqgpc, 2019.