Design and Analysis of Routing Protocols for the Internet of Drones

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Abstract. *The Internet of Drones (IoD) is an emerging technology enabling a new era of drone services and applications. However, many barriers and challenges remain until it is possible to control a complex IoD network. The scientific community is still discussing, studying, and investigating the best way to implement this network to become the IoD viable, reliable, and efficient. Furthermore, the principles that guide terrestrial wireless networks and even traditional Unnamed Aerial Vehicles (UAV) networks do not apply to IoD mainly because it allows distinct drones performing different applications to share the airspace. This thesis aims to provide procedures and discussions that can guide future development to overcoming barriers related to fundamental problems in IoD, such as communication and mobility.*

1. Introduction

UAV Networks is attracting growing attention as a solution to meet the surging demand for services involving drone delivery, monitoring, and surveillance across a wide range of domains. Certain studies [Gharibi et al. 2016, Guerber et al. 2019, Zhao et al. 2019, Kumar et al. 2021] propose architectures for the organization of airspace, allowing simultaneous operation of multiple drones and services. Gharibi et al. [2016] introduced an architecture for the Internet of Drones (IoD) to orchestrate the airspace to accommodate the concurrent and equitable operation of multiple drone services. This architecture is inspired by three networks: the Internet, Cellular Networks, and Air Traffic Control (ATC).

Current research developments in the area are far from making IoD a reality and are not capable of solving the increasing demand for UAV applications. The specific characteristics of Drone networks, such as 3D mobility, the high speed of nodes, and the irregular UAV distribution, must be considered in the design of routing protocols in the area [Arafat and Moh 2019]. In addition, it needs to manage different applications that may vary at various levels, ranging from drone hardware to network topologies. Moreover, all these drones must be able to share the same airspace in a coordinated, secure, and fair way [Boccadoro et al. 2021, Svaigen et al. 2023].

Considering this new world, IoD has a gap in fundamental network problems like communication that must be explored and overcome. Furthermore, the utilization of drone-generated data gathered across various applications, including urban sensing, communication resilience during disasters, monitoring, and drone delivery services, to

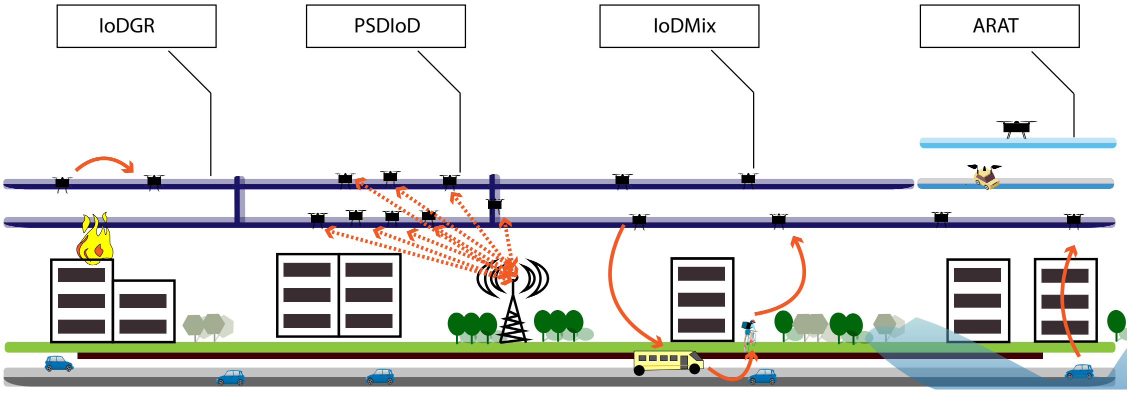

Figure 1. Overview of the Protocols Developed

name a few, can enhance Urban Computing (UC) applications [Bine 2023, Section 3.2]. IoD is a new way of creating new and complementary data to existing ones and providing services through drones, contributing to the UC's objective of improving people's lives.

However, it is imperative to design an architecture that facilitates the seamless sharing of airspace among multiple drones before commencing data collection with UAVs. Additionally, it is essential to formulate routing protocols that are well-suited to this extensive-scale scenario. IoD is still beginning its development and has many steps and challenges related to communication and mobility to overcome.

2. Objectives and Contributions

The main objectives of this thesis are **to propose topologies and frameworks for organizing the airspace and developing protocols for efficient data dissemination Intra-IoD and Inter-IoD** (intra-communication pertains to interactions between drones, while inter-communication involves communication between IoD and other networks). Specifically, this thesis aimed to design protocols to focus on sparse and emergency scenarios. In addition, it develops routing protocols so they can collaborate with the UC. The design of protocols for IoD must consider the aspects that make this environment unique, such as the airways, demanding collaboration between drones, energy constraints, fair use of airspace, and collaboration with UC. In general, it explores the distinct aspects of IoD and uses them as advantages for communication protocol design.

The protocols proposed by this thesis are mainly distinguished by the scenario and context in which they are inserted. The Geocast Routing Protocol for the Internet of Drones (IoDGR) and Position-based Routing Protocol for Software-Defined IoD (PSDIoD) protocols are Intra-network protocols. On the other hand, Delay-tolerant Internet of Drones Protocol in a Multi-vehicle Scenario (IoDMix) and Altitude-based Routing Protocol for Hybrid Aerial-terrestrial Networks (ARAT) are Inter-network protocols. The IoDGR is a geocast protocol for a sparse network and emergence situation (IoDGR – Figure 1). PSDIoD is applied in a scenario where ZSPs can directly communicate with Drones, forming an IoD-Defined Network (PSDIoD – Figure 1). IoDMix collaborates with IoD and other terrestrial networks (IoDMix – Figure 1). Finally, ARAT promotes cooperation between IoD and other Aerial Networks (ARAT – Figure 1).

The thesis advanced the start-of-the-art of IoD by (i) developing guidelines for collecting IoD data to improve UC applications; (ii) developing two routing protocols for IoD, one focusing on geocast message dissemination in emergence scenarios and the other considering a Software Defined Network (SDN) approach; (iii) proposing two routing protocols for joint IoD and Other Networks. The first one considers a partnership between IoD and Terrestrial Networks, and the other one considers other kinds of Aerial Networks; (iv) proposing an airspace and airway topological infrastructure for IoD and a coverage path planning method for this scenario; and (v) analyzing and comparing drone delivery and traditional deliveries to allow insights about how to make path planning for drone delivery in an IoD architecture that uses airways.

3. Guidelines, Frameworks, and Surveys

First, this thesis originated an in-depth survey of the connection between UC and IoD (A1). IoD can contribute to Urban Computing goals. UC needs data to understand the population and make people's lives more comfortable, efficient, and productive. The services provided and data collected by drones can contribute to leveraging the research related to UC. Each application must be analyzed independently and studied to determine if it is more advantageous to carry out using drones. For instance, static sensors coupled with various mobile devices such as cell phones, cars, and drones can collect air quality data. Thus, one should consider whether using drones in this application is advantageous.

Consequently, this survey aimed to discuss how urban computing can help understand the challenges of IoD through IoD applications in the urban context. Specifically, it presents the applications related to IoD-UC considering the following topics: urban planning, transportation systems, environment, urban energy consumption, social applications, economy, and public safety and security. It also explores the definitions of these two concepts (IoD and UC), the applications and requirements necessary for them to be implemented, and presents the challenges and critical issues related to these areas.

Second, this thesis proposed a framework for IoD applications in the context of UC (A2). UC is a cross-disciplinary domain where Computer Science intersects with various fields, including economics, civil engineering, urban planning, and sociology [Zheng et al. 2014]. The UC aims to analyze and integrate diverse data sources to enhance urban operational systems and people's overall quality of life [Silva et al. 2019]. These data sources encompass sensors, human mobility, Location-Based Social Networks (LBSNs), Internet of Things (IoT) devices, and other similar sources. Recently, drones have emerged as a novel data source for urban applications. Considering the IoD context, the proposed framework presents new approaches to data acquisition, integration, and analysis in urban computing.

Next, this thesis discusses airspace organization, describes possible partnerships between IoD and Terrestrial Networks (TNs), and highlights the potential and challenges in converging IoD and Terrestrial Networks for the next generation of smart cities (A3). In future smart cities, it is reasonable to assume that distinct networks will collaborate to improve network communication and safety. Shortly, smart cities will have a reliable and autonomous intelligent transport system. In addition, different types of vehicles are expected to be integrated. People move around using distinct transportation modes such as buses, cars, and bicycles, and the choice depends on certain conditions such as weather, availability, and costs.

Analogously, the integration between networks depends on several factors. Specifically, availability, cost, energy expenditure, weather conditions, and network coverage, to name a few. Most recent work focuses on collaboration between Vehicle Ad-hoc Networks (VANETs) and UAV networks [Krishna 2020]. However, this thesis explores other networks as possible associations for drones. This discussion considers the following questions: How can IoD and TNs form a successful collaboration regarding data communication and delivery? And what characteristics should be considered when creating a partnership between IoD and Terrestrial Networks?

Finally, this thesis systematically analyzes the existing terminologies of UAV networks (Drone/UAV-based network, UAV/Unmanned Aerial System, Flying Ad Hoc Network, Internet of Flying Things, and Internet of Drones), considering their requirements and applications, shedding light on their intersections and differences (A4). We elaborate a Venn diagram to represent the intersections between each terminology. It is necessary to understand the demands of the next generation of UAV networks and discuss how they impact the design of UAV-related applications, aiding in designing new protocols, tools, and technologies for industry and academia.

A1 Bine, L. M. S., Boukerche, A., Ruiz, L. B., and Loureiro, A. A. F. "Connecting Internet of Drones and Urban Computing: Definitions, Applications, and Challenges". **Computer Networks**, p. 110136, 2023. **Qualis CAPES A1**.

A2 Bine, L. M., Boukerche, A., Ruiz, L. B., and Loureiro, A. A. "Leveraging Urban Computing with the Internet of Drones". **IEEE Internet of Things Magazine**, v. 5, n. 1, p. 160-165, 2022. **Qualis CAPES B1**.

A3 Bine, L. M. S., Boukerche, A., Ruiz, L. B., and Loureiro, A. A. F. "Internet of Drones and Terrestrial Networks: A Successful Partnership". **IEEE Internet of Things Magazine**, v. 6, n. 4, p. 104-110, 2023. **Qualis CAPES B1**.

A4 Bine, L. M. S., Boukerche, A., Ruiz, L. B., and Loureiro, A. A. F. Flavors of the Next Generation of Unmanned Aerial Vehicles Networks **Internet of Things Journal**. **Qualis CAPES A1**.

4. Internet of Drones Protocol

State-of-the-art IoD protocols do not consider the use of airways or that the drone network in a given location is unique, allowing for a continuous flow of drones [Arafat and Moh 2019]. Regarding an IoD network, all active drones belong to a single network, facilitating drone control and avoiding collisions and vehicle congestion (See Table 1). Furthermore, when dealing with a large number of drones, for instance, in urban centers, it is expected that it will be necessary to limit the flight locations to better control the airspace. This research considers the use of airways, which is a common approach for aircraft traffic.

This thesis proposed, modeled, and evaluated two routing protocols for IoD considering the use of airways. The first one, IoDGR (Geocast Routing Protocol for Internet of Drones), seeks to solve the problem of geocast message dissemination in emergence scenarios (A6, A7). In IoD, some scenarios will need to block different airways, such as in firefighting, places with risk of explosion, and safety during significant events, to name a few. In this case, a routing protocol that transmits a message warning all drones in a particular region informing them of the blocked airways is used. A suitable protocol for this situation is a geocast protocol, i.e., a protocol responsible for delivering messages to a set of nodes identified by their geographical location [Bousbaa et al. 2020]. Specifically, IoDGR uses the concept of airway topology and path planning of drones to improve the delivery rate of packets.

Table 1. Some protocol requirements for VANETs, traditional UAV networks and IoD

Requirement	VANET	Traditional UAV	IoD
Management	A Road Side Unit (RSU) coordinates vehicles in a given region	Drones in a given region do not coordinate access to air space. Collaborations between multiple drones and multiple swarms can occur. However, each drone or swarm is generally controlled individually	All drones in a given region coordinate access to the air space. ZSPs carry out this control and coordination. All drones are connected in a single network
Speed of nodes	High	High, usually more than VANETs in urban scenarios	High, usually more than VANETs in urban scenarios
Mobility	2D mobility	3D mobility	3D mobility and use of airways at different altitudes
Use of defined roads or airways	Use of roads is necessary	Use of airways is not necessary	Use of airways is necessary
Power Supply	Battery; lifetime usually high	Battery; lifetime usually low	Battery; lifetime usually low. However, the ZSP is responsible for energy management.

It is expected that IoD promotes constant drone traffic in airspace, enabling a dense and sparse network over time. The IoDGR protocol focuses on strategies that take advantage of airways, path planning, and shortcut concepts to improve the dissemination of emergency messages when the network is sparse. The drone's energy capacity must be considered when planning a drone mission. Thus, in addition to the energy used to fulfill its objective, the drone must consider an extra margin of safety. Therefore, in emergencies external to the drone, it is more interesting to maintain the network security using more energy. An IoD network is highly dynamic, requiring several geocast protocol solutions.

A5 Bine, L. M. S., Boukerche, A., Ruiz, L. B., and Loureiro, A. A. F. "PSDIoD: A Position-based Routing Protocol for Software-Defined Internet of Drones". **Proceedings of the IEEE International Conference on Communications (ICC)**, p. 1064-1069, 2022. **Qualis CAPES A1**.

A6 Bine, L. M. S., Boukerche, A., Ruiz, L. B., and Loureiro, A. A. F. "IoDAGR: An Airway-based Geocast Routing Protocol for Internet of Drones". **Proceedings of the IEEE International Conference on Communications (ICC)**, p. 1-6, 2021. **Qualis CAPES A1**.

A7 Bine, L. M. S., Boukerche, A., Ruiz, L. B., and Loureiro, A. A. F. "IoDGR: A Geocast Routing Protocol for Sparse Internet of Drones". **First Round of Review**.

The second protocol, called PSDIoD (Position-based Routing Protocol for Software-Defined), considers an SDN approach and a scenario where a Zone Service Provider (ZSP) can communicate directly with drones (A5). Controlling a drone network is a complex process involving airspace control and communication-related issues. Drones of different models from several companies are expected to provide many services and share the same airspace. Thus, integrated airspace control is necessary for better traffic control, route planning, and energy savings, providing greater network security. One way to promote centralized control of the network is to use SDN. Thus, PSDIoD takes advantage of this factor to disseminate messages between drones.

The Internet of Drones presents a scenario where we employ SDN to enhance network programmability and expedite changes due to different factors (e.g., dense or sparse IoD). We can expect an IoD where drones will have to inform a base station of their position as proposed by the Federal Aviation Administration (FAA). This approach can have a high energy cost. Energy expenditure is is a critical factor due to the power limitation of drones. In addition, a technology that drones can use to send their position to the base station also has a high deployment cost. However, considering that the structure already exists, constantly knowing the drone's position is a valuable piece of infomation for building efficient message routing.

5. Internet of Drones and Other Networks

Regarding communication protocols between IoD and another network, most studies in the literature investigate the scenario of UAV-aided VANETs [Krishna 2020] (See Table 2). An interesting factor is that the drones move according to the needs of the network being assisted. However, this thesis considered a futuristic scenario in which the IoD will allow multiple drones to perform different applications and share airspace. Drone delivery will form a continuous flow of drones in the sky. Hence, it will not be possible to change the path of these drones to make collaboration between IoD and other networks possible. Thus, this thesis investigates a scenario in which collaboration occurs without interfering with the mobility of nodes.

Table 2. Related studies to routing protocols, IoD and collaboration with other networks

Year	Ref.	IoD	UAV	VANET	PTN	Bicycle	IoFC	Highlights
2017	[Oubbati et al. 2017]		✓	✓				A reactive routing protocol for transmitting packets in the sky
2020	[Oubbati et al. 2020]		✓	✓				A reactive protocol for UAV-aided VANETs
2021	[Du et al. 2021]		✓	✓				A routing protocol for UAV-Assisted Vehicular Delay-Tolerant Networks
2022	[Azzoug and Boukra 2022]		✓	✓				A bio-inspired UAV-aided vehicular delay-tolerant network routing protocol for urban VANET environments
2022	**IoDMix**	✓	✓	✓	✓	✓		**A store-carry-forward protocol for joint PTNs, VANET, BSNs, and IoD to fill the gaps in IoD communications**
2023	**ARAT**	✓	✓	✓			✓	**A store-carry-forward protocol for joint IoD, VANET, and others aerial networks such as IoFC (Internet of Flying Cars)**

This thesis proposed, modeled, and evaluated two routing protocols for IoD considering the use of airways. The first (A8, A10, A11), IoDMix (Delay-tolerant Internet of Drones Protocol in a Multi-vehicle Scenario), performs cooperation between drones, Public Transportation Networks (PTN), Bicycle Sharing Networks (BSN), and VANET to fill the communication gaps in scenarios where the IoD network is not connected. Also, the different characteristics of the networks mentioned define message forward priority. For instance, PTNs are frequent and maintain the periodicity of the routes almost every day. Thus, planning the drone's path is possible by considering public transport routes. The IoD-terrestrial networks collaboration is promising. Works in the literature show that ground vehicles can be a means to allow more extended trips, energy savings, and even be a charging point for drones in operation. These advantages and the high predictability of some terrestrial networks enable routing protocols to exploit the collaboration of IoD-terrestrial networks to improve efficiency, message delivery, and decrease delay.

The second (A9) ARAT (Altitude-based Routing Protocol for Hybrid Aerial-terrestrial Networks) considers a cooperation scenario between VANET and Aerial networks. The airspace is expected soon to encompass multiple networks with different types of nodes. Among these networks are IoD and the Internet of Flying Things. Although they share the same airspace, each network has other characteristics such as node type, altitude, speed, power supply, and processing capacity. A new trend was recently raised to evolve these networks towards an integrated network [Shi et al. 2018]: Hybrid Aerial-terrestrial Network. Therefore, this thesis explores the integration of IoD and other aerial networks. Specifically, in an emergency scenario, no terrestrial node may be nearby. The only way to deliver a message to the ZSP is to send it to a robust node in the aerial network.

The integration between networks can allow different solutions for emergency scenarios. Protocol development for hybrid networks must consider heterogeneous nodes with different sizes, mobility, speeds, and processing capabilities. In the literature, we have a few geocast protocols for UAVs [Bousbaa et al. 2020]. However, they do not have a recovery mechanism when a message reaches an isolated node. Scenario emergencies can be unpredictable and require efficient message delivery. Aiming at this scenario, we proposed the ARAT protocol. Our results show that ARAT performed better in sparse scenarios. We expected this fact since the ARAT protocol was designed precisely for sparse network cases. That means that the denser the scenario, the greater the chance other networks are available to collaborate and disseminate emergency messages.

A8 Bine, L. M. S., Boukerche, A., Ruiz, L. B., and Loureiro, A. A. F. “IoDMix: A novel routing protocol for Delay-Tolerant Internet of Drones integration in Intelligent Transportation System”. **Ad Hoc Networks**, v. 148, p. 103204, 2023. **Qualis CAPES A1**.

A9 Bine, L. M. S., Boukerche, A., Ruiz, L. B., and Loureiro, A. A. F. “ARAT: An altitude-based routing protocol for Hybrid Aerial-terrestrial Networks”. **Proceedings of the IEEE International Conference on Communications (ICC)**, 2023. **Qualis CAPES A1**.

A10 Bine, L. M. S., Boukerche, A., Ruiz, L. B., and Loureiro, A. A. F. “IoDSCF: A Store- Carry-Forward Routing Protocol for joint Bus Networks and Internet of Drones”. **Proceedings of the 42nd IEEE International Conference on Distributed Computing Systems (ICDCS)**, 2022. **Qualis CAPES A1**.

A11 Bine, L. M. S., Boukerche, A., Ruiz, L. B., and Loureiro, A. A. F. “Um Protocolo de Roteamento Store-Carry-Forward para Unir Redes de Ônibus e Internet dos Drones”. (In Portuguese) **Proceedings of the 40th Brazilian Symposium on Computer Networks and Distributed Systems (SBRC)**, 2022. **Qualis CAPES A4**.

6. IoD Path Planning

This thesis devised a method for building coverage path plans for multiple drones in the context of IoD and presents comprehensive guidelines for designing drone delivery decision systems. Both contributions are detailed in the sequence.

6.1. Coverage Path Planning

Overall, the state-of-art CPP for drones considers two phases [Cabreira et al. 2019, Mannan et al. 2023]. The first executes the decomposition of the area, and the second performs the coverage by the decomposed area. The decomposition phase allows for greater flexibility in path planning when compared to airway-based IoD. In airway-based IoD, airways can be arranged parallel to landways. In traditional CPP, the goal is to cover the entire delimited area, while in CPP-IoD, the goal is to cover all airway segments in the coverage area. Also, in traditional CPP, drones can fly in any direction and at any altitude, while in CPP-IoD, drones must follow the airway altitudes and directions.

This thesis proposed a coverage path planning method that considers and takes advantage of the airway-based IoD. Specifically, the process has two steps: path planning improvement and balancing the paths between the drones. Our results showed a decrease in the distance traveled by the drones to cover the evaluated area. Specifically, there was an improvement of approximately 9.59% in the cost of results when using the loop deletion heuristic and 12.46% when using the loop deletion heuristic and mutation algorithm. For balancing, the fewer drones used, the better the results obtained.

6.2. Drone Delivery

To comprehend the benefits of drone delivery, certain studies concentrate on healthcare delivery and examine the transportation of specific items such as medicine, human organs, and blood [Nisingizwe et al. 2022]. In medicine, human organs, and blood deliveries, fast delivery is crucial as human lives can be contingent on the successful arrival of these items. Drone delivery of blood, for instance, is already being implemented, offering the advantage of rapid transportation [Nisingizwe et al. 2022]. Furthermore, these studies also assess whether drone delivery can help mitigate waste, considering that such products require specific storage conditions [Nisingizwe et al. 2022].

Other research endeavors conduct a comprehensive analysis of drone delivery, focusing on the advantages in terms of energy efficiency, cost-effectiveness [Chiang et al. 2019], sustainability [Chiang et al. 2019], and delivery time [Nisingizwe et al. 2022]. Despite significant advancements in drone delivery, it remains essential to understand the circumstances where drone delivery offers advantages in terms of why, where, and when it should be employed. This thesis introduces a comprehensive guideline for developing decision systems for drone delivery within the IoD (Figure 2). Specifically, it presents a systematic approach to the drone delivery decision problem that tackles those questions (why, where, and when). Our approach covers the definition of the Internet of Drones and is validated using real-world data. We applied our method to a case study, and our results show that employing our guideline in decision systems decreases the delivery time by 49% compared to real delivery time.

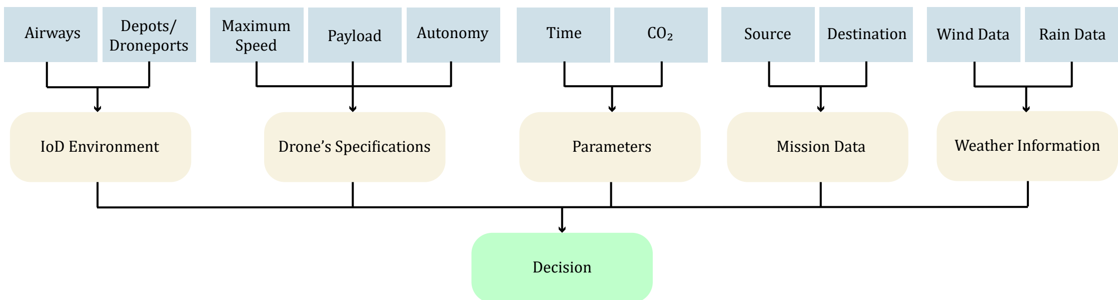

Figure 2. Drone Delivery Guidelines for IoD

A12 Bine, L. M. S., Boukerche, A., Ruiz, L. B., and Loureiro, A. A. F. "A Novel Ant Colony-inspired Coverage Path Planning for Internet of Drones". **Computer Networks**, v. 235, p. 109963, 2023. **Qualis CAPES A1**.

A13 Bine, L. M. S., Boukerche, A., Ruiz, L. B., and Loureiro, A. A. F. "Coverage Path Planning for Internet of Drones". **Proceedings of the ACM International Symposium on Performance Evaluation of Wireless Ad Hoc, Sensor, & Ubiquitous Networks**, pp. 49-57, 2022. **Qualis CAPES B4**.

A14 Bine, L. M. S., Boukerche, A., Ruiz, L. B., and Loureiro, A. A. F. "Drone Delivery: Why, Where, and When". **Proceedings of the ACM International Symposium on Performance Evaluation of Wireless Ad Hoc, Sensor, & Ubiquitous Networks. Qualis CAPES B4**.

7. Conclusions

This thesis has four main parts that divide the contributions. The first concerns understanding the IoD characteristics and necessities through IoD-UC applications. Therefore, some gaps were identified in the literature for the elemental network problems: communication and mobility. This thesis addresses the communication problem by developing two routing protocols for IoD. After, it integrates the IoD with other networks. As IoD has the potential for multiple applications in the urban scenario, IoD needs to communicate with different networks.

The last contribution is related to the mobility problem. Using airways can bring different perspectives to traditional issues. This research explores drone delivery applications in urban scenarios and compares them with typical deliveries. Also, it investigates a Coverage Path Planning problem in the IoD scenario. This research followed directions essential for unlocking the full potential of drones in urban environments and addressing the challenges associated with communication and mobility for drone integration into the urban scenario.

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