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 that will enable 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, Boutaba, & Waslander, 2016; Guerber, Larrieu, & Royer, 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 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 & Moh, 2019). In addition, it needs to manage different applications that may vary at different 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 fairway (Boccadoro, Striccoli, & Grieco, 2021; Svaigen, Boukerche, Ruiz, & Loureiro, 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 name a few, can enhance Urban Computing (UC) applications (Bine, 2023, Section 3.2).

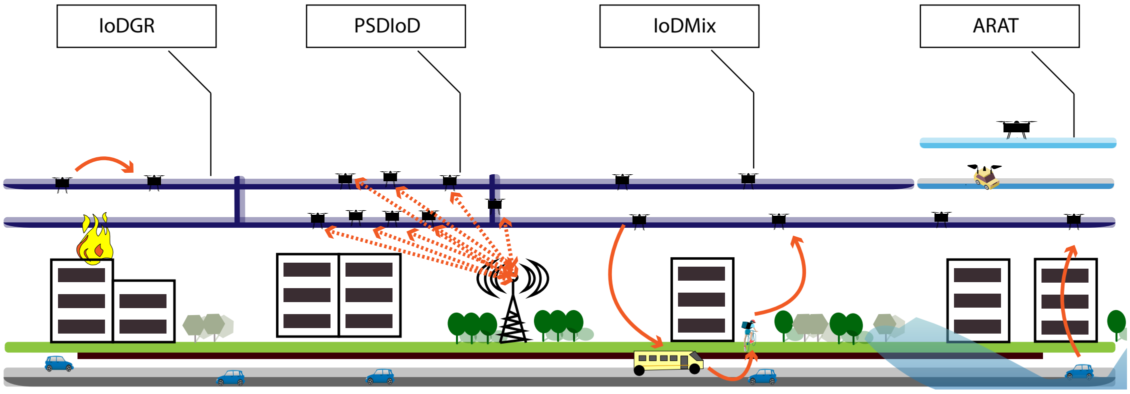

Figure 1. Overview of the Protocols Developed

Urban Computing benefits from a large amount of data generated in urban centers. 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, designing an architecture that facilitates the seamless sharing of airspace among multiple drones before commencing data collection with UAVs is imperative. 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 to overcome related to communication and mobility.

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. Many factors mentioned also influence the drones' mobility and path planning. Therefore, this thesis focuses on the identification and proposes solutions to two fundamental problems: communication and mobility.

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 (J1, Table 1). This survey aimed to discuss how Urban Computing can help understand the IoD challenges through IoD applications for the urban context. Specifically, it 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 (J2, Table 1). UC is a cross-disciplinary domain where Computer Science intersects with various fields, including economics, civil engineering, urban planning, and sociology (Zheng, Capra, Wolfson, & Yang, 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 TNs, and highlights the potential and challenges in converging IoD and Terrestrial Networks for the next generation of smart cities (J3, Table1). Most recent work focuses on collaboration between 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 to form 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 (U1, Table 1). 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.

Table 1. List of publications related to Guidelines Contributions

Cat.	Ref.	Work	Qualis	IF	H5
Journals	J1	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.	A1	5.6	87
	J2	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.	B1	3.5	28
	J3	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.	B1	3.5	28
U.	U1	Bine, L. M. S., Svaigen, A. R., Boukerche, A., Ruiz, L. B., and Loureiro, A. A. F. Flavors of the Next Generation of Unmanned Aerial Vehicles Networks. **Internet of Things Journal** (Accepted)	A1	10.6	171

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 & Moh, 2019). When it comes to an IoD network, all active drones belong to a single network, facilitating drone control and avoiding collisions and vehicle congestion. 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. In these considerations, 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 (C1, U2, Table 2). 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 2. Intra-IoD protocols list of publications

Cat.	Ref.	Work	Qualis	IF	H5
Conferences	C1	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.	A1	–	76
	C2	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.	A1	–	76
Unp.	U2	Bine, L. M. S., Boukerche, A., Ruiz, L. B., and Loureiro, A. A. F. "IoDGR: A Geocast Routing Protocol for Sparse Internet of Drones". (Under 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 (C2, Table 2). 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.

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). 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 performing different applications to share the 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.

This thesis proposed, modeled and evaluated two routing protocols for IoD considering the use of airways. The first (J4, C4, C5, Table 3), 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 second (C3, Table 3) 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, Liu, Fadlullah, & Kato, 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. Therefore, the only way to deliver a message to the ZSP is to send it to a robust node in the aerial network. These contributions are reported in Table 4.

Table 3. Inter-IoD protocols list of publications

Cat.	Ref.	Work	Qualis	IF	H5
Jour.	J4	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.	A1	4.8	59
Conferences	C3	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)**, p. 1-6, 2021.	A1	–	76
	C4	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.	A1	–	47
	C5	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.	B2	–	8

6. IoD Path Planning

This thesis devised a method for building coverage path plans for multiple drones in the context of IoD. Also, it 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, Brisolara, & Paulo R., 2019; Mannan, Obaidat, Mahmood, Ahmad, & Ahmad, 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 proposes a coverage path planning method that considers and takes advantage of the airway-based IoD (J5, C6, Table 4). CPP for IoD poses unique requirements, combining elements of CPP for both drones and ground robots. Specifically, it must account for 3D movement and drone collaboration while accommodating road network constraints, including overlapping roads. Additionally, energy consumption is a crucial factor due to the limited battery life of drones. Furthermore, the IoD scenario is highly dynamic, requiring adaptive algorithms such as bio-inspired techniques. To address these challenges, this thesis proposes an ant colony optimization-based algorithm for CPP in IoD, considering the energy expenditure of drones.

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, Li, Shang, & Urban, 2019), sustainability (Chiang et al., 2019), and delivery time (Nisingizwe et al., 2022). These studies can be classified into two categories: those that aim to develop more efficient algorithms and models for path planning and drone systems (Chiang et al., 2019), and those that compare drone delivery with ground vehicles (Nisingizwe et al., 2022). Current work focuses on route planning and creating models for more efficient drone deliveries. However, these studies do not consider decision models to verify which types of delivery are most efficient for every kind of merchandise.

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. Specifically, it presents a systematic approach to the drone delivery decision problem that tackles those questions (why, where, and when) (C7, Table 4).

Table 4. IoD path planning list of publications

Cat.	Ref.	Work	Qualis	IF	H5
Jour.	J5	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.	A1	5.6	87
Conferences	C6	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.	B2	–	3
	C7	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.**	B2	–	3

7. Publications

This thesis produced 14 papers. The main accomplishments of this research can be summarized as follows:

- Seven papers in periodic journals (e.g., Ad Hoc Networks, Computer Networks, and Internet of Things Magazine). Five papers have already been published, one was accepted and one is under review;
- Seven papers in Conferences, such as the International Conference on Communications, the International Conference on Distributed Computing Systems, and the International Symposium on Performance Evaluation of Wireless Ad Hoc, Sensor & Ubiquitous Networks. The seven papers have already been published.

8. 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 other 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.

Acknowledgment

This work was partially supported by the NSERC CREATE TRANSIT, NSERC DIVA Strategic Research Network, Canada Research Chairs Program, CAPES, CNPq (grants 311685/2017-0 & 310620/2019-8), and grants 15/24494-8 & 18/23064-8, São Paulo Research Foundation (FAPESP).

References

Arafat, M. Y., & Moh, S. (2019). Routing Protocols for Unmanned Aerial Vehicle Networks: A Survey. *IEEE Access*, *7*, 99694–99720.

Bine, L. M. S. (2023). *Design and Analysis of Routing Protocols for Internet of Drones* (PhD thesis). Federal University of Minas Gerais, Belo Horizonte, MG, Brazil.

Boccadoro, P., Striccoli, D., & Grieco, L. A. (2021). An Extensive Survey on the Internet of Drones. *Ad Hoc Networks*, *122*, 102600.

Bousbaa, F. Z., Kerrache, C. A., Mahi, Z., Tahari, A. E. K., Lagraa, N., & Yagoubi, M. B. (2020). GeoUAVs: A New Geocast Routing Protocol for Fleet of UAVs. *Computer Communications*, *149*, 259–269.

Cabreira, T. M., Brisolara, L. B., & Paulo R., F. J. (2019). Survey on coverage path planning with unmanned aerial vehicles. *Drones*, *3*(1), 4.

Chiang, W.-C., Li, Y., Shang, J., & Urban, T. L. (2019). Impact of Drone Delivery on Sustainability and Cost: Realizing the UAV Potential Through Vehicle Routing Optimization. *Applied energy*, *242*, 1164–1175.

Gharibi, M., Boutaba, R., & Waslander, S. L. (2016). Internet of Drones. *IEEE Access*, *4*, 1148–1162.

Guerber, C., Larrieu, N., & Royer, M. (2019). Software Defined Network Based Architecture to Improve Security in a Swarm of Drones. In *2019 international conference on unmanned aircraft systems (icuas)* (pp. 51–60).

Krishna, M. (2020). A Survey UAV-Assisted VANET Routing Protocol. *International Journal of Computer Science Trends and Technology (IJCST)–Vol*, *8*.

Kumar, A., Krishnamurthi, R., Nayyar, A., Luhach, A. K., Khan, M. S., & Singh, A. (2021). A Novel Software-Defined Drone Network (SDDN)-based Collision Avoidance Strategies for On-road Traffic Monitoring and Management. *Vehicular Communications*, *28*, 100313.

Mannan, A., Obaidat, M. S., Mahmood, K., Ahmad, A., & Ahmad, R. (2023). Classical Versus Reinforcement Learning Algorithms for Unmanned Aerial Vehicle Network Communication and Coverage Path Planning: A Systematic Literature Review. *International Journal of Communication Systems*, *36*(5), e5423.

Nisingizwe, M. P., Ndishimye, P., Swaibu, K., Nshimiyimana, L., Karame, P., Dushimiyimana, V., … Law, M. R. (2022). Effect of Unmanned Aerial Vehicle (Drone) Delivery on Blood Product Delivery Time and Wastage in Rwanda. *The Lancet Global Health*, *10*(4), e564–e569.

Shi, Y., Liu, J., Fadlullah, Z. M., & Kato, N. (2018). Cross-layer data delivery in satellite-aerial-terrestrial communication. *IEEE Wireless Communications*, *25*(3), 138–143.

Silva, T. H., Viana, A. C., Benevenuto, F., Villas, L., Salles, J., Loureiro, A., & Quercia, D. (2019). Urban Computing Leveraging Location-based Social Network Data: A Survey. *ACM CSUR*, *52*(1), 1–39.

Svaigen, A. R., Boukerche, A., Ruiz, L. B., & Loureiro, A. A. (2023). Security in the Industrial Internet of Drones. *IEEE Internet of Things Magazine*, *6*(3), 110–116.

Zhao, Z., Cumino, P., Souza, A., Rosario, D., Braun, T., Cerqueira, E., & Gerla, M. (2019). Software-defined UAV Networking for Video Dissemination Services. *Ad Hoc Networks*, *83*, 68–77.

Zheng, Y., Capra, L., Wolfson, O., & Yang, H. (2014). Urban Computing: Concepts, Methodologies, and Applications. *ACM TIST*, *5*(3), 1–55.