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TDMA MAC protocols for scalable and dense wireless decentralized networks

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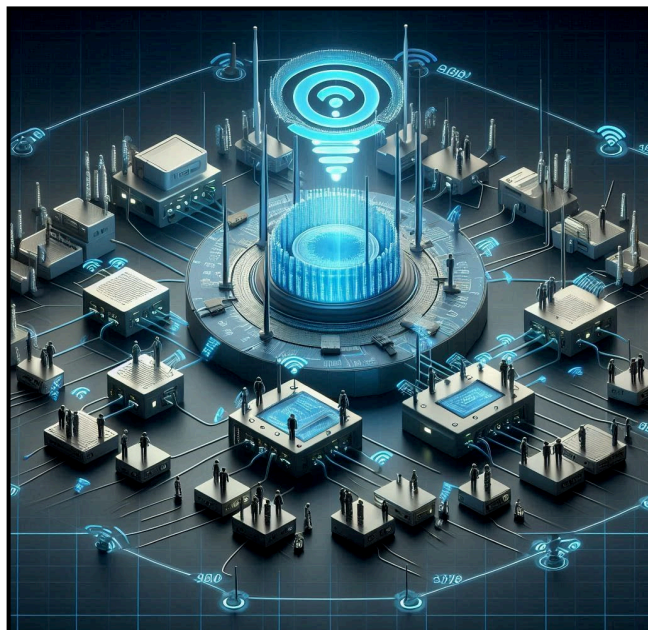
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Par **Khaled ABID**

TDMA MAC protocols for scalable and dense wireless decentralized networks

Thèse présentée
pour l'obtention du grade
de Docteur de l'UTC



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by

Khaled ABID

TDMA MAC protocols for Scalable and Dense Wireless Decentralized Networks

Spécialité : Informatique

Defended on 13/11/2023 in front of the committee composed of:

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Dedication

To my parents, who have always encouraged and supported me in every way possible. Your unwavering love and guidance have been the driving force behind my success, and I am forever grateful for your sacrifices and unwavering faith in me.

To my wife, who has been my constant source of inspiration, strength, and unwavering support. Your belief in me has been the guiding light through all the challenges and triumphs of life.

To my dear brother and sister, who have stood by my side through every twist and turn of life's journey. Your love, support, and unwavering belief in me have been my pillars of strength, and I am blessed to have you as my family.

And to my friends, my extended family, who have shared in the laughter and tears, and whose unwavering friendship has illuminated the path of my life with cherished memories and moments of joy.

This thesis is dedicated to all of you, with all my heart.

To all of you,
I dedicate this work.

Khaled Abid



Abstract

This thesis focuses on resource allocation in wireless communication at the Medium Access Control (MAC) layer. Resource allocation has been extensively studied to maximize system-wide throughput or minimize the average delay per user. One of the main challenges in wireless networks is mitigating communication collisions caused by simultaneous transmissions from multiple nodes located close to one another over a common channel. As the number of devices increases, the usability of the spectrum decreases due to interference. Additionally, high mobility, variable topology, and high density pose significant challenges for MAC protocols to handle communication collisions, leading to network disruptions, high delays, packet loss, and energy wastage.

In the first part of this thesis, we review the existing research works on contention-free MAC protocols for wireless networks. First, we discuss the challenges and requirements that MAC protocols face in wireless networks. Then, we categorize the recently proposed MAC protocols into three categories based on the node's mobility degree (Static, Low / Medium, and High mobility). Finally, we discuss the applicability of each protocol to networks with different mobility degrees than those for which they were proposed.

In the second part of this thesis, we propose an Machine Learning (ML)-based solution for predicting and avoiding collisions in wireless mobile networks. This solution can be implemented on almost any IoT device since it uses only control data exchanged between neighboring nodes to predict collisions. Furthermore, it does not rely on GPS localization systems. The obtained simulation results demonstrate the promising potential of using intelligent models as a novel approach to avoid communication collisions.

In the third part of this thesis, we propose a Preventive Time-slot Allocation Framework in a hybrid Road Side Unit (RSU)-assisted vehicular network called "PTA-MAC". This solution allows predicting the sojourn-time of incoming vehicles within a road segment using a ML model. Based on this prediction, a time-slot assignment protocol assigns the best time-slot to vehicles, reducing the probability of future collisions and resolving them when they occur.

Keywords— Medium Access Control (MAC), Time Division Multiple Access (TDMA), Wireless Sensor Networks (WSNs), Mobile networks



Résumé

Cette thèse a pour objet l'allocation des ressources de communication sans fil au niveau de la couche MAC. L'allocation des ressources a été largement étudiée pour maximiser le débit global du système ou minimiser le délai moyen d'accès au canal par utilisateur. L'un des principaux défis dans les réseaux sans fil consiste à réduire les collisions de communication causées par des transmissions simultanées de plusieurs nœuds qui sont situés à proximité les uns des autres sur un canal commun. Avec l'augmentation du nombre de dispositifs, l'utilisabilité du spectre diminue en raison des interférences. De plus, la mobilité des nœuds, la topologie variable et la densité élevée du réseau posent des défis importants pour les protocoles MAC afin de gérer les collisions de communication, qui entraînent des perturbations du réseau, des délais de communication élevés, des pertes de paquets et un gaspillage d'énergie.

Dans la première partie de cette thèse, nous avons mené une étude des travaux existants sur les protocoles MAC sans contention pour les réseaux sans fil. Tout d'abord, nous discutons des défis et des exigences auxquels les protocoles MAC sont confrontés dans les réseaux sans fil. Ensuite, nous classons les protocoles MAC récents en trois catégories en fonction du degré de mobilité des nœuds du réseau (Statique, Faible/Moyen, et Haute mobilité). Enfin, nous discutons de l'applicabilité de chaque protocole sur des réseaux avec des degrés de mobilité différents de ceux pour lesquels ils ont été proposés.

Dans la deuxième partie de cette thèse, nous proposons une solution d'évitement de collision basée sur l'apprentissage automatique pour les réseaux mobiles sans fil. Cette solution peut être mise en œuvre sur presque tous les appareils IoT car elle utilise uniquement les données de contrôle échangées avec des nœuds voisins pour prédire les collisions. De plus, elle ne nécessite pas l'utilisation de systèmes de localisation GPS. Les résultats de simulation que nous avons obtenu montrent le potentiel prometteur de l'utilisation de modèles intelligents comme nouvelle approche pour éviter les collisions de communication.

Dans la troisième partie de cette thèse, nous proposons une solution d'allocation préventive de créneaux horaires (time slots) pour un réseau hybride véhiculaire assisté par RSU nommé "PTA-MAC". Cette solution permet de prédire le temps de séjour des véhicules entrant dans un segment de route à l'aide d'un modèle d'apprentissage automatique. Sur la base de cette prédiction, un protocole d'attribution de créneaux horaires attribue le meilleur créneau horaire aux véhicules, réduisant ainsi la probabilité de futures collisions et les résolvant lorsqu'elles se produisent.

Mots-clés:— Medium access control (MAC), Time Division Multiple Access (TDMA), Réseaux de Capteurs sans fils, Réseaux mobiles



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Finally, I want to thank all the participants who generously shared their time and insights with me. This research would not have been possible without their willingness to participate in this study.

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Acronyms

AI Artificial Intelligence. 4

CDMA Code Division Multiple Access. 12

CH Cluster Head. 13

CSMA/CA Carrier-sense multiple access collision avoidance. 12

DoS Denial of Service. 20

FANETs Flying Ad-hoc Networks. 23, 40

FDMA Frequency Division Multiple Access. 12

FI Frame Information. 66

GPS Global Positioning System. v, 3, 53

KNN k-Nearest Neighbors. 59

MAC Medium Access Control. v, 3, 21

MANETs Mobile Ad-hoc Networks. 23, 34, 54

ML Machine Learning. v, 53, 55

NE Nash equilibrium. 41, 42

PLR Packet Loss Rate. 38, 61, 63, 77

PTA-MAC Preventive Time slot Assignment MAC. v

QoS Quality of Service. 3, 14, 22, 47

RFC Random Forest Classification. 59

RMSE Root Mean Square Error. 76

RSU Road Side Unit. v, 10

SAT Slot Assignment Table. 31

SDMA Space Division Multiple Access. 12

TDMA Time Division Multiple Access. v, 12, 21

TOT Topological Ordering Table. 31

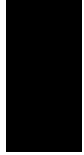
UAV Unmanned Aerial Vehicle. 26, 40

VANETs Vehicular Ad-hoc Networks. 4, 23, 54

WMNs Wireless Mesh Networks. 23

WSNs Wireless Sensor Networks. v, 13, 22

XGB XGBoost. 59



Introduction

The Internet of Things (IoT) has gained popularity in various civil and industrial domains due to the ease of integrating wireless and low-cost devices. In an IoT system, devices are connected and exchange data with each other and other digital components without human intervention. It is widely used in several fields, such as smart cities, smart buildings, healthcare, smart grids, and industrial manufacturing. The exponential growth in the demand for wireless networks in these domains has led researchers to dedicate their efforts over the past two decades to developing efficient communication solutions for IoT networks. The objective is to ensure reliable and secure connectivity, enabling effective data transmission and exchange among connected devices.

Problem statement

Wireless networks are challenged by limited communication resources, i.e., bandwidth, unlike wired and optical networks. This limitation arises from the nature of the shared medium between nodes, "Air". Any device can transmit data using this common medium or spectrum. However, one of the significant challenges in wireless networks is mitigating collisions that occur when multiple nodes in close proximity to each other transmit data simultaneously over a shared channel. Therefore, two or more nodes must not transmit data simultaneously when they are in each other's vicinity since they cause conflicts and collisions. As the number of devices increases, the usability of the spectrum is degraded due to interference. Therefore, designing

wireless networks requires an appropriate MAC protocol to control the access of nodes to the shared medium.

Packet collisions can still occur due to contention or multiple nodes using the channel simultaneously while approaching each other, even with a TDMA-based MAC protocol. Generating an adaptive conflict-free schedule for networks where nodes are in motion is a challenging problem. Several challenges must be addressed at the MAC layer level to provide good Quality of Service (QoS). From the perspective of safety services, communication systems in dynamic networks should be able to periodically broadcast a safety-related message that includes useful information, such as accident alerts and environmental conditions, with high reliability and low latency.

Most proposed solutions for collision avoidance in dynamic networks are based on node localization information. In heterogeneous networks specifically, not all nodes are equipped with a GPS module. Moreover, Global Positioning System (GPS) modules consume much energy, and many users may switch them off to conserve energy. The heterogeneity of devices and existing obstacles in the field (such as buildings and tunnels) make it challenging for classical approaches that rely on GPS to predict collisions because GPS coordinates are unavailable or due to precision leaks. Furthermore, existing solutions that assign random periods of time to network devices are not optimal since an allotted period can still cause a collision in the near future with a potential neighboring node.

Objectives

To thoroughly understand the topic, a comprehensive review and analysis of the existing literature and case studies of recent MAC protocols for wireless decentralized networks is required. The objective is to gain insights into the current state of MAC protocols for wireless networks and their potential to support mobility. We also aim to provide exciting discussions and recommendations on using these techniques in major IoT applications. The findings of this research can provide valuable information for organizations, researchers, and policymakers interested in promoting solutions for efficient resource allocation for dynamic networks.

Wireless communication nightmares often arise from communication collisions, with node movement being a primary cause. However, this collision rate can be mitigated through proactive measures. Enabling each node in the network to predict collisions in its immediate vicinity before they happen can alert the affected nodes and prompt them to find resolutions. To achieve this, intermediate nodes can anticipate whether two neighboring nodes occupying the same time-slot, located three hops away, will become two-hop neighbors in the future, thereby avoiding potential communication collisions. Furthermore, developing a GPS-free protocol would enhance the robustness of the solution, making it impervious to GPS disturbances, which is a critical consideration for heterogeneous networks.

The resource allocation strategy is composed of multiple phases. We observed a lack of emphasis on the time-slot allocation phase in previous works. However, slot allocation is the most crucial step, and if investigated well, it can significantly improve the network performance. Therefore, our objective will be to allocate to each node in the network the best among eligible time-slots to minimize the probability of future collisions, making the network more stable and energy-efficient.

To conclude, it is essential to design an efficient, flexible, and adaptable MAC protocol that ensures a reliable network connection and effectively avoids or reduces message collisions.

Overview

This thesis discusses resource allocation in wireless decentralized networks. It proposes the design of contention-free MAC protocols for dynamic networks with the integration of Artificial Intelligence (AI), which has been shown to improve resource allocation in wireless networks.

Chapter 1 provides background information on the context of this thesis. Chapters 2, 3, and 4 detail our three main contributions. In Chapter 2, we survey existing contention-free MAC protocols for wireless networks and provide insight into their strengths and weaknesses. In Chapter 3, we propose GPS-free, Machine Learning model-based protocol to predict and avoid collisions in dynamic networks before they occur. In Chapter 4, we propose an efficient TDMA MAC protocol for VANETs, named PTA-MAC, for hybrid vehicular networks. Finally, Chapter 4.6 summarizes our results and proposes possible directions for future works.

The current version of this work presents the following contributions:

- [1] Khaled Abid, Hicham Lakhlef, Abdelmadjid Bouabdallah: A survey on recent contention-free MAC protocols for static and mobile wireless decentralized networks in IoT. *Comput. Networks* 201: 108583 (2021).
- [2] Khaled Abid, Hicham Lakhlef, Abdelmadjid Bouabdallah: Machine Learning-Based Communication Collision Prediction and Avoidance for Mobile Networks. *AINA 2022*: 194-204.
- [3] Khaled Abid, Hicham Lakhlef, Abdelmadjid Bouabdallah: Preventive Time-Slot Allocation Medium Access Control Protocol for Vehicular Networks. *IWCMC 2023*: 39–744.
- [4] Khaled Abid, Hicham Lakhlef, Abdelmadjid Bouabdallah: Preventive Time-Slot Allocation Framework for Collision Avoidance in Dense Vehicular Networks. *IEEE Transactions on Vehicular Technology*: (2023) (under review).

Chapter

1

Background

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Introduction

In this chapter, we provide a background on the context of this thesis. This chapter serves as a general overview of the relevant fields, while the subsequent chapters that present the protocol design will offer a detailed examination of the related concepts.

Our focus is on contention-free MAC protocols proposed for wireless decentralized networks. Firstly, we clarify the distinctions between various network types, such as wired vs. wireless, centralized vs. decentralized, and static vs. dynamic networks. Secondly, we present different classifications of MAC protocols based on their characteristics, such as contention-based vs.

contention-free and centralized vs. distributed protocols. Thirdly, we delve into the specifics of a commonly used contention-free MAC protocol, TDMA. Finally, we thoroughly investigate distributed MAC protocols' primary challenges and requirements.

1.1 Types of networks

In what follows, we categorize networks based on different criteria: communication medium, centralization, and mobility.

1.1.1 Wired/Wireless Networks

In a wired network, devices are connected using cables, whereas radio waves are predominantly used for connectivity in a wireless network. Various wired and wireless technologies are available, with the most common being Ethernet (for wired networks), Wi-Fi, and Bluetooth (for wireless networks). Many networks incorporate both wired and wireless connections. Table 1 briefly compares wired and wireless networks.

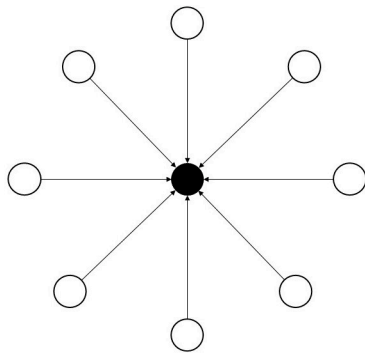
Table 1. Comparison between wired and wireless networks.

Factor	Wired	Wireless
Speed	Fast, less interference, fewer errors	Interference, delay
Security	More secure, difficult to tamper with	Less secure, risk of interception
Range	High	Low, signal strength reduced by obstacles
Setup	Inflexible	Flexible
Cost	Expensive	Not expensive

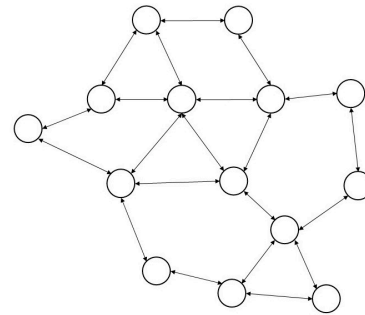
1.1.2 Centralized/Decentralized Networks

Wireless networks can be further classified into centralized and decentralized networks:

- Centralized networks (see Figure 1a): These are usually traditional cellular networks, such as 5G, LTE-A, and GSM. They rely on a reliable infrastructure, including base stations, to facilitate communication.
- Decentralized networks (see Figure 1b): These networks are typically multi-hop networks, such as ad-hoc and sensor networks. Decentralized networks exhibit vital characteristics such as decentralization, lack of infrastructure, self-organization, flexible networking, and dynamic topology. In these networks, nodes transmit their generated traffic and forward packets from other nodes. Moreover, nodes collaborate to accomplish their tasks. This decentralized approach is well-suited for communication and networking in highly dynamic and large-scale spatial scenarios.



(a) Centralized network



(b) Decentralized network

Figure 1. Centralized and decentralized networks.

1.1.3 Static and dynamic Networks

In static networks, nodes remain stationary and maintain the exact coordinates throughout network operation.

Dynamic networks differ from static networks because some or all nodes can move. Similar to hybrid ad hoc networks, MANETs can also connect to infrastructure, such as a private network or the Internet. Due to varying levels of node mobility, communication is limited to nodes within each other's transmission range.

Vehicular Ad-hoc Networks (VANETs) are a distinct instance case of MANETs, where vehicles serve as mobile nodes. In vehicular communication, two types of nodes are commonly found:

- On-Board Unit (OBU): Embedded in the vehicle, responsible for generating and communicating messages connected to an Application Unit (AU) that enables access to safety and non-safety applications.
- Road Side Unit (RSU): Fixed units acting as coordinators for node communication.

Flying Ad-hoc Networks (FANETs) are composed of Unmanned Air Vehicles (UAVs) that communicate with each other without the need for a point of access, although at least one of them must be connected to a base or satellite. UAVs have numerous critical potential applications that can enhance wireless networks' coverage, capacity, reliability, and energy efficiency, particularly in situations where human lives may be at risk. Advances in electronics and sensor technology have expanded the scope of FANET applications to include traffic monitoring, wind estimation, and remote sensing. UAVs typically have speeds ranging from 30 to 460 km/h, operating in a 3D space, resulting in rapid changes in network topology.

In various types of networks, such as static, MANET, VANET, and FANET, nodes interact differently. These interactions can be classified into cooperation, assistance, and warning. Nodes exchange information regarding traffic density, congestion, events, failures, and detours. Based on this shared information, each node makes decisions and predictions about its position and ongoing events. Consequently, safety-related, alert, and warning messages are sent among the nodes as needed.

The critical distinction between MANETs, VANETs, and FANETs is their ability to handle node movement. MANETs are designed to accommodate node mobility but do not assume constant movement, particularly at higher speeds. They are better suited for scenarios where node mobility is present but not necessarily rapid or continuous. On the other hand, VANETs and FANETs are specifically designed to handle nodes capable of rapid movements. These networks are well-equipped to handle scenarios where nodes, such as vehicles or flying devices, frequently change their positions and velocities.

1.2 Types of MAC protocols

Wireless communications involve broadcasting data over a wireless link, allowing multiple receivers within the communication radio range of the transmitter to receive the transmitted

data. However, this broadcast nature can lead to overlapping transmissions, interference, and packet collisions. Hence, the primary role of the MAC layer is to coordinate access to the shared wireless medium, resolving contention and minimizing collisions among competing nodes. MAC protocols in the data link layer determine when contending and colliding nodes can access the shared wireless medium.

MAC protocols for wireless communication can be classified based on various criteria:

- Contention-based and Contention-free: Contention-based protocols allow nodes to contend for channel access, while contention-free protocols provide scheduled access to the wireless medium without contention.
- Centralized and Distributed: MAC protocols could be categorized as either centralized or distributed, depending on whether a central entity is coordinating access or if the coordination is achieved through distributed algorithms among the nodes.
- Fixed assignment protocols, Demand assignment protocols, and Random access protocols: MAC protocols can also be classified based on the method used for assigning channel access. Fixed assignment protocols allocate specific time-slots or frequencies to nodes, demand assignment protocols dynamically assign resources based on demand, and random access protocols allow nodes to access the medium without a predefined schedule.

Researchers used additional criteria to classify MAC protocols, as presented in Table 2.

Table 2. Classification criteria of MAC protocols.

Criterion of classification	Categories	Reference
Synchronization	Asynchronous/ Synchronous	[5]
Network topology	Star topology/ ad-hoc topology	[6]
Type of network	Sensor/ Vehicular/ UAV networks	[7], [8], [9]
Type of antenna	Directional/ Omnidirectional antenna	[10], [11]
Number of antenna	Single-radio/ Multi-radio	[12]
Number of channels	Single-channel/ Multi-channel	[11]
QoS	QoS aware/ non-QoS Delay-aware/ Reliability-aware/ Power-aware	[11] [13], [11]
Type of TS assignment	Fixed assignment protocols/ Demand Assignment Multiple Access/ Random access	[14]
Scheduling	Node-scheduling/ Link-scheduling	[15]

1.2.1 Contention-based/Contention-free MAC protocols

MAC protocols for wireless communication can be classified into three main categories:

- **Contention-Based MAC Protocols:** In these protocols, nodes compete for access to the communication channel. Examples include ALOHA [16] and Carrier-sense multiple access collision avoidance (CSMA/CA) (IEEE 802.11p) [17]. While contention-based protocols offer predictable throughput and adaptability, they are less efficient in utilizing the medium. They suffer from high control overhead, hidden and exposed terminal problems, and degradation in performance due to packet re-transmissions caused by collisions, especially in dense networks.
- **Contention-Free MAC Protocols:** Also known as schedule-based MAC protocols, these protocols establish a schedule among nodes, ensuring each node knows when to listen, transmit, or remain inactive. Examples include Frequency Division Multiple Access (FDMA), Code Division Multiple Access (CDMA), Space Division Multiple Access (SDMA), and Time Division Multiple Access (TDMA). Contention-free protocols eliminate collisions but require time synchronization and time-slot reuse to improve efficiency. They are categorized as centralized or distributed, as detailed in the subsequent section.
- **Hybrid MAC Protocols:** These protocols combine the advantages of both contention-based and contention-free protocols. In cases where the required conditions are not met, most hybrid protocols fall back on the IEEE 802.11 [18] standard. However, hybrid protocols may also inherit some drawbacks of contention-based and contention-free approaches.

The distinction between these categories is as follows:

In high-dense scenarios, contention-based protocols suffer from message collisions, leading to decreased throughput [19]. To address this issue, contention-free MAC protocols propose periodic message exchanges for free channel reservation, eliminating collisions. However, time synchronization challenges may arise in large-scale sensor networks. Hybrid protocols aim to leverage the benefits of both contention-based and contention-free protocols to overcome bottlenecks.

While FDMA, CDMA, and SDMA may not be suitable as primary technologies for many MAC protocols due to their implementation complexity, antenna complexity, and sophisticated signal processing requirements, TDMA has been widely preferred. TDMA guarantees access to the wireless channel and imposes low complexity requirements on transceivers and microcontrollers. This makes TDMA suitable for various network types, including Wireless Sensor Networks (WSNs).

1.2.2 Centralized/Distributed MAC protocols

MAC protocols can be categorized into centralized and distributed protocols. In centralized protocols, a central coordinator, such as Roadside Unit (RSU) or Cluster Head (CH), assigns time-slots and manages communication among the nodes. In RSU-based MAC protocols, the RSU collects node information within its range and determines the schedule based on vehicle information and channel quality. It then allocates time-slots to the nodes. In cluster-based MAC protocols, neighboring nodes dynamically select a node as a CH. The CH is responsible for time-slot allocation, scheduling for transmission, and communication within the cluster. RSUs can also be present and act as intermediaries for inter-cluster communication. These protocols face significant challenges regarding three main aspects: cluster formation, CH selection, and cluster stability.

In distributed MAC protocols, nodes communicate with each other based on one-hop distance toward the destination, using cooperation or relaying mechanisms. The message is broadcast from the source node to the nodes in its one-hop neighborhood, which then relay the message to the destination node. RSUs can be part of this approach by relaying messages between registered nodes in different RSUs.

Hybrid MAC protocols aim to strike a balance between the benefits of centralized control (better coordination and management) and distributed access (flexibility and adaptability) in wireless communication scenarios. This combination can lead to improved network performance, reduced contention, and efficient spectrum utilization. Different hybrid MAC protocols may be tailored to specific wireless communication environments based on their unique requirements and characteristics.

1.3 TDMA MAC protocols for wireless networks

TDMA is a contention-free channel access mechanism used in wireless communication networks. In TDMA, time-frames are divided into time-slots, and each node is assigned a specific time-slot for transmission. The nodes take turns transmitting in their designated time-slots, ensuring collision-free transmission.

One of the critical advantages of TDMA is its ability to minimize collisions by assigning different time-slots to nodes. However, in dynamic networks, the movement of nodes can lead to collisions as nodes come into each other's vicinity. These collisions result in packet loss, communication delay, disruption within the network, and energy loss. To address the dynamic nature of ad-hoc networks, enhancements and variations of TDMA have been proposed. These variations aim to accommodate the constraints of dynamic networks and improve collision minimization.

Efficient TDMA scheduling is crucial for channel utilization in wireless networks. The scheduling problem involves assigning time-slots to nodes for data transmission while avoiding collisions. In some cases, TDMA scheduling is integrated with other sub-problems, such as routing and channel assignment, to optimize overall network performance. Application-specific constraints, such as Quality of Service (QoS) requirements, may also need to be considered in TDMA scheduling for WSNs.

1.3.1 Communication collision

Communication collisions can occur in wireless networks when multiple nodes transmit simultaneously and overlap. Different types of collisions can occur as explained in [8], including:

- Hidden Terminal (figure 2a): When two nodes are not within direct communication range but contend for the same time-slot, causing a hidden terminal problem.
- Exposed Terminal (figure 2b): When two sender nodes are in each other's communication range, but their expected receivers are far apart. This can lead to inefficient re-usability of time-slots.
- Merging Collision: When two mobile nodes that have reserved the same time-slot come into direct communication range, causing a conflict.

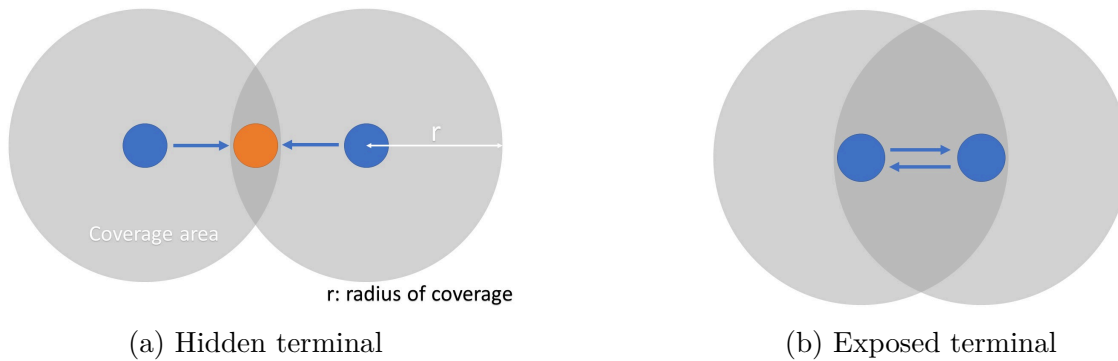


Figure 2. Collision and Conflict in wireless communication.

- **Encounter Collision:** A particular case of merging collision occurs when two moving nodes that have reserved the same time-slot encounter each other.
- **Access Collision:** When two nodes within direct communication range contend for the same time-slot.
- **Reservation Collision:** When nodes reserve the same time-slot without the occurrence of access collision, then reservation collision occurs.
- **Transmission Collision:** A combination of access and merging collision, typically resolved by allocating dynamic frames based on varying traffic density.
- **Cooperation Collision:** Occurs when nodes acting as cooperating nodes for relaying lost messages try to reserve the allocated time-slot.

These collisions can degrade network performance, and effective MAC protocols, such as TDMA, aim to minimize them through appropriate scheduling and coordination of access to the wireless medium.

1.3.2 Distance-2 coloring problem

Distance-2 coloring problem is used to solve collision problems in wireless decentralized networks. It consists in assigning the minimum number of colors to nodes under the condition that each two-hop neighbor node should not have the same color (Figure 3), where colors represent a unit of communication resources (time-slot). Therefore, the problem is to assign time-slots to the nodes for their data transmission, ensuring that two neighbors can't broadcast in the same

time-slot and one node will not receive information simultaneously from more than one node. The number of slots significantly impacts the network's performance since excessive slots results in low efficiency, while the insufficient number of time-slots leads to terrible collisions. Most of the TDMA algorithms formulate this problem using a conflict graph. A wireless network can be considered a connectivity graph, with nodes as the graph's vertices and edges between two nodes if the corresponding nodes can directly communicate. This problem has been proven to be NP-complete. Therefore, many existing solutions have relied on heuristic algorithms, which can provide near-optimal solutions.

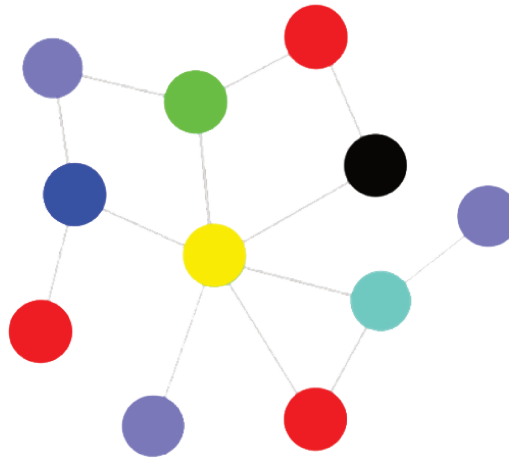


Figure 3. Distance-2 coloring problem.

1.4 Distributed MAC Protocols: Challenges & requirements

For several reasons, distributed MAC protocols for wireless decentralized networks represent an important research subject. These protocols are more suitable for scalable and fault-tolerant networks; they are topology independent and offer flexibility, installation speed, simplicity, and mobility. However, despite these benefits, distributed protocols face new challenges, such as agent coordination and collaboration, as well as heterogeneity and scalability. In what follows, we will explain most challenges when designing distributed MAC protocols.



Figure 4. Distributed MAC protocols: Challenges & Requirements.

a) Collaboration

In IoT, collaboration among agents in the network is a crucial approach that enhances network performance. This approach is fundamental in complex tasks like post-disaster search and terrain scanning. Agents involved in complex and critical tasks must exchange control information frequently, prioritizing robustness and high priority to collaborate effectively and complete their tasks. This control information aids in making communication decisions such as spectrum access, routing, and transmission power control. However, this cooperation comes with the cost of increased communication overhead. Hence, communication efficiency must be a consideration when designing a communication protocol.

Group collaboration can significantly improve network performance for networks with no mobility, medium mobility, and high mobility degrees. Collaboration between agents enhances the convergence speed of the slot assignment process and reduces interference and collisions. However, the importance of agent collaboration in the network becomes even more critical as network mobility increases. The lack of agent collaboration can lead to physical collisions and mission failures. On the other hand, in a static network, it merely delays algorithm convergence.

b) Real-time

Real-time communication involves the near-instantaneous exchange of information between agents. To ensure effective control of information exchange in a wireless network, it is crucial to establish real-time communication, especially when the agents have medium or high mobility. Failure to provide real-time position, interference level, and neighboring information can lead to physical and communication collisions in a dynamic network. Specific applications, such as rescue missions, require communication with negligible latency. Therefore, MAC protocols must be designed to provide real-time information according to the application's needs.

c) Quality of Service (QoS)

Designing and optimizing Quality of Service (QoS) in wireless networks is more complex than in traditional networks. This complexity arises due to the network's scalability and energy efficiency needs. QoS indicators vary across application domains and technologies, but timely and reliable communication remains essential in almost every IoT application. Additionally, throughput plays a crucial role in multimedia applications. Energy efficiency is also essential in networks with energy constraints, such as WSNs.

d) Density

High-density applications impose significant requirements on resource management. To meet these demands, devices must exchange control information more frequently to avoid collisions. However, increased information exchange in dense scenarios leads to interference and conflicts within the network. Consequently, designing a resource allocation protocol for a dense network presents a challenge.

e) Heterogeneity

One of the most significant challenges in designing a wireless network lies in managing and controlling multiple heterogeneous devices. Heterogeneity arises from the variation in communication technologies, identification protocols, storage and computational capacities,

features, and application requirements. This challenge becomes particularly pronounced in large and ultra-large-scale networks, significantly impacting network scalability.

f) Scalability

As the demand for IoT devices in wireless networks continues to multiply, MAC protocols face the challenge of scalability. However, this scalability should not come at the expense of Quality of Service, especially in mission-critical and industrial applications. Agents within a wireless network must adapt to environmental changes and future needs, such as increased data and the number of devices. These capabilities ensure that the system performs well and eliminates the need for extensive re-engineering when the system requirements change. Generally, the higher the network mobility, the more challenging it becomes to handle scalability effectively.

g) Dynamicity

In dynamic networks, the topology undergoes frequent changes, leading to dynamic shifts in the interference relationships between agents, node formations, and the external environment. Agents' movements can result in link failures, collisions, and load imbalances. Consequently, designing flexible communication protocols with rapid reconfiguration capabilities, dynamic slot synchronization, and adequate bandwidth management is crucial.

h) Fairness

Fairness is often associated with resource allocation. Designing a MAC protocol requires addressing various fairness issues, such as energy usage, achieving the required QoS, and spectrum sharing. To ensure fairness, the MAC protocol should continuously adjust resource allocation to compensate for any agents that have been mistreated in the past.

i) Robustness

A robust wireless network should be capable of adapting and remaining flexible in the face of perturbations caused by interference, node or link failures, and cyber-attacks. This challenge has

become increasingly important, mainly due to the rise in cyber-attacks. Moreover, exchanged information may be incomplete or corrupted by noise. Therefore, robust algorithms are required to address the challenges of randomness, dynamics, and uncertainty. The network can maintain its persistence and resilience by incorporating a robust MAC protocol.

j) Security

Implementing effective security policies ensures the network can fulfill its tasks. Wireless networks can face various types of attacks, such as jamming or flooding with static noise, which result in collisions of wireless signals. This is known as a Denial of Service (DoS) attack, which can lead to network shutdown or severe slowdowns. Furthermore, malicious agents that gain access to the network or even authorized agents with malicious intent can threaten the network's integrity by engaging in activities that drain connection speeds, consume bandwidth, and hinder overall network performance. Rogue agents can also deceive authorized devices within the network and cause them to disconnect. Considering these threats when designing a MAC protocol helps prevent network failures and physical damage.

Conclusion

In this chapter, we provided an overview of the context of this thesis. We discussed various categories of networks and MAC protocols. Additionally, we delved into the background of contention-free MAC protocols, with a specific focus on TDMA. Furthermore, we extensively examined the key challenges and requirements of developing contention-free MAC protocols. The upcoming chapter will present, analyze, and discuss recent contributions to contention-free MAC protocols for decentralized wireless networks.

Chapter

2

Study and analysis of recent MAC protocols for wireless networks

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Introduction

In this chapter, we present a survey of Medium Access Control (MAC) protocols for wireless networks. Designing a MAC protocol is an important task to ensure good network performance. Its primary role is facilitating coordination among network nodes, enhancing channel utilization, and avoiding collisions. Contention-free channel access methods, for the most part, rely on Time Division Multiple Access (TDMA). In TDMA, the time frame is divided into multiple time-slots, which are allocated to nodes and reused in a manner that minimizes interference.

In this chapter, we will present, analyze, and discuss recent contributions to contention-free MAC protocols for decentralized wireless networks.

2.1 Existing classification approaches for wireless MAC protocols

The existing surveys on MAC protocols share a common emphasis on traditional classification criteria. These criteria include contention (divided into contention-based and contention-free algorithms) [11, 20, 9], as well as the implementation method of the algorithm (centralized, distributed, and clustered) [21, 8, 22, 7]. Some papers focus only on contention-based [23] or contention-free algorithms [6, 15, 21, 8, 22, 7], allowing for a more in-depth exploration of existing protocols, encompassing a wider range of contributions within the same research domain. In [7], different classification criteria were proposed, including protocol objectives (such as throughput, fairness, latency, energy, and overhead), assumptions (related to application, topology, transceiver, and channel properties), and design methodology (including problem formulation, method of implementation, frequency of scheduling, and type of algorithm). They classified TDMA scheduling algorithms for Wireless Sensor Networks (WSNs) based on the method of implementation at the primary level and scheduling objectives at the secondary level. Authors in [13] classified MAC protocols according to two performance metrics: delay and reliability. Other classification criteria were utilized as well, such as Quality of Service (QoS) awareness [11], network type [6], synchronous/asynchronous algorithms [5], the number of radio transceivers in IoT devices [24], and antenna type [10].

From this, it is apparent that none has addressed a significant and emerging problem in wireless networks: mobility. Numerous research works recently investigated the challenges of node mobility in wireless networks. In their work [20], the authors provided an overview of existing MAC protocols incorporating mobility-handling capabilities. They conducted a comparative study of these protocols and examined mobility patterns, models, and estimation algorithms for WSNs. While several surveys discussed the mobility problem in MAC protocols, none have incorporated mobility as a classification criterion in their research. To address this gap, we propose a new classification criterion for MAC protocols, considering different types of mobility. We will classify these protocols based on their applicability in varying degrees of mobility: Static, Low/Medium mobility, and High mobility networks.

Due to the increasing computational power of certain IoT devices, they can now analyze data, make decisions, and take action without human involvement. Despite the growing popularity

of intelligent solutions in the IoT domain, only a few surveys considered these solutions in their work. For instance, authors in [25] have investigated the challenges, requirements, and solutions for intelligent Unmanned Swarm Communication. Although intelligent solutions have been presented for a long time, they are still considered a relatively new area of research in IoT communication. Their adoption has gained attention, particularly with the utilization of game theory in IoT, enabling the deployment of Machine Learning (ML) algorithms in a distributed manner instead of being restricted to centralized architectures. In our work, we will consider and study existing intelligent solutions, which represent a revolutionary aspect of the IoT domain.

Most of the existing surveys focused only on specific types of networks. For instance, surveys [26], [13], [5], [20], and [7] have solely considered WSNs, while the survey in [24] exclusively focuses on ad-hoc networks. Some surveys were concentrated on subcategories of specific network types, such as surveys [24], [8], and [9] that respectively investigated Mobile Ad-hoc Networks (MANETs), Vehicular Ad-hoc Networks (VANETs) and Flying Ad-hoc Networks (FANETs). In contrast, our work aims to encompass all types of networks, including Wireless Mesh Networks (WMNs), WSNs, MANETs, VANETs, and FANETs. Moreover, we will concentrate on recent advancements and solutions (from 2016 to the present), which is not the case in the existing surveys.

By comparing our proposed contribution with the surveys above, Table 3 highlights the distinctive aspects of our work. We provide a comprehensive study that includes a novel classification approach, examining the mobility challenges across all types of decentralized wireless networks. Additionally, we offer an overview of recent contributions in this field, specifically focusing on intelligent solutions. Furthermore, we conduct a comparative analysis of the proposed solutions, considering various network performance metrics such as QoS, robustness, fairness, and scalability.

Table 3. Survey comparison.

Reference	year	Mobility degree			Network type			Intelligent solutions	Recent works
		Static	Low/Medium	High	WMN	WSN	Ad-Hoc		
[11]	2004		✓				✓		
[26]	2006	✓				✓			
[6]	2009	✓			✓	✓			
[13]	2012	✓				✓			
[5]	2013	✓				✓			
[24]	2014		✓				✓		
[15]	2015	✓	✓		✓	✓	✓		
[21]	2015	✓	✓		✓	✓	✓		
[20]	2018	✓	✓			✓			✓
[8]	2020		✓				✓		✓
[9]	2020			✓			✓	✓	✓
[22]	2020	✓				✓			✓
[7]	2020	✓				✓			
[10]	2020			✓				✓	✓
[25]	2020			✓				✓	✓
Our work	2021	✓	✓	✓	✓	✓	✓	✓	✓

The key contributions of this chapter are as follows:

- Proposal of a new classification scheme for contention-free MAC protocols based on the degree of network mobility: static, low/medium mobility, and high mobility networks.
- Presentation and discussion of the challenges and requirements related to communication between IoT devices, along with a study of slot access problems in wireless decentralized networks.
- Survey of recent contributions in this area, covering all types of networks (WSNs, WMNs, ad-hoc, etc.), with a particular emphasis on intelligent algorithms.
- Comparison of the enumerated approaches based on selected metrics, addressing the mobility problem inherent in dynamic networks and exploring the applicability of these approaches to networks with specific mobility degrees.
- Suggest new research directions to tackle unresolved communication issues in wireless networks.

By incorporating these contributions, our work provides a comprehensive and detailed examination of the mobility challenge in wireless networks, considering various network types, intelligence solutions, and performance metrics.

2.2 Classification Approach and Methodology

In the context of dynamic networks, the design of network protocols, especially MAC protocols, faces new challenges. Understanding the network characteristics and mobility properties before designing the desired protocol is crucial. From a mobility perspective, networks can be differentiated based on their mobility patterns, mobility model, mobility type, and mobility detection [20]. In this chapter, we adopt a new classification criterion and group recently proposed MAC protocols based on the network mobility degree for which they were developed. Figure 5 illustrates our proposed classification scheme.

To gain a better understanding of the differences between the three types of networks based on their mobility degrees, we first present the main characteristics of each one of them:

- **Static networks:** These networks are composed of connected static IoT devices (such as fixed location sensors) through wireless links. In this case, network topology

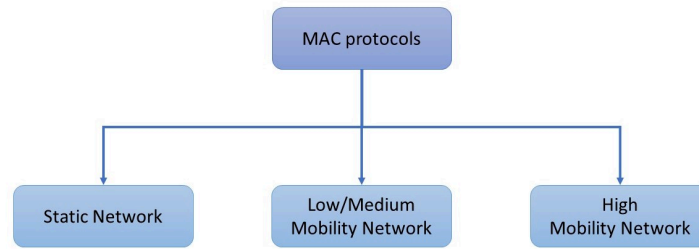


Figure 5. Contention-free MAC protocol classification.

remains unchanged during operation. Static networks are typically characterized by high node density and long lifetimes. Examples of applications for static networks include agriculture, surveillance, and industry.

- **Low and medium mobility networks:** These networks comprise a set of connected mobile nodes through wireless links, forming a network where the mobility degree is low or medium. Examples of mobile nodes in this type of network include people, animals, and vehicles. Applications such as safe driving and real traffic monitoring support this type of mobility. In low and medium-mobility networks, the topology dynamically changes with a relatively low frequency. Node movements can be predictable (e.g., vehicle movements) or unpredictable (e.g., animal movements). Compared to static networks, low and medium-mobility network nodes generally have a shorter network lifetime due to the need for frequent information exchange to adapt to topology changes. Generally, nodes are deployed less densely than in static networks. Notable examples of low and medium-mobility networks are MANETs and VANETs.
- **High mobility networks:** These networks are composed of high-mobility mobile nodes, such as fixed and rotating Unmanned Aerial Vehicle (UAV). Due to the high mobility of nodes, the network topology changes frequently. Nodes in high-mobility networks must process environmental data frequently to adapt to these changes. High mobility networks are commonly used in surveillance and search and rescue operations. FANETs are a well-known example of high-mobility networks.

We summarize the features of each network type using a radar chart, as depicted in Figure 6.

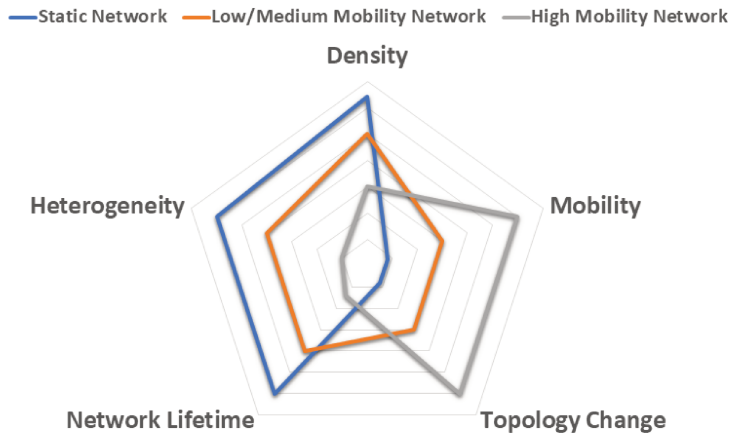


Figure 6. Network characteristics based on mobility degree.

2.3 Static Networks

In previous research works, several efficient spectrum-sharing solutions have been developed for networks with fixed node locations. These solutions often relied on randomized and sequential algorithms. Some protocols, such as RAND [27] and its distributed version DRAND [28], have become standards for researchers. Additionally, S-MAC [29], ETDMA [30], and DD-TDMA [31] are well-known solutions in this field.

In a recent work [32], the authors proposed a conflict-free time-slot allocation scheme that considers the fairness of resource distribution in a full mesh network. In this scheme, nodes exchange their IDs, minimum and maximum needed time-slots. The objective is to allocate time-slots fairly to nodes based on their needs until the available bandwidth is fully utilized. To

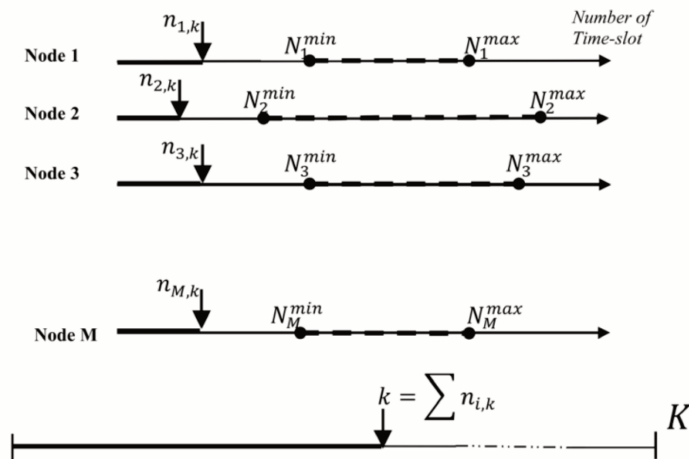


Figure 7. Time-slot allocation algorithm.

illustrate the problem, Figure 7 depicts the minimum and maximum needed time-slot for three nodes and the total number of time-slots available. For node M , the values $n_{M,k}$, N_M^{min} , and N_M^{max} represent the number of allotted time-slots, the minimum, and the maximum time-slots required, respectively. The proposed algorithm aims to allocate each time-slot to the node with the greatest need until all K slots are allocated. Compared to a sequential method (sorted by IDs), the proposed algorithm demonstrates better fairness in time-slot allocation and improved communication delay. However, the proposed method has some limitations. Firstly, it assumes that all nodes have the same priority, which is not true in many applications. The time-slot distribution is also performed sequentially, which can be time-consuming, especially in large networks. Moreover, scalability is a significant concern in mesh networks, as increasing users leads to longer frame lengths and higher delays.

In the work presented in [33], the authors proposed a Genetic Algorithm-based scheduling algorithm called ETDMA-GA. This algorithm utilizes routing information in a routing tree to schedule communication between nodes and minimize total network latency. The algorithm consists of two phases: an initialization phase and a TDMA schedule construction phase. In the initialization phase, the sink node generates the routing tree, constructs its traversal, calculates the TDMA schedule, and broadcasts this information to the WSN. The TDMA schedule construction phase employs the GA algorithm with latency as the fitness function to find the best routing tree traversal order and the corresponding TDMA schedule. ETDMA-GA outperforms existing approaches, such as Rand-LO, Depth-LO, DepthRe-LO [34], IDegRe-LO and IDeg-LO [35]. It performs better regarding average latency, average normalized latency, and average schedule length. However, some challenges are associated with ETDMA-GA, such as the communication of routing information to the controller, which may cause collisions during this process. Additionally, the algorithm's complexity makes it difficult for the network to scale, as the convergence time of the algorithm is exponential.

In [36], the authors developed optimal collision/conflict-free distance-2 coloring algorithms for tree networks. They proposed both sequential and parallel algorithms. The sequential algorithm uses a depth-first tree traversal-like approach, where each node computes its color and sends termination messages to its parent. The parallel algorithm performs a parallel traversal of the tree network. It ensures collision/conflict-free coloring by having each node compute the colors of its children and broadcast during the associated time-slot of its color. The proposed

algorithm has a time complexity of $O(d\Delta)$, where d is the depth of the tree and Δ is the maximal degree of the network. It requires $\Delta + 1$ colors to color the tree, which is optimal. However, this algorithm assumes network synchronization, making it inflexible to changes in network conditions and challenging to apply in large-scale networks.

To address the limitations of the previous algorithms, the authors in [37] developed a distributed algorithm that provides distance-2 coloring for any connected graph. They proposed a sequential algorithm based on a depth-first traversal of the network. In this algorithm, a node proposes a color to one of its neighbors, and if the neighbors and their neighbors do not already use the color, the node accepts it; otherwise, it requests the color proposer to correct its choice. This algorithm is collision and conflict-free and suitable for networks with communication or local memory constraints. However, sequential algorithms have long running times, and implementing a parallel algorithm without causing collisions can be challenging.

The authors investigated frugal coloring in [38]. In this specific vertex graph coloring problem, the same color can be allocated up to γ times in a node's neighborhood. This means a node can receive messages simultaneously from up to γ neighbors without collision. The authors proposed a deterministic, parallel, color-optimal, collision, and conflict-free distributed coloring algorithm specifically designed for tree networks. This algorithm is compared with the DRAND, demonstrating superior performance in execution time, number of broadcasts, and latency. By developing this algorithm, the authors addressed the challenge of frugal coloring in tree networks and provided an efficient and effective solution compared to the existing DRAND algorithm.

In [39], the authors proposed a TDMA-based algorithm called Dynamic Slot Scheduling (DYSS) for providing collision-free, timely, and efficient communication in WSNs. The algorithm begins by allotting slots based on the average two-hop neighbor count instead of the maximum two-hop neighbor count used in HDSS (Hybrid Dynamic Slot Scheduling) [40]. This reduction in the number of slots in the schedule may result in some nodes in dense areas remaining unallotted. To address this issue, the authors introduced a three-step approach for allocating slots to the remaining un-allotted nodes:

- Slot Allotment Request: Each un-allotted node selects an extra slot and checks its availability. If the slot is available, it sends a “DynamicSlotAllocation” message to its

neighbors containing relevant information for the slot request. This message is stored in a vector at the node's end.

- Slot Allotment Message Handler: Upon receiving the "DynamicSlotAllocation" message, a node checks if another node already requests the requested slot. If the request exists, the node examines the hop count and the requested time of the slot. The message is then forwarded after decrementing the hop-count field.
- Slot Allotment Status: After a certain period of time, each node checks the content of the vector at its end. If a node finds itself the originator for a particular slot, it is allotted that slot. If not, it proceeds to the next slot in the sequence.

The authors theoretically demonstrated the algorithm's correctness and conducted extensive simulations, testing different deployment scenarios and node densities. Compared to HDSS, RD-TDMA [41], and DRAND, DYSS utilizes a significantly smaller number of slots during the feasible schedule, leading to reduced latency and better collision handling. Additionally, the algorithm requires minimal time for the slot allocation process.

In [42], the authors proposed a Local Voting algorithm for transmission scheduling in multi-hop wireless networks. The algorithm's objective is to semi-equalize the load among nodes to minimize the total delivery time in the network. The algorithm allows neighboring nodes to exchange slots based on exchanged information. At the end of each frame, every node calculates the number of slots to allocate or release based on its own and its neighbors' states. A node gains a slot if the calculated value is positive and an available time-slot is not allocated to its one-hop or two-hop neighbors or if a neighbor has a negative value. To evaluate its performance, the authors compared the Local Voting algorithm with other scheduling algorithms such as DRAND [28], Load-Based Transmission Scheduling (LoBaTS) [43] and Longest Queue First (LQF) [44], in terms of average delay, maximum delay, and fairness. Compared to the centralized LQF algorithm, the Local Voting algorithm performs very closely despite being distributed. Compared to other distributed algorithms, Local Voting performs better in most performance metrics. The main strength of the algorithm is that it achieves load balancing through slot exchange between nodes without causing collisions. However, one identified problem in the algorithm is the maximality criterion. It states that there should be no free time-slot in the neighborhood of any node in the network. In local Voting, a time-slot is assigned to a node with a positive queue

only when it will not cause a collision. However, there are situations where swapping time-slots between nodes can increase the slot utilization ratio and improve the algorithm's performance. This suggests that the maximality criterion could be revised for such scenarios.

In [45], the authors proposed a distributed TDMA slot scheduling algorithm called DSTO (Distributed Slot Time Ordering) for wireless sensor networks (WSNs). The algorithm improves upon the DRAND algorithm by considering the nodes' local neighborhood size in the allocation priority rather than relying solely on random probability. The main objective of DSTO is to establish a scheduling order between nodes in a neighborhood based on their priorities, which are determined by the number of neighbors and a randomized numerical value. The higher the number of neighbors and the numerical value, the higher the node's priority. This allows each node to know precisely when it is their turn to reserve a time-slot. The important added value in this algorithm is the node awareness mechanism. It aims to reduce the number of exchanged messages for nodes to be aware of slot assignments in their neighborhood. This is done due to a Slot Assignment Table (SAT): a tool for nodes to keep track of the changes in slot assignment inside its neighborhood. Figure 8 shows an example of SAT and Topological Ordering Table (TOT) tables. The performance of DSTO is compared with DRAND and DTSS (Distributed TDMA Slot Scheduling) [46] in terms of running time and the number of generated messages. While DTSS has a superior running time, DSTO outperforms it regarding the maximum number of assigned slots and the number of message transmissions. DSTO also performs significantly better than DRAND. Scalability in a fully distributed topology is a key strength of the proposed DSTO algorithm. Additionally, by reducing the running time and message overhead, DSTO helps conserve energy, which is crucial for energy-constrained networks. Figure 8 in the paper illustrates an example of the SAT and TOT tables used in DSTO for slot assignment. Overall, DSTO provides an efficient and scalable solution for TDMA slot scheduling in WSNs, improving the limitations of existing algorithms like DRAND.

To improve the previous work, the authors in [47] proposed a distributed TDMA slot scheduling algorithm called E-T-DRAND (Energy-Topology DRAND). This algorithm is based on energy and topology factors to determine the priority for time-slot allocation in wireless sensor networks (WSNs). Nodes with more neighbors and lower residual energy are prioritized in requesting time-slot allocations. While E-T-DRAND shows improvement compared to the DRAND algorithm in terms of execution time and energy consumption, it still experiences

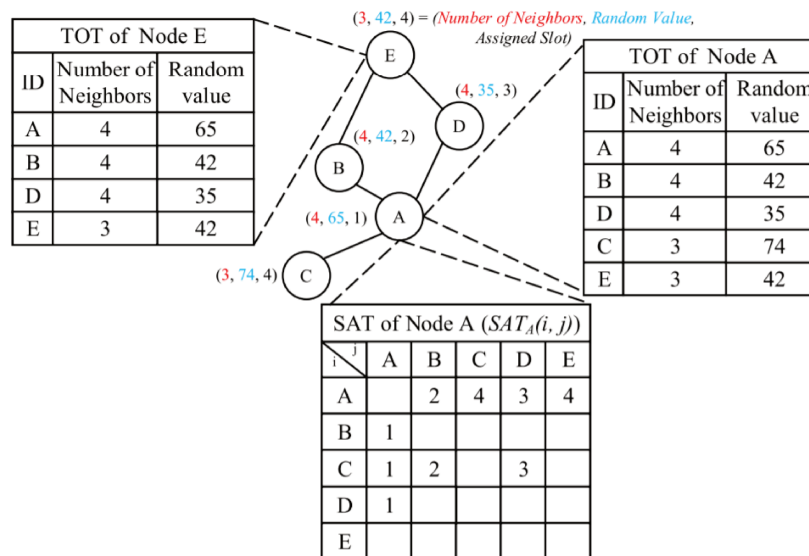


Figure 8. Example of a Slot Assignment Table and a Topological Ordering Table.

collisions during its execution. To address this issue, the authors proposed an enhanced version called EB-ET-DRAND (Exponential Backoff E-T-DRAND) [48]. In EB-ET-DRAND, they introduced the idea of Lamport's bakery algorithm, a mutex algorithm, to adjust the priority of time-slot allocation and reduce message collisions and time-slot allocation failures. The priority control in EB-ET-DRAND is based on the exponential backoff rule and the energy-topology factor. Simulation results demonstrate the improvement achieved by EB-ET-DRAND and E-T-DRAND over the DRAND algorithm. They are also compared to DSA-AGGR (Distributed Color Constraint Heuristic for data aggregation) [49] regarding message complexity, time complexity, the number of rounds, and energy consumption. E-T-DRAND outperforms DRAND regarding message complexity (28.1% less) and execution time (28.6% less), reducing energy consumption. EB-ET-DRAND outperforms DSA-AGGR, E-T-DRAND, and DRAND in all performance metrics. It uses 41.1% fewer messages, achieves 41.2% to 67.3% reduction in running time, and consumes 38.3% to 55.7% less energy than DRAND. One important finding mentioned by the authors is that the increase in running time with the number of neighbor nodes in EB-ET-DRAND is convergent, unlike the other protocols that exhibit a divergent trend. This is attributed to the influence of the backoff time in the scheduling algorithm, which significantly reduces time-slot allocation failures and message collisions. Overall, the proposed EB-ET-DRAND algorithm provides enhanced performance regarding message complexity, execution time, and energy consumption compared to DRAND and other scheduling protocols.

Incorporating the exponential backoff rule and the energy-topology factor effectively addresses collision issues and improves the overall efficiency of the algorithm.

In [50], the authors proposed a clustered solution called Bit-Map-Assisted Energy-Efficient MAC (BEE-MAC) for scheduling nodes in a wireless network. The main objective of this algorithm is to reduce energy consumption by minimizing the number of times the schedule is broadcasted in a round. The BEE-MAC protocol consists of three phases. First, during the setup phase, the network is partitioned into separate clusters, similar to the LEACH (Low Energy Adaptive Clustering Hierarchy) algorithm [51]. In the announcement phase, the CH broadcasts a TDMA schedule within its cluster. Finally, nodes can book one or more data slots in the data transmission phase by sending a claim in the control slot allocated to them. The authors showed through mathematical calculations that BEE-MAC consumes less energy than BEST-MAC (Bit-Map Enhanced Slot-based Token MAC) algorithm [52]. This energy efficiency is achieved by broadcasting the schedule only once a round, reducing the energy consumption required for sending and receiving schedules multiple times. However, the authors acknowledged two important problems not addressed in their work. The first problem is an inter-cluster collision, which occurs when two nodes from different clusters located at the cluster border allocate the same data slot. This collision needs to be considered to ensure efficient data transmission between clusters. The second problem is high delay in high traffic load situations. Each node can transmit in a maximum of x consecutive slots in BEE-MAC. Therefore, a high-load node must wait for the next data frame to transmit if it has more data to send. Meanwhile, low-load nodes may not use free time-slots, resulting in low slot utilization and increased delay. The authors suggested dynamically varying the maximum number of data slots a node can allocate in one data frame based on the node's priority level within the cluster. This approach can help optimize slot utilization and reduce delay.

In conclusion, the BEE-MAC algorithm proposes a clustered scheduling solution to minimize energy consumption in wireless networks. While it shows energy efficiency compared to BEST-MAC, it does not address the issues of inter-cluster collision and high delay in high-traffic load situations. The authors suggested a dynamic adjustment of the maximum number of data slots a node can allocate to alleviate these problems.

In [53], the authors proposed a communication method based on hybrid intra-cluster communication for wireless sensor networks. The protocol utilizes a cluster-based approach

similar to LEACH-C (Low Energy Adaptive Clustering Hierarchy with Cluster-Head Rotation) [54] and consists of the setup and steady-state stages. During the setup stage, clusters are formed, and Cluster Heads (CHs) are selected. This stage is similar to the clustering process in LEACH-C, where nodes are grouped into clusters, and CHs are elected to coordinate the communication within their respective clusters. In the steady-state stage, which occurs in each round, time-slots are allocated by the base station to nodes that have data to send. At the beginning of the round, the base station assigns time-slots to nodes with data. However, if a node receives data but has not been allotted a time-slot, it sends a beacon containing its ID to the nearest time-slot owner node. The time-slot owner node then relays the beacon and its data to the base station. Finally, the base station assigns the time-slot to the node that sent the beacon. Through simulation experiments, the authors demonstrated that the proposed protocol outperforms LEACH-C and TAICC (Threshold-based Adaptive Intra-Cluster Communication) [55] in terms of throughput, slot efficiency, and energy efficiency. The hybrid intra-cluster communication method improves the network's overall performance by optimizing time-slot allocation and reducing energy consumption.

2.4 Low/Medium Mobility Networks

Researchers have developed new protocols for dynamic networks to address the challenges of node mobility and frequent topology changes. Although standard algorithms like DRAND can be used, they often result in poor network performance. To overcome the inherent issues faced in dynamic networks, such as adaptivity and long-running time, new protocols have been proposed that implement dynamic resource allocation.

In [56], a new dynamic TDMA scheduling strategy was proposed, focusing on service priority in Mobile Ad-hoc Networks (MANETs). The authors first introduced a service priority-based dynamic scheduling algorithm, referred to as "SP-DS", which employs a dynamic TDMA scheduling approach for time-slot reservation. Each node in the network is assigned a priority level, and the algorithm considers the routing path between the source and destination nodes during the slot assignment phase. This approach aims to enhance transmission throughput and minimize end-to-end delay. To ensure the continuity of service information transmission, the order of time-slot reservations among different nodes aligns with the order of nodes on the

transmission path. A random token generation mechanism is employed to resolve the issue in a priority conflict. As a result, only nodes with the highest priority have the opportunity to enter the reservation phase. The authors adopted an adaptive time-slot allocation mechanism based on a binary tree model to ensure fairness in the slot assignment process among nodes. This mechanism considers different service priority information's data size and real-time requirements. By doing so, slot starvation for low-priority nodes is avoided.

Additionally, the authors proposed a distributed vertex coloring-based frame structure optimization algorithm called the Modified Distributed Color Constraint Heuristic (MD-CCH) scheme. This algorithm aims to optimize frame length and improve time-slot utilization. In the MD-CCH scheme, nodes with higher "Node level" (calculated based on the number of one-hop and two-hop neighbors, with priority given to nodes with more one-hop neighbors in case of equality) initiate the coloring process within their neighborhood. One-hop neighbors are colored based on the number of their one-hop neighbors, while the remaining nodes are colored based on a color score. Simulations were conducted with two main objectives: comparing the performance of different priority services and evaluating the performance of the MD-CCH+SP-DS algorithm against other algorithms such as DRAND, EB-ET-DRAND [48], and DSA-CCH [49]. The results show that high-priority services achieve lower end-to-end delay and higher throughput than low-priority services. Moreover, the MD-CCH+SP-DS algorithm demonstrates lower running time, fewer reservation rounds, and improved end-to-end delay and throughput compared to the other mentioned algorithms. However, it is worth noting that there are limitations to the mechanism proposed. For instance, when starting nodes are four hops apart, their one-hop neighbors may choose the same color simultaneously, causing conflicts. This issue arises due to the independence of neighborhoods in terms of coloring priorities. Additionally, the mechanism does not adequately address the crucial requirement of topology adaptivity, despite working within the dynamic network context.

Authors in [57] proposed a distributed MAC scheme for a two-hop IoT-enabled MANET called TA-MAC. The scheme consists of three main parts:

- Firstly, the authors designed a distributed TDMA-based super-frame structure to allocate different TDMA duration to different one-hop groups of nodes to eliminate the hidden terminal problem. Additionally, they introduced a probabilistic token-passing scheme to allocate time-slots to nodes within each group.

- Secondly, the authors aimed to optimize network performance, including average end-to-end delay, average delay for local packet transmissions, and aggregate network throughput. They achieved this by determining the MAC parameters, such as the number of scheduled token rotation cycles and the number of time-slots in a super-frame, through closed-form functions based on the MAC protocol parameters and network traffic load.
- Thirdly, the authors established an optimization framework for minimizing the average end-to-end delay when a predefined super-frame is used. They proposed a distributed computation algorithm to determine the optimal super-frame length and the optimal number of token rotation cycles for each token ring, ensuring minimal average end-to-end delay.

TA-MAC offers several advantages: It achieves good Quality of Service (QoS) by adapting MAC parameters to different network conditions, resulting in minimal end-to-end delay and high aggregate throughput. It demonstrates adaptability to changes in the number of nodes within each token ring caused by node movements. It exhibits better scalability compared to LA-MAC and DTSA [58].

However, despite these advantages, allocating different TDMA duration to different one-hop groups of nodes raises efficiency concerns, as time-slots cannot be optimally reused using this method.

Authors in [59] proposed a cluster-dynamic TDMA slot assignment protocol "C-DTSAP" based on "USAP" [60] for large-scale MANET. In classic USAP, nodes can choose slots from the unscheduled slots among their neighbor nodes to coordinate the announcement and confirmation of slot assignment within the two-hop range and ensure no conflict after the assignment. C-DTSAP protocol proposes an improvement compared to USAP. It consists of three main phases:

- In the first phase, the network is organized into multiple clusters, each operating on a unique frequency. The architecture includes three types of nodes: CH nodes responsible for intra-cluster management, gateway nodes responsible for inter-cluster communication, and normal nodes.
- In the second phase, nodes coordinate with each other to dynamically allocate or release time-slots based on the traffic flow in the network. When a node requires an additional

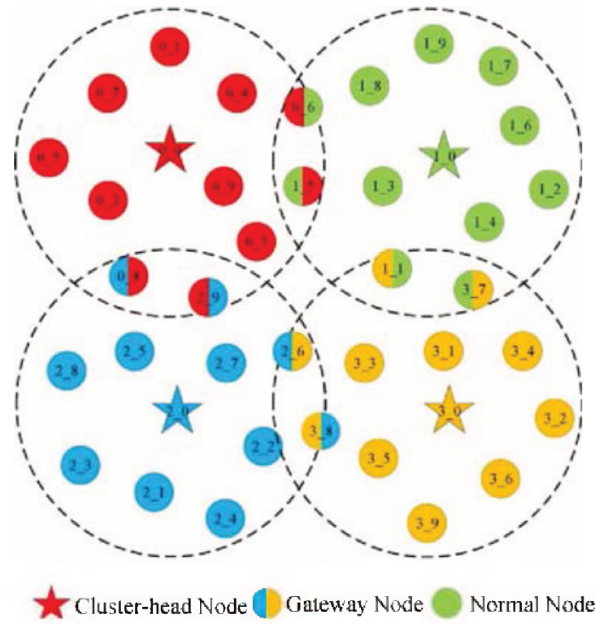


Figure 9. Cluster network topology.

time-slot, it selects an unassigned slot, announces it to its neighbors, and awaits their confirmation. The corresponding time-slots are released if a node no longer needs a time-slot or becomes inaccessible in the network.

- The final phase focuses on resolving slot conflicts between gateway nodes and their neighboring nodes. Since gateways receive packets from multiple clusters, nodes need to know the frame in which the gateway node operates for their respective clusters. This is achieved by utilizing the cluster ID and the time-frame number.

Based on experimental results, the authors demonstrated that C-DTSAP outperforms FC-USAP regarding slot reuse and traffic received ratios. Moreover, C-DTSAP exhibits improved end-to-end delay performance in large-scale networks. The main strength of the proposed algorithm lies in its ability to eliminate inter-cluster collisions while enabling inter-cluster communication. However, it suffers from bandwidth efficiency issues due to each cluster operating on a different frequency, which limits the overall utilization of available bandwidth.

Authors in [61] proposed a novel algorithm to facilitate the integration of a new node into a network and obtain a communication slot. The strength of this algorithm lies in its ability to assign the correct color to the joining node without requiring the entire time-slot assignment algorithm to be re-run. The protocol consists of two main phases:

- In the first phase, the joining node informs its future neighbors about its presence by sending hello messages across all channels until all neighbors become aware of its existence.
- In the second phase, the future neighbors exchange information with the joining node to assist it in selecting the appropriate color. This information primarily relates to the colors already used by the neighbors and their one-hop neighbors.

The proposed solution can be extended to cover other applications as well. For instance, it can aid nodes in changing their cluster membership within a clustered architecture. Additionally, in an ad-hoc network, it can assist a node in choosing the correct color upon entering a new neighborhood. However, there are certain limitations to consider. When a node joins the network, a cluster, or a neighborhood, all future neighbors must cease broadcasting until the joining node selects a color. This can result in service timeout. Furthermore, a color optimality problem may arise when no available color is found, despite the network degree remaining unchanged.

In [62], the authors proposed a dynamic time-slot allocation algorithm called TDMA-NNI. This algorithm is designed to address the packet conflict caused by node mobility in a network. The protocol operates based on a simple concept: each node listens for control packets periodically broadcasted by its neighbor nodes during the control period. Using this information, each node constructs a slot occupancy table. The time frame is divided into N control slots and M information slots, where N is the number of nodes in the network and M is equal to or greater than N . Each node is assigned a control slot during initialization and broadcasts a control packet. Nodes occupy one or multiple slots for data slots based on their traffic flow requirements. To handle conflicts arising from node movement, the authors provided solutions for different cases, as depicted in Figure 10. The performance of TDMA-NNI is compared with the FPRP [63] and IEEE802.11 protocols in terms of network throughput, average end-to-end delay, and Packet Loss Rate (PLR). TDMA-NNI demonstrates relatively low average delay and PLR compared to the abovementioned protocols. Additionally, it achieves relatively high throughput and packet delivery rates. However, the weakest aspect of the proposed protocol is the lack of a detailed explanation for the conflict resolution mechanism, which may limit the understanding and implementation of this algorithm.

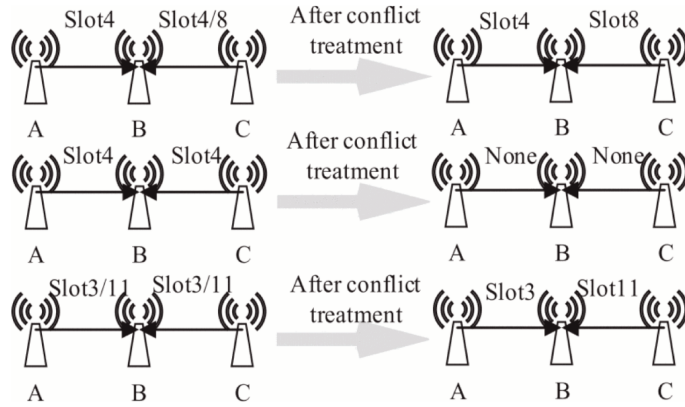


Figure 10. Eliminate packet conflict.

The authors in [64] proposed a distributed TDMA slot assignment protocol for mobile nodes in MANETs that operate on very narrow-band (SAP-NB) with low data rates. The protocol consists of three main phases:

- Neighborhood discovery phase: Each node requires two control cycles to identify its one-hop and two-hop neighbors during this phase. The node constructs a network information table (NIT) containing information about its neighbors by listening to broadcasted control packets.
- Slot allocation phase: In this phase, each node utilizes the local information from the NIT to allocate slots. The node with the smallest ID assigns the first available time-slot within a neighborhood while the other nodes wait for their turn. A slot update phase is initiated if a conflict occurs due to node movement. When conflicts arise, the node with the smaller ID retains its data slot (DS) while the other nodes re-run the slot assignment phase. If a DS is missing in a neighborhood, the node with a DS number greater than the maximum slot number in its NIT releases its DS and re-executes the slot assignment phase.
- Frame length selection phase: The frame length is dynamically changed based on the changes in the NIT.

The main advantage of the proposed protocol is that it relies solely on local topology knowledge for slot allocation. This approach improves average channel utilization compared to ASAP/LD [65], and USAP-MA [66]. Additionally, the protocol utilizes limited bandwidth more efficiently by exchanging fewer control packets than ASAP/LD.

2.5 High Mobility Networks

To ensure the success and timeliness of high mobility networks like UAV swarms, it is essential to have a fast time-slot access process to prevent any failures or outdated outcomes. To achieve this, effective information exchange among the agents is vital for completing their tasks. Although some research has been conducted on dynamic networks, most cannot be directly implemented in high-mobility networks.

The authors in [67] proposed the ITT-TDMA (Idle Time-slot Transfer TDMA) algorithm specifically designed for a fully connected FANETs. The key feature of this algorithm is that instead of competing for an additional time-slot, nodes automatically transfer their idle slots to nodes experiencing high load. The algorithm concept is straightforward: a frame is divided into N slots, where N represents the number of nodes in the network. Each slot has two segments: the Slot Information (SI) and the data segments. The SI segment indicates which node the current slot belongs to and determines the transmission state of that node. Every node in the network establishes a slot occupancy table by listening to the SIs broadcast. When a node has no data to send, it transfers its time-slot to the node with the heaviest load (i.e., the node with the longest queue length). This algorithm enables slot sharing within the network, reducing delays and balancing traffic distribution between high-load and light-load nodes. Through simulations, the authors demonstrated that ITT-TDMA effectively addresses the issue of time-slot wastage and improves communication delay compared to classic TDMA and TDMA-CSMA algorithms. If adapted to ad-hoc networks, this algorithm must consider challenges such as communication collisions, conflicts, and time-slot reuse.

In [68], the authors proposed an interference-aware online spectrum access scheme for a multi-cluster FANETs. The scheme aims to prevent collisions between UAV clusters operating on the same frequency. Initially, the problem is formulated as a data-assisted multistage channel access game with two main objectives: mitigating interference among UAV clusters and reducing channel switching costs. The authors proposed an interference-aware online channel preserving-based concurrent best response (IOCPCBR) algorithm to address this. In IOCPCBR, each cluster head (CH) is equipped with two transceivers: one for inter-cluster communication and the other for sensing and intra-cluster communication. UAV clusters change

their locations during missions, and the IOCPCBR algorithm is repeatedly executed in each time-slot. Figure 11 illustrates an example of cluster trajectories and interference between clusters, where different symbols indicate the cluster’s location for different time-slots. With

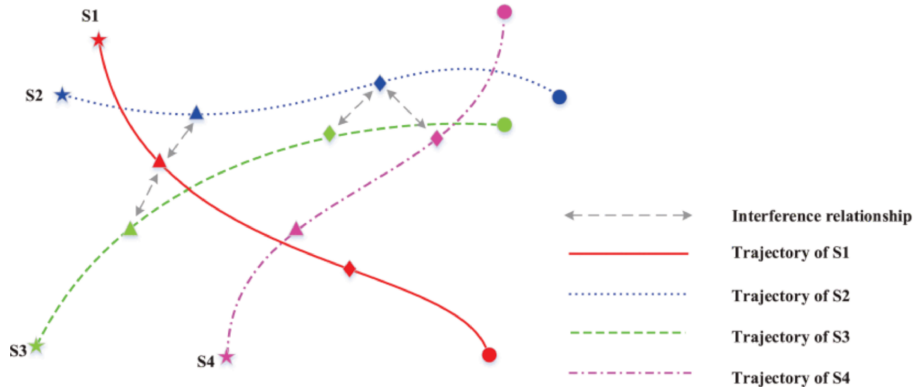


Figure 11. An example of the interference graph, where trajectories of four clusters.

IOCPCBR, clusters sense their utilities and autonomously adjust their actions using the best response rule to achieve desirable solutions. One condition that must be satisfied is that only non-neighboring clusters can switch their channel selection simultaneously. After data transmission, clusters exchange mutual interference information, estimate utilities, and learn from previous experiences. Ultimately, each cluster selects the best channel for intra-cluster data transmission. The algorithm considers a channel switching cost, denoted as C , meaning that each UAV cluster considers this cost when making decisions. The proposed algorithm performs superior to the random selection algorithm and achieves performance close to the best Nash equilibrium (NE). However, a disadvantage of the algorithm lies in the non-neighboring cluster update condition. When more than two clusters sharing the same channel are within each other’s coverage, it becomes crucial to simultaneously update their channel selections; otherwise, collision resolution may span multiple time-slots.

In [69], the authors presented an adaptive slot assignment TDMA (ASA-TDMA) scheme designed for a 3-dimensional airborne network. The scheme addresses three significant aspects: traffic load-based slot reassignment, slot sharing for collision-free concurrent transmissions, and node loss detection with slot resource retrieval. Firstly, the scheme implements traffic load-based slot reassignment, where slot allocation is determined by changes in the load level and nodes’ requests for new time-slots. This enables efficient utilization of slots based on the network’s

current traffic conditions. Secondly, a slot-sharing competition mechanism is introduced to prevent collisions caused by simultaneous slot access. This mechanism ensures that concurrent transmissions are collision-free, improving overall network performance. Finally, when a node is deemed lost from the network, all its slots are retrieved to free up resources. This ensures efficient resource management in the face of node failures or departures. The ASA-TDMA scheme demonstrates high slot utilization and the ability to dynamically adjust the scheduling strategy to handle network emergencies, such as node failures. Compared to protocols like P-TDMA [70] and fixed TDMA, ASA-TDMA exhibits lower delays and higher packet reception rates. The main strength of the proposed algorithm lies in its ability to match demand and resource allocation by adaptively assigning more time-slots to forwarding nodes. This adaptive approach enhances the efficiency and performance of the network.

In [71], the authors explored the problem of opportunistic spectrum access for multi-UAV networks from a game-theoretic standpoint. Initially, they formulated the joint channel-slot selection problem as a weighted interference mitigation game, considering the individual demands of each UAV in the network. The utility function of this non-cooperative game is designed to capture various aspects of a multi-UAV network. The log-linear algorithm is chosen to achieve a NE because information exchange between players in a multi-UAV system is non-trivial and can lead to collisions. The key idea is that each UAV randomly selects updates to its joint channel-slot selection based solely on its individual utility, and the next selection is determined stochastically. The authors proposed a low-complexity and realistic channel and slot initialization scheme for UAVs to expedite convergence. In this scheme, each cluster selects a single channel, and the cluster members select time-slots within that channel, thereby avoiding inter-cluster interference. UAVs attempt to choose adjacent time-slots to minimize slot overlapping and maximize resource utilization. While simulations demonstrated promising performance, such as fast convergence to optimal network utility and achieving a NE close to the best NE, this approach is limited by the lack of information exchange between agents. Information sharing can enhance convergence speed but comes at the cost of increased energy consumption and potential collisions.

An original idea to replace information exchange between agents in a network was first proposed in [72] and later improved and applied to UAV swarm communication in [73].

In [73], the authors aimed to address the slot access problem in UAV swarms through cooperation between neighboring UAVs. They presented a collision discovery mechanism that does not rely on exchanging topology information between UAVs. The collision discovery mechanism divides each time-slot into three sub-slots, each serving a different purpose. In sub-slot 1, broadcasters transmit their signals; in sub-slot 2, they receive feedback indicating the existence of collisions; and in sub-slot 3 is utilized for reporting slot occupancy. Notably, the mechanism requires only a single bit to declare a collision’s presence or occupy a slot. This approach allows UAVs to identify the existence of collisions without knowing the exact number of collisions, making it suitable for dynamic networks where topology changes frequently. Figure 12 and 13 provide an example illustrating this mechanism, with UAVs 4, 8, and 9 broadcasting in sub-slot 1, detecting collisions by listening to 5 and 7 (which failed to receive in sub-slot 1), and detecting slot occupancy through 1 and 6.

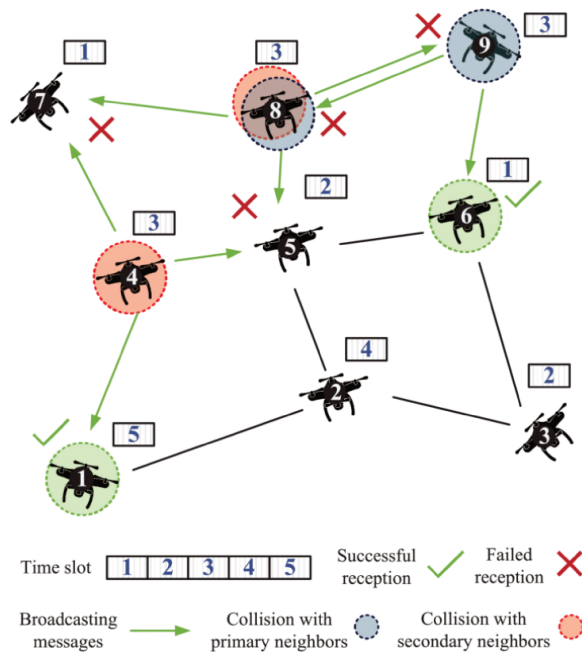


Figure 12. An example of a single-channel UAV swarm.

Furthermore, a cooperative game-theoretic method was employed to model the slot selection problem. The authors proposed two synchronous and distributed algorithms to achieve a NE in this game: Simultaneous Best Response (S-BR) and Simultaneous Log-Linear (S-LL). In the initialization stage, each UAV randomly selects a time-slot. Then, all UAVs simultaneously and independently update their selections based on the feedback obtained from the collision discovery mechanism. In S-BR, UAVs search for better utilities by changing their selected time-slots, while

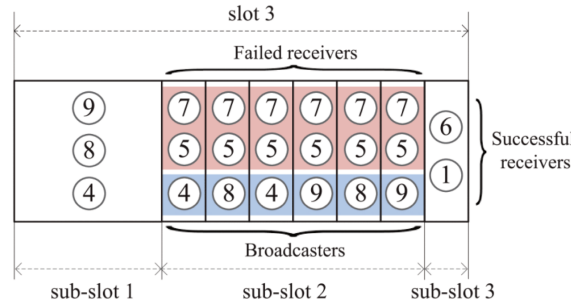


Figure 13. The slot structure of slot 3 in figure 12.

in S-LL, UAVs explore new actions to avoid getting trapped in a non-optimal NE. Simulation results demonstrate that S-BR converges rapidly to a NE, while S-LL converges asymptotically to the best NE. Finally, the authors investigated the number of slots required in different typical topologies and extrapolated their findings to general topologies. The main strength of this proposed solution lies in the fact that UAVs can detect collisions without the need for packet exchange. As a result, UAVs can quickly adapt to topology changes, which is a crucial objective in highly dynamic networks.

In [74], the authors leveraged intelligent algorithms to enhance inter-UAV communication, focusing on channel and time-slot allocation models for the dynamic management of UAV flight formations. They proposed an intelligent solution to expedite the discovery of an optimal flight strategy. To address resource allocation challenges, the authors adopted a priority mechanism in the UAV communication model, where high-priority UAVs are given resource allocation precedence over low-priority ones to ensure efficient resource utilization. Machine learning (ML), specifically reinforcement learning (RL), is suitable for resolving these challenges. Despite the time-consuming training process and difficulty in obtaining sufficient data samples for training, RL allows UAVs to interact with the environment and other UAVs in the network, learn from experience, and make informed decisions based on a reward mechanism. The authors combined deep reinforcement learning (DRL) with a long short-term memory (LSTM) network. LSTM preserves historical observation data, providing valuable information about the environment's characteristics and enabling quicker learning. This choice aims to improve convergence speed and facilitate predicting future environment states. The reward function used for learning incorporates various factors, such as communication system delay, throughput, UAV access collisions, and residual channel capacity. The proposed solution, the LSTM+DQN algorithm,

is compared with Deep Q-network (DQN) and Q-learning algorithms in terms of average collision rate (ACR), mean opinion score (MOS), and throughput. The LSTM+DQN algorithm demonstrates faster convergence speed and superior channel allocation strategy, outperforming the two baseline schemes of throughput by 5% compared to DQN and 10% compared to Q-learning. It should be noted that the proposed solution may not apply to low-energy and memory-constrained devices due to the computational and memory requirements associated with the LSTM+DQN algorithm.

In [25], the authors presented a multi-agent learning framework for Unmanned Swarm Communication Systems (USCS). They distinguished between two types of multi-agent learning structures:

- **Mobile-Computing-assisted multi-agent learning:** In this structure, one or multiple UAVs in a swarm possess high computational power and act as mobile edge servers. These UAVs upload essential information, such as spectrum state, to feed the spectrum-sharing algorithm running on the server. The mobile edge server then disseminates the results of data fusion and the outputs of the multi-agent collaboration algorithm. This architecture reduces data processing delays, which is crucial in highly dynamic networks. Additionally, it allows for using advanced computation-demanding algorithms like reinforcement learning to enhance network performance. An example is illustrated in the top part of Figure 14, where a deep neural network (DNN) is implemented in the server to facilitate multi-agent collaborative decision-making.
- **Distributed multi-agent learning:** In a distributed architecture, each agent in the network makes decisions autonomously based on information exchanged with other agents or observations from the environment. As shown in the bottom part of Figure 14, each UAV runs its own DNN, sensing the spectrum, making decisions, obtaining feedback, and training the DNN. Game theory is the most suitable approach to model the decision-making relationships in this distributed multi-agent learning scenario.

The authors provided several case studies to illustrate the application of their framework. For mobile-computing-assisted multi-agent learning, they proposed an online learning algorithm, such as reinforcement learning, and suggested potential improvements for network performance. For instance, an "offline-learning online-planning" framework can save learning time, especially

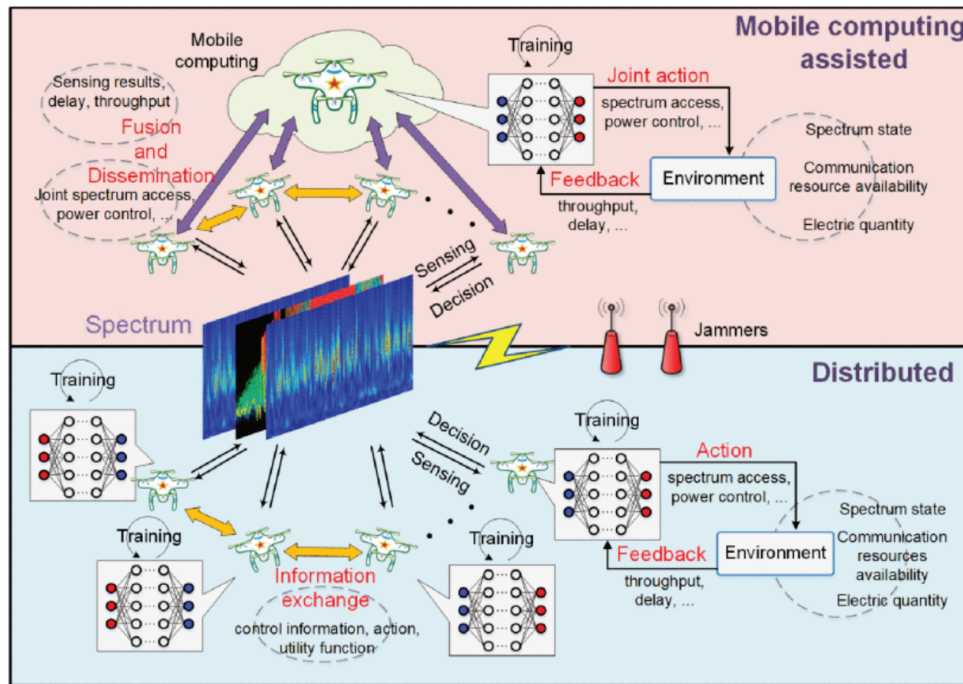


Figure 14. Multi-agent learning framework for the intelligent unmanned swarm communication system with mobile-computing-assisted structure and distributed structure.

in highly dynamic networks. They also explored fixed UAV swarm formation, where an offline solved problem using game theory or dynamic programming can provide optimal schemes for agents based on specific situations. In addition, the authors proposed task-driven dynamic spectrum access and task-driven data dissemination methods for distributed multi-agent learning. Overall, the framework presented in the paper offers insights into different multi-agent learning structures and provides practical case studies for improved performance in USCS.

2.6 Discussions

In what follows, we discuss the studied works and the mobility-related challenges in designing MAC protocols for wireless networks. It is true that contention-free MAC protocols were initially developed for static networks and were not considered suitable for dynamic networks due to the changing network architecture. However, researchers have since proposed distributed contention-free solutions based on local information exchange, which have proven efficient for dynamic networks, particularly in high-density scenarios. These protocols address collisions, idle listening, and overhearing, major contributors to energy consumption.

In recent years, MAC protocol research has shifted towards supporting multitasking, mobility, and QoS metrics, such as throughput and delay, rather than solely energy consumption. TDMA-based channel access has been widely used in these protocols as it provides guaranteed end-to-end delay performance. Table 4 provides a classification of contention-free MAC protocols based on the network performance metrics they aim to improve.

Different protocols consider different metrics depending on the degree of network mobility. For static networks, the emphasis has been on addressing collision-free and scalability challenges. Dynamic and fair MAC protocols have been developed in low to medium-mobility networks. In high-mobility networks, a particular focus is on QoS metrics driven by application requirements, especially for multimedia applications. Figure 15 illustrates the network performance metrics per network mobility degree.

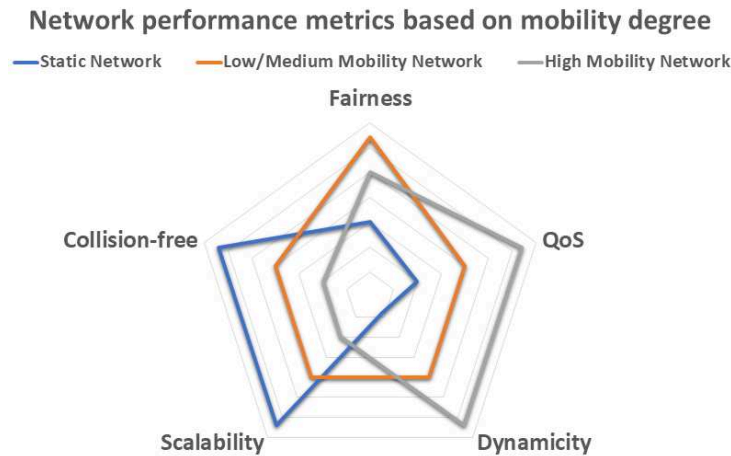


Figure 15. Network performance metrics based on mobility degree.

Table 4. Qualitative comparison between Algorithms.

Performance metrics	Static	Low/Medium Mobility	High Mobility
QoS	[33] [38] [42] [39] [53] [45] [50] [53]	[57] [56] [59] [62]	[67] [68] [69] [71] [74] [73]
Energy Efficiency			[68] [71] [73]
Adaptive	[42] [50] [39] [53]	[57] [56] [61] [64]	[69] [71]
Color-optimal	[32] [36] [37] [38] [39]	[61] [64]	[67] [73]
Collision-free	[32] [36] [37] [38] [42] [45] [50] [39] [53] [48]	[59] [61] [64]	[67] [69]
Robustness	[42] [50] [39]		[69]
Fairness	[32] [42] [50] [53] [48]	[56] [59]	[67] [69] [71] [74]
Scalability	[42] [45] [50] [39]	[57] [56] [59] [61]	[68] [71]
Dynamicity	[42] [50] [39] [53]	[57] [56] [59] [61] [62] [64]	[67] [68] [69] [71] [74] [73]

Figure 16 provides a visual representation of the advantages and disadvantages of the studied protocols grouped according to the chosen criterion of network mobility degree.

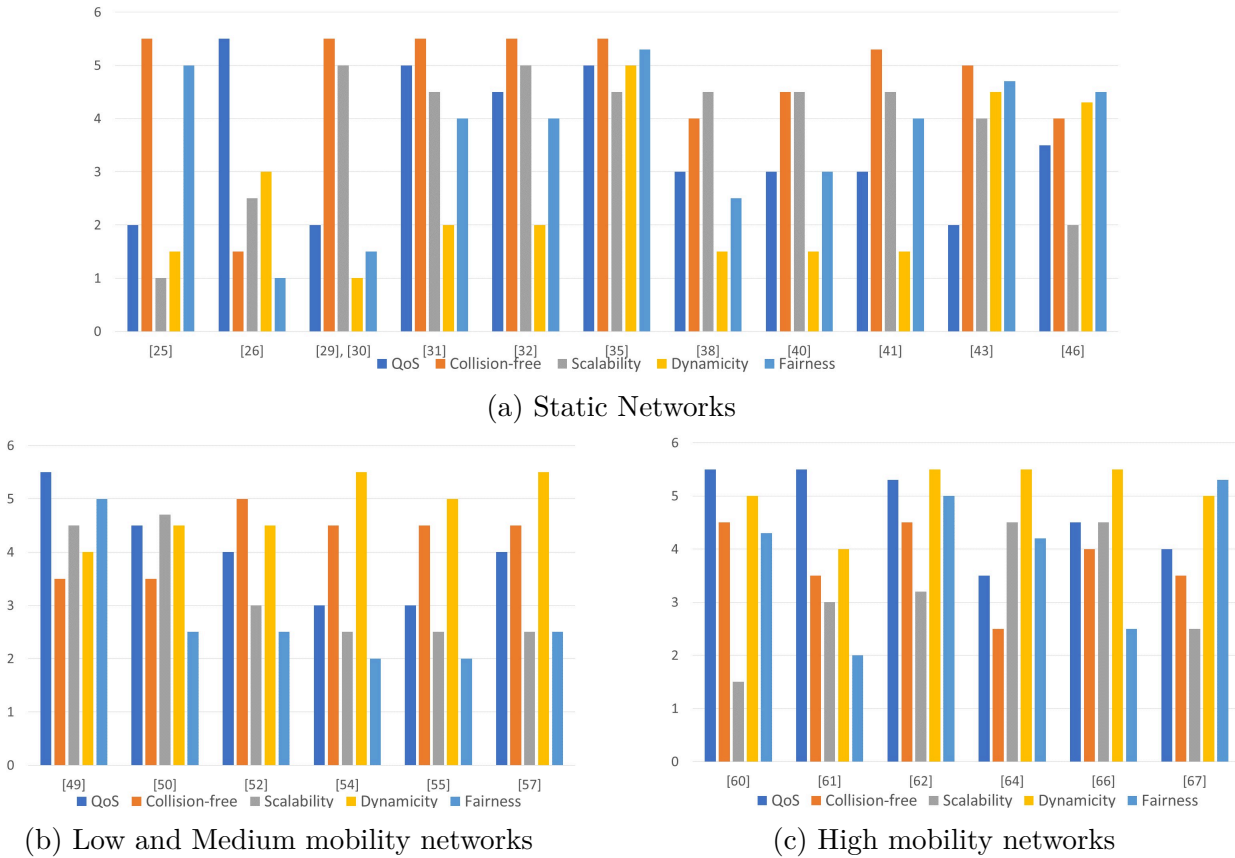


Figure 16. Comparison between MAC protocols according to some network metrics.

Overall, the advancements in contention-free MAC protocols have made them suitable for dynamic networks, and researchers are now addressing various performance metrics to cater to the specific requirements of different network mobility degrees. On the other hand, we can observe that certain performance metrics are interconnected. For instance, dynamicity and adaptivity are consistently addressed since an adaptive network must allocate resources among agents dynamically. However, a MAC protocol incorporating QoS often overlooks other parameters, such as energy efficiency and scalability.

It is undeniable that recent advancements in MAC protocols for wireless networks have proven valuable and beneficial for both scientific and industrial domains. Nevertheless, several limitations can be identified. Some studies have proposed protocols for specific network types with a particular degree of mobility but failed to consider the associated mobility challenges. For example, in [59], the authors introduced a slot assignment protocol for MANET that included a time-slot reservation mechanism similar to DRAND, which essentially neglected node movement

and dynamicity. Consequently, the development of a dynamic and adaptive MAC protocol that addresses mobility challenges remains an unresolved issue. Furthermore, simulation results have been presented in certain research works comparing the proposed protocols with unsuitable ones from a mobility standpoint. An example can be found in [69], where the authors compared their adaptive slot assignment protocol for airborne ad-hoc networks with the fixed-TDMA protocol. Fixed-TDMA is evidently unsuitable for dynamic networks, especially those with high mobility, as it lacks adaptivity. Therefore, a mobility-oriented algorithm should be compared against previously developed protocols for dynamic networks.

Significant differences exist between the three types of networks (static, low/medium mobility, and high mobility), which affect the design of MAC protocols. An important question is whether protocols developed for one type of network can be applied to another. In the literature, some works have implemented MAC protocols designed for static networks on dynamic networks. However, these implementations generally exhibit poorer performance as the mobility degree increases. In [56], the authors compared their protocol with the DRAND protocol in MANET and found that DRAND performed poorly. Due to its slow convergence speed, lack of adaptivity, and dynamism, which are not crucial in static networks, DRAND cannot be directly applied in a dynamic environment. In the case of high-mobility networks, the situation becomes even more challenging and critical. Many earlier applications involving UAVs have employed inefficient MAC protocols only suitable for traditional networks. Recent research works have focused on intelligent solutions to address the rapid movement of nodes and topology changes in highly mobile scenarios. Given the lack of standards for FANETs or high mobility networks in general, researchers have compared the performance of their work to the best and worst-case scenarios in a slot allocation game. From the considerations mentioned above, it can be concluded that the performance of a slot allocation protocol deteriorates when applied to a network with a higher degree of mobility. Moreover, MAC protocols designed for existing networks face challenges regarding their applicability due to the requirements of highly dynamic and mobile scenarios.

On a related note, it is worth examining the feasibility of applying a FANET slot allocation algorithm in a static network. While it is true that almost every protocol demonstrates improved performance as network mobility decreases, the efficiency of the solution must be considered. MAC protocols designed for high-mobility networks often involve a significant exchange of control information, increased power consumption, and high computational requirements. If

implemented in a static network, where sophisticated processing units and ample energy storage are not always available, nodes must execute complex algorithms that surpass the network's requirements.

Various techniques, known as cross-layer solutions, have been proposed to enhance network performance involving interactions between protocol stack layers. For instance, the MAC protocol can collaborate with the routing protocol in the slot assignment process.

Conclusion

Efficient MAC protocols for wireless networks have garnered significant attention from the research community. In this chapter, we delved into the important challenges faced in designing and developing MAC protocols. Subsequently, we reviewed recent solutions proposed for wireless decentralized networks. These solutions were categorized based on the mobility degree of the network, namely Static, Low/Medium mobility, and High mobility networks. This classification proves particularly useful in comprehending the design space, encompassing both the problem space and the solution space, for mobility-related MAC algorithms. We also provided a critical analysis of existing works in the literature, which can aid researchers in exploring new research directions and seeking solutions for the problems mentioned above. Lastly, we explored the impact of mobility on MAC protocol design and the feasibility of deploying these protocols across different network types.

In the subsequent chapter, we will introduce a GPS-free ML-based Collision Prediction & Avoidance MAC Protocol for Wireless Dynamic Networks.

Chapter

3

GPS-free ML-based Collision Prediction & Avoidance MAC Protocol for Wireless Dynamic Networks

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Introduction

Few previous research works have proposed Global Positioning System (GPS)-based protocols for collision avoidance. However, in the context of heterogeneous networks, it cannot be guaranteed that every node is equipped with a GPS module. Since such modules consume significant energy, many users switch them off to conserve power. The heterogeneity of devices and the presence of obstacles in the field, such as buildings and tunnels, pose challenges for classical approaches that rely on GPS for collision prediction. These challenges arise from the unavailability of GPS coordinates or precision errors.

In this chapter, we propose GPS-free Machine Learning (ML)-based models that proactively

predict and avoid collisions in dynamic networks. Our solution relies only on the historical interactions between neighboring nodes, allowing the system to predict collisions independently of GPS coordinates. Notably, our system requires no input from a GPS module, making it robust and energy-efficient. We demonstrate the influence of different ML models on network performance and investigate the impact of network density on model performance.

3.1 Related works

Many research works have been conducted aimed at improving network communication performance. In [73], the authors proposed a collision discovery mechanism that does not rely on exchanging topology information between unmanned aerial vehicles. This mechanism divides each time-slot into three sub-slots, each serving a different purpose. In sub-slot 1, broadcasters transmit their signals; in sub-slot 2, they receive feedback regarding potential collisions, and sub-slot 3 provides a report on time-slot occupancy. However, this mechanism suffers from a bandwidth efficiency issue, requiring time for collision discovery in each time-frame. Moreover, collisions between nodes result in significant delays and packet loss.

In [75], the authors presented a procedure for detecting and resolving collisions in Mobile Ad-hoc Networks (MANETs). In their proposed solution, every node allocates a control time-slot and a data time-slot. Through the control information, each node becomes aware of the occupied slots of its 1-hop neighbors. If a node discovers that two neighboring nodes are using the same data slot (collision), it notifies them to resolve the conflict. Unfortunately, this approach leads to substantial communication delays and packet loss since two neighboring nodes cannot change their selected slot until they receive the collision alert.

Several research works have proposed various prediction-based collision avoidance protocols. The authors in [76] presented the Prediction-Based TDMA MAC protocol designed specifically for Vehicular Ad-hoc Networks (VANETs) with two-way roads and four-way intersections. This protocol enables the prediction and potential elimination of collisions in both traffic scenarios, regardless of varying traffic loads on different road segments. By exchanging information about location, speed, moving direction, and slot occupation, intermediate vehicles between 3-hop

neighbors can predict potential collisions and notify the closest vehicle to change its occupied slot.

In [77], the authors introduced a collision avoidance method based on a vector-based mobility model in TDMA-based VANETs. This protocol aims to prevent access and merge collisions by predicting the mobility of nearby vehicles using exchanged control information. Each node utilizes information from more than 2-hop neighbors, including direction, longitude, latitude, speed, and acceleration, to anticipate potential collisions based on a vector-based mobility model.

It should be noted that these proposed protocols are specifically applied to VANET networks where vehicles have known mobility models, which may not be the case for dynamic networks in general, such as those in smart cities, smart agriculture, and military applications, where node mobility models can vary. Furthermore, these protocols often require the implementation of a GPS module in each node to extract position-related information, which may not be feasible in many applications. Moreover, the deployment cost and energy consumption associated with GPS modules can be significant due to satellite communication.

In this chapter, we propose a GPS-free ML-based protocol that leverages a node's previous interactions with neighbors to predict potential collisions between 3-hop neighbors using an intermediate node. This approach is cost-effective, improves network performance, and conserves energy.

3.2 Proposed solution

In what follows, we will explain our proposed solution by providing details of the system architecture, proposed protocol, data structure, and model evaluation.

3.2.1 System architecture

We consider a network composed of a set of mobile nodes that must communicate important information, such as security-related data, between each other. The wireless medium is shared among the nodes using the TDMA channel access method. Time is divided into time-frames, and each time-frame is composed of N time-slots. Upon network entry, each node selects an

available time-slot for broadcasting and continues to listen during other time-slots. We adopt the range propagation loss model for radio propagation ¹, which means that messages can only be received by nodes within a certain range, denoted as m meters. A node can collide with its primary neighbors, as two adjacent nodes cannot transmit and receive in the same time-slot. Additionally, collisions can occur with secondary neighbors, as a node cannot receive packets from two or more adjacent nodes simultaneously.

3.2.2 Proposed protocol

Our proposed solution identifies possible collisions in the near future between 3-hop neighbors using an intermediate node, considering only the history of interactions within the 2-hop neighborhood of each node. In other words, if a 1-hop neighbor and a 2-hop neighbor of an intermediate node share the same time-slot, a collision will occur when the 2-hop neighbor becomes a 1-hop neighbor. Consequently, we can effectively predict collisions by predicting the neighborhood's status. For every 3-hop neighbors that share the same time-slot in the network, we want an intermediate node to classify whether they will become 2-hop neighbors in the future or not. We assume that 3-hop neighbors cannot become 1-hop neighbors during one time-frame, as the node's speed does not exceed a predefined limit. In case of a probable collision, the intermediate node alerts the conflicting nodes to resolve the collision before it happens by switching to a free time-slot from their Slot Occupancy Table (SOT).

An example is shown in Figure 17, where colors represent the allocated time-slots. Node 2 broadcasts control information about itself and its 1-hop neighbor (node 4). Since node 4 and node 3 occupy the same time-slot (Figure 17a), node 1 computes the received information from its neighbors and realizes that those nodes have a high probability of becoming 2-hop neighbors in the near future (collision). Therefore, it sends an alert message to node 3, providing information about the collision resolution process. Finally, node 3 changes its time-slot to avoid a merging collision (Figure 17b).

Algorithm 1 explains the data transmission process, information processing, and collision avoidance.

¹A single attribute *MaxRange* (in meters) determines path loss. Receivers within *MaxRange* meters receive the transmission at the transmit power level. Receivers beyond *MaxRange* receive at power $-1000dBm$ (effectively zero).

Algorithm 1 Collision avoidance & resolution

Require: N : Set of time-slots

Require: $Node_id$: Id of the node

$Node_id.Time_Slot \leftarrow select_time_slot()$ ▷ Select free time-slot (network entry)

while True do

$receive(packet)$

$process(packet)$

if $packet.alert_of_collision(Node_id)$ then ▷ If the the packet contains a collision alert

$Node.id \leftarrow collision_resolution()$ ▷ Collision resolution

end if

$SOT.update()$

if $Current_time_slot == Node_id.Time_Slot$ then ▷ Own transmission time-slot

$Packet = construct_packet()$ ▷ Packet construction

for i in $Node_id.neighbors$ do

for j in $Node_id.two_hop_neighbors$ do

if $i.Time_Slot == j.Time_Slot$ then ▷ If 3-hop neighbors share a time-slot

$flag \leftarrow Predict_collision()$ ▷ flag = 1 if predicted collision

if flag then

$packet.add_alert_of_collision(i)$ ▷ Add an alert to the packet

$flag \leftarrow 0$

end if

end if

end for

end for

$send(packet)$ ▷ Send the packet

end if

end while

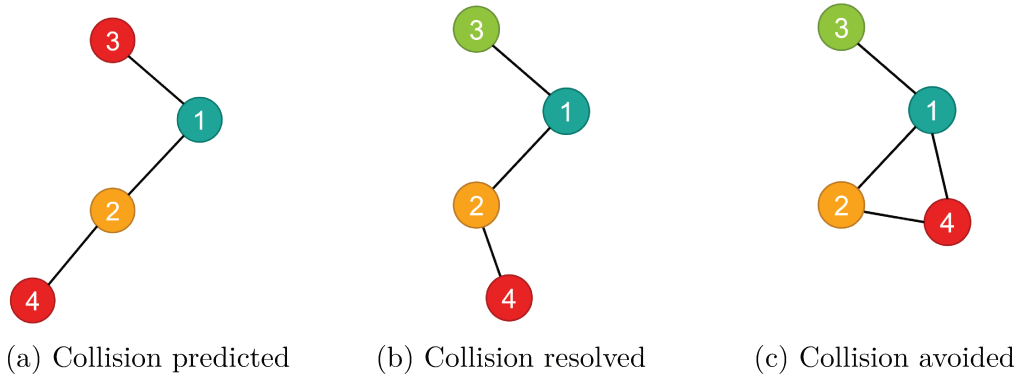


Figure 17. Collision prediction & avoidance.

The nodes' colors represent the allocated time-slot. We consider only node 4 is on movement. In fig(17a), node 1 processes exchanged control information, predicts a collision between nodes 3 and 4, and sends an alert message to node 3. In fig(17b), node 3 receives the alert from node 1 and resolves collision by switching to a free time-slot. In fig(17c), when node 4 becomes a 2-hop neighbor of node 3 (as predicted by node 1), the collision is already resolved.

3.2.3 Data Structure

To achieve collision avoidance, nodes are required to share control data among themselves. This control data is acquired through packet exchanges between nodes. When a node receives a packet from another node within a specific time-frame, it designates the sender as its neighbor. To ensure the control information reaches the 2-hop neighbors, which are considered intermediate nodes, every node forwards the received control data to its neighbors. The packet contains the following information:

- Slot occupancy information
- Sets of 1-hop and 2-hop neighbors
- Set of interactions with 1-hop neighbors during the last f time-frames

For the initial step of control data processing, each node utilizes received control data from its 2-hop neighbors to extract valuable features useful in predicting collisions. The features include the following:

- *was_neighbor*: Indicates whether the target node was a neighbor in the past f time-frames.

- *density_difference*: Represents the difference between the neighborhood density of the intermediate node and the target node. Neighborhood density is calculated based on the number of 1-hop and 2-hop neighbors.
- *neighboring_relationship*: Represents a function of the number of common 1-hop and 2-hop neighbors.
- *nature_of_movement*: Indicates whether the node is moving alone or following a group of nodes. The nature of the movement is determined based on the number of interactions with neighbors in the past f time-frames.
- *staying_time*: Represents the average time the node spent with its neighbors in the past f time-frames.
- *common_neighbor_evolution*: Represents the evolution of the number of common neighbors in the past f time-frames.

It's important to note that automatic data collection is challenging since establishing communication between hundreds of nodes in a real-life application is not feasible. Therefore, we consider a traffic simulation dataset generated using SUMO simulator [78]. The data construction process involves three stages:

1. Extracting nodes' coordinates over time from SUMO
2. For each time-step, construct a neighborhood status dataset that contains the list of 1-hop and 2-hop neighbors of every node in each time-step based on the radio coverage radius
3. For each node, extracting the desired features from the neighborhood status dataset

The final dataset is unrelated to the GPS coordinates of the nodes, time, or nodes' identities. Out of the entire dataset, 70% is used for training and 30% for testing purposes. We used three classification models for our collision detection problem: k-Nearest Neighbors (KNN) [79], Random Forest Classification (RFC) [80], and XGBoost (XGB) [81]. These models were implemented with their default parameter values and evaluated using 10-fold cross-validation during the training phase.

3.2.4 Model Evaluation

The classification problem in our study is binary (two classes); positive (collision) and negative (no collision). The predictions of the classifier can fall into one of the following four states:

- True Positive "TP": Correctly predicted collision
- False Positive "FP": Incorrectly predicted collision
- True Negative "TN": Correctly predicted no collision
- False Negative "FN": Incorrectly predicted no collision

The performance of collision detection models is evaluated using two widely used measures: precision and recall. These measures are based on a confusion matrix, which counts the number of samples correctly and incorrectly predicted as positive and negative.

The definitions of these measures are as follows:

- $Precision = \frac{TP}{TP+FP}$: This measure is calculated as the fraction of true positive predictions out of all positive predictions. Precision indicates the proportion of positive predictions that are actually correct.
- $Recall = \frac{TP}{TP+FN}$: This measure is calculated as the fraction of true positive instances out of all actual positive instances. Recall represents the proportion of positive instances that are correctly predicted as positive.

Precision can be seen as a measure of the quality of predictions, while recall is a measure of the quantity of relevant results. Higher precision means that the algorithm returns more relevant results, while higher recall means that the algorithm captures most of the relevant results.

In collision detection, we expect a higher recall rate, as it is important to identify as many collisions (TP) as possible rather than missing some of them (FN). However, we also aim for good precision to minimize the number of false positive predictions, which could lead to unnecessary alert messages and collision resolution processes, consuming bandwidth and energy. Unfortunately, it is impossible to maximize both precision and recall simultaneously, as improving one often comes at the cost of the other.

3.3 Simulation results

The collision detection performance was evaluated through a series of experiments using Python.

3.3.1 Comparison between different ML models

From Figure 18, it can be observed that all the models achieve at least 70% precision and 60% recall in all network architectures, indicating the fairness of the models. The recall values of XGB are better than the other two models in the priority and traffic lights intersection architectures. This implies that XGB could detect most of the collisions in the network, resulting in minimal energy wastage due to collisions. On the other hand, KNN has better precision values in the priority intersection architecture, while XGB performs better in the other architectures. This suggests these models have fewer false collision detection in their respective architectures.

The choice of the best model depends on the specific application requirements. Recall is the most important performance metric for safety-related applications where collision prediction is crucial. In applications with energy constraints, a combination of precision and recall (e.g., F1-score) can be used to select the best model.

In vehicular networks, where delivering safety-related information for physical collision avoidance in real-time is vital, the model with the highest recall and TP-to-FN ratio (XGB in this experiment) would be preferable to minimize collisions and energy wastage. However, for smart agriculture applications, where the lifespan of nodes is more significant than the delay and Packet Loss Rate (PLR), the model with the highest F1-score (either KNN or XGB) would be the best choice.

The confusion matrix in Figure 19 further visualize the differences between the different ML models. Additionally, to assess the performance of the XGB model, the confusion matrix for the different network architectures is shown in Figure 20. These visualizations provide a detailed understanding of the model's performance regarding true positives, true negatives, false positives, and false negatives.

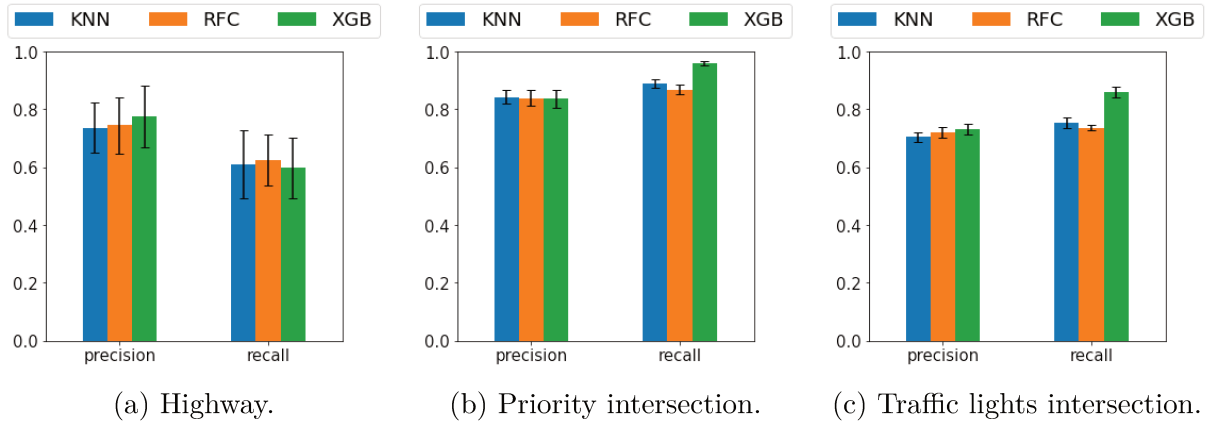


Figure 18. Performance metrics comparison for different ML models.

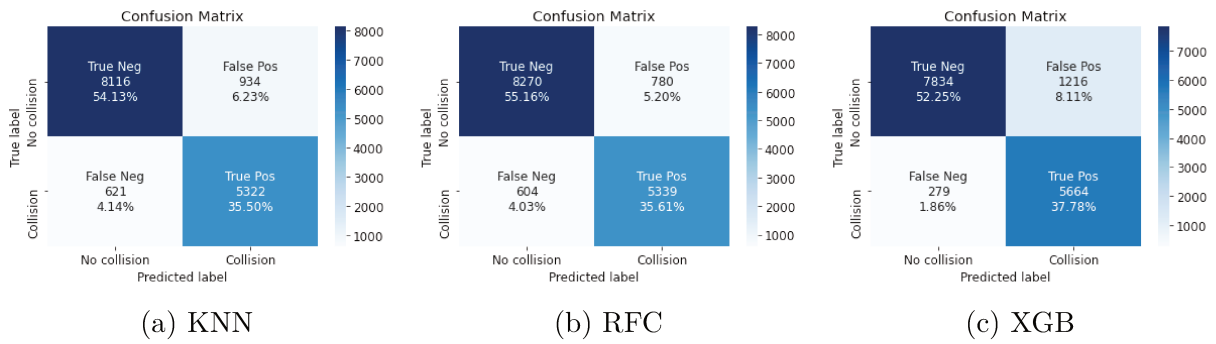


Figure 19. Confusion matrix comparison between different ML models in priority intersection architecture.

3.3.2 Impact of traffic density on the network performance

The bar charts in Figure 21 present the performance of XGB model for different traffic densities across different network architectures. Based on the observations, it can be seen that the proposed model performs better for intersection architectures than highway architecture (as mentioned above). The model achieves at least 80% recall and 70% precision for both priority and traffic light intersections, indicating its effectiveness in detecting and predicting collisions in these types of architecture. This suggests that the model is well-suited for vehicular networks in urban areas.

It is important to note that the model's performance may vary depending on the specific characteristics of the network architecture and traffic density. Different architectures may have different levels of complexity and collision-prone scenarios, which can impact the model's performance. Therefore, it is essential to evaluate and fine-tune the model based on the specific requirements and characteristics of the target network architecture.

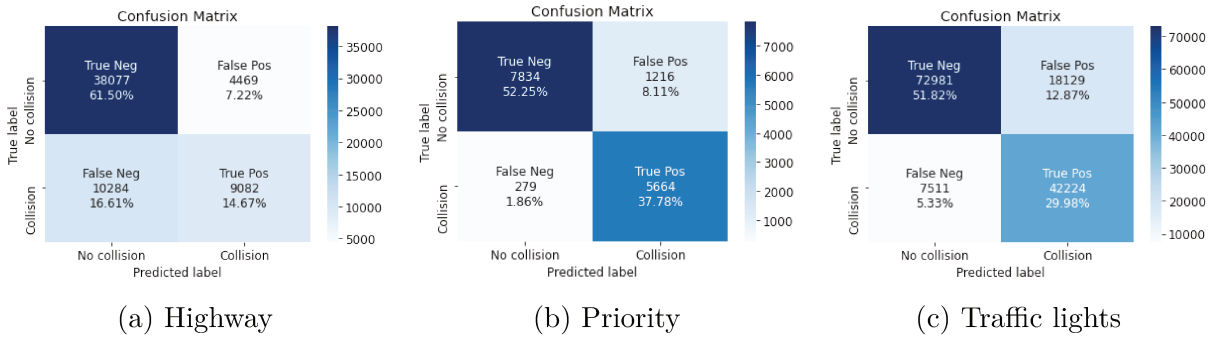
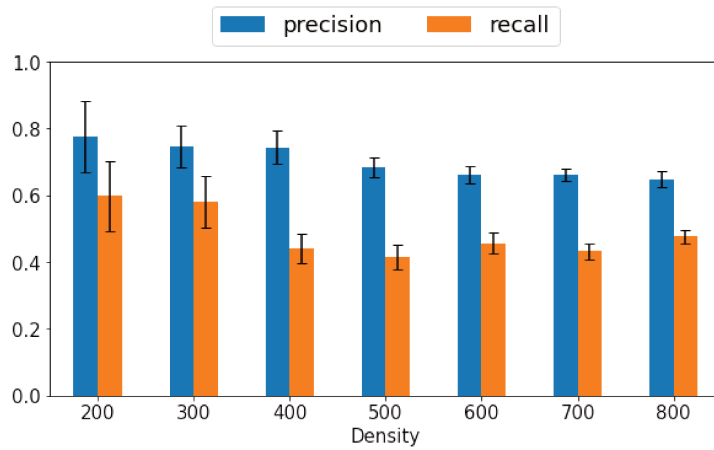


Figure 20. Confusion matrix comparison between different architectures for XGB model.

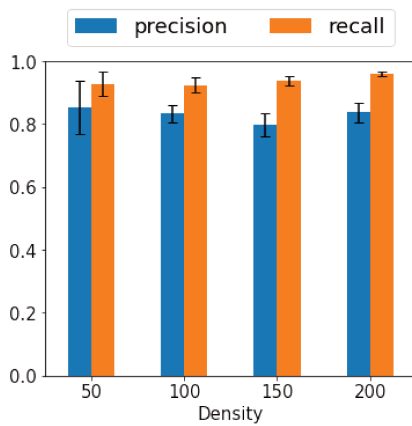
Conclusion

Collisions are the primary cause of delays and Packet Loss Rate (PLR) in wireless dynamic networks, and predicting and resolving them before they occur can improve the quality of communication. Therefore, accurately predicting collisions can help decrease PLR and energy consumption. In this chapter, we presented initial work toward a collision prediction model designed to detect possible collisions in a dynamic network with a predefined architecture. The experimental results demonstrate that the collision prediction models exhibit high accuracy and precision. In the future, we plan to explore the impact of other factors (e.g., different speeds of vehicles) on prediction effectiveness.

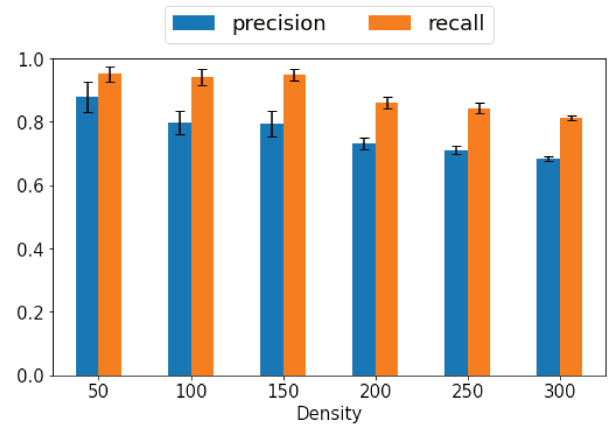
In the following chapter, we will present a Preventive Time-Slot Allocation Framework for a hybrid RSU-assisted vehicular network called "PTA-MAC".



(a) Highway.



(b) Priority intersection.



(c) Traffic lights intersection.

Figure 21. Performance metrics comparison for different traffic densities in different network architectures.

Chapter

4

PTA-MAC: Preventive Time-Slot
 Allocation Framework for RSU-assisted
 vehicular network

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Introduction

Vehicular communication systems provide robust and timely inter-vehicle communication to ensure driving safety. However, high mobility, variable topology, and high density represent great challenges for MAC protocols to deal with communication collision as it originates from network disruption, high delay, packet loss, and energy wastage. Most proposed solutions are based on vehicle localization information and random time-slot assignment. Furthermore, these solutions use a lot of energy, have a high overhead, and are inefficient.

In this chapter, we present a Preventive Time-Slot Allocation Framework for RSU-assisted vehicular network named "PTA-MAC". First, we propose a sojourn-time prediction model for incoming vehicles within a road segment. Then, based on that prediction, we propose a time-slot assignment protocol that decreases the probability of future collisions and resolves them if they happen. Simulation results demonstrate the superior performance of the proposed framework compared to the state-of-the-art protocols for VANETs.

4.1 Related Work

Multiple TDMA MAC protocols was proposed for message exchange for vehicular networks. ADHOC MAC [82] was designed for Ad-hoc networks. It grouped a set of time-slots into a frame and defined a concept of Frame Information (FI) that contains the time-slot status. Using ADHOC MAC, each vehicle broadcasts its FI to its one-hop neighbors, containing information about occupied slots by itself and its one-hop neighbors. So, every vehicle will know all its neighbors' slot information within a two-hop range. A new joining vehicle needs to listen to the channel for a frame and then select an available time-slot to transmit data at the next frame. Upon reception of the FI message, other vehicles add this new slot information into their FI messages to indicate the success of the time-slot contention and the new vehicle's successful join.

VeMAC [83] is a popular distributed TDMA-based MAC protocol for VANET, which provides a reliable broadcasting mechanism for periodic message exchange. It also proposed a collision mitigation mechanism to avoid merging collisions between vehicles moving in opposite directions. VeMAC adopts fixed-sized frames evenly divided into two sets of time-slots for left

and right directions on a two-way road. However, vehicles moving in the same direction can possess the same time-slot, and merging collisions between them can occur. In addition, if the vehicle density in one direction increases beyond the size of its dedicated partition, the VeMAC permits the vehicle to acquire a time-slot from another partition, which can also cause a merging collision between the two vehicles moving in opposite directions. Although such a compromise can somewhat increase slot utilization, its random slot borrowing scheme increases the probability of encounter collisions among vehicles in opposite directions. The more slots borrowed from the opposite direction, the more likely an encounter collision will happen. If the number of borrowed slots is large, the partition scheme becomes meaningless and can no longer efficiently eliminate the encounter collisions. In addition, before a vehicle can contend for a slot assigned to the other direction, it may already experience several contention collisions.

In [84], the authors proposed a centralized protocol, "CTMAC" for real-time communications in VANETs in which each vehicle is equipped with a GPS module. To avoid collision between vehicles in the overlapping regions, they proceeded with the following steps: Each time-frame is partitioned into two sets of time-slots and is associated with vehicles moving in the adjacent RSU areas. These sets of time-slots are re-used along the highway so that no vehicles belonging to the same set of two-hop neighbors use the same time-slot. If two or more nodes in a 2-hop neighborhood send a slot request at the same time-slot to the RSU (access collision), their neighbors will inform the RSU of this request so that it can resolve the collision. This solution faces the problem of bandwidth utilization efficiency as time-slots are not reused in all RSUs regions. Moreover, collision is likely between vehicles running in opposite directions, engendering communication delay and packet loss.

Since most access and merging conflicts occur due to vehicle movement patterns and traffic conditions, the collision rate can be reduced if each vehicle can predict other vehicles' location, movement direction, and resource occupancy information. Some works proposed TDMA MAC protocols to avoid a collision before it happens.

In [76], the authors proposed a prediction-based protocol, "PTMAC" that detects potential collisions between vehicles outside the range of two-hops by exchanging the observed slot status and information about position, speed, and moving direction. A slot-merge collision between two vehicles three-hop apart is predicted using their two intermediate vehicles. The two intermediate vehicles can detect a common slot used by two vehicles by examining the one-hop set. Then, they

classify this detection as a possible collision based on the speeds and directions of susceptible vehicles. Then one of the vehicles is indicated to vacate and acquire a new time-slot. However, intermediate vehicles need extra coordinating overhead and transmission delays.

In [77], the authors proposed a collision avoidance method based on the vehicle mobility prediction model in TDMA-based VANET. The proposed algorithm allocates time-slots of TDMA to avoid access and merging collisions by predicting the mobility of nearby vehicles using control time-slot occupancy information, vehicle ID, hop information, vehicle movement direction, and longitude and latitude of a vehicle. The performance gain of the proposed algorithm is enhanced in road environments when traffic density is high, and vehicles have high mobility and change their travel directions frequently. However, the vacating vehicle, unaware of free slots within its three-hop range, can only select a new time-slot based on its two-hop information, which can again lead to a similar collision situation. The problem worsens with the increasing vehicle density, as obtaining a new time-slot free in its three-hop communication range is harder. Most of these schemes assume that all necessary information can be shared accurately. Additionally, they can all detect merging collision but cannot readily resolve it, thereby reducing the packet delivery ratio and delaying inter-basic safety messages.

The authors in [85] proposed a hierarchical architecture based on SDN "sdnMAC" for physical resource management in VANET. They designed a two-tier architecture, one for managing the RSUs by a controller and the other for managing vehicles by RSUs. In the proposed architecture, every RSU can access the vehicle's position, direction, and speed within its communication range due to control packet exchange. Using this information, the controller can calculate the densities of vehicles and gives pre-warning of collision and agility to topology change and varying densities of vehicles, hence scheduling the share of slots information among the RSUs. At the same time, RSUs detect impending collisions and re-allocate slots for impending collisions based on the shared slots' information of neighbors, thus providing pre-warning of collisions to vehicles.

In [86], the authors proposed a TDMA protocol for hybrid network architecture where the centralized network (nodes within the coverage of RSU) and the distributed network (others) coexist. To solve the problem of collisions between nodes in different working modes, they estimated the node arrival probability and the number of competing nodes and designed a frame structure with a variable frame length, which can lower the access delay. The designed

frame divides the time-slot into two disjoint parts to avoid collisions between different working modes to support a multi-mode switching processing mechanism.

Considering almost all the limitations cited above, we propose a new network architecture and a resource management protocol that is believed to give better network performance in the following sections.

4.2 System Model & Problem Statement

In what follows, we explain the network architecture and frame structures. Then, we define the problem statement.

4.2.1 Network architecture

The VANET under consideration comprises a set of N vehicles moving in two opposite directions on two-way vehicle traffic roads, forming an ad-hoc network, and a set of M RSUs as shown in figure 22. We adopt the range propagation loss model for radio propagation, which means that messages can only be received by nodes within a certain range, denoted as m meters. We define a communication range m_v for vehicles and m_{rsu} for RSUs, so messages can only be received in the specified range. The dotted circle represents the RSU's communication range, and d represents the distance between two consecutive RSUs. Each RSU is placed at the beginning of a road segment which will be responsible for it.

Like VeMAC, the network has one control channel, denoted by c_0 , and k service channels, denoted by $c_1; c_2; \dots; c_k$. Channel c_0 is used to transmit two kinds of information: high-priority short applications and control information required for the nodes to determine which time-slots they should access on the application channel. The k service channels are used to transmit safety or non-safety-related application messages. Each node has two half-duplex transceivers: one for the control channel and the other for the service channel.

Each node is identified by a unique identifier (ID). We define $N^1(x)$ and $N^2(x)$ as the set of IDs of one-hop and two-hop neighboring nodes of x . We define $T(x)$ as the set of time-slots occupied by the node's one- and two-hop neighbors for x .

In this contribution, we are only interested in resource management on the control channel.

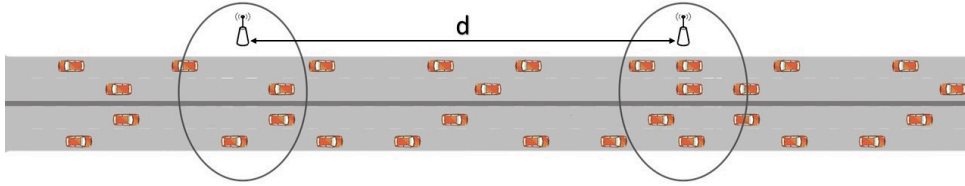


Figure 22. Network architecture.

4.2.2 Time-frame & Packet structures

We consider that the time is partitioned into frames and further divided into fixed duration time-slot. Each frame is composed of N time-slots partitioned into three sets: \mathcal{L} , \mathcal{R} and \mathcal{F} as shown in figure 23. The \mathcal{L} and \mathcal{R} sets are associated with vehicles moving in left and right directions, respectively, while the \mathcal{F} set is associated with RSUs.

We consider that nodes within two hops cannot broadcast messages simultaneously; otherwise, a message collision will occur. Each vehicle listens to the control channel when entering the network and occupies one unused time-slot to send data if needed. It must acquire exactly one time-slot in a frame to periodically broadcast a packet. Once it acquires a time-slot, it keeps accessing the same slot in all subsequent frames unless a transmission collision is detected or an RSU assigns a new time-slot.

Due to vehicles' high mobility and potential collision detection and avoidance, vehicles must exchange useful information through a control packet. Each node must transmit a packet during its time-slot, even if it has no data to include in the high-priority applications field. The packet message includes the ID of itself and its neighbor vehicles, each vehicle's hop information, and additional collision detection information. A node can receive packets from all its neighbors during one time-frame. When a node x receives a packet from node y , it updates $N^1(x)$, $N^2(x)$ and $T(x)$.

When an incoming vehicle x enters within the coverage of a new RSU, the latter will request important information for the proposed protocol execution. A Slot Request field is added to the control packet to do this. This will be explained in subsection (4.3.2). After the time-slot assignment process, the RSU responds to the vehicle x containing the assigned slot and additional information.

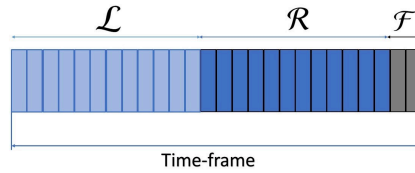


Figure 23. Partitioning of a time-frame.

4.2.3 Problem Statement

Unlike other types of mobile ad hoc networks in which nodes have random and unrestricted mobility, vehicle mobility is subject to road topology and layout, as well as road signs and traffic lights. However, in the context of multi-lane roads, the configuration of the network of vehicles can change significantly. For instance, vehicles traveling in faster lanes will frequently approach and pass slower vehicles in the slower lanes. As a result, the distance between two initially far-apart vehicles can become less than $2R$. This reduction in distance is the primary factor leading to merging collisions.

In this work, we consider hybrid architecture where RSUs assign time-slots to incoming vehicles. Our solution brings answers to the following questions:

- How to minimize possible collision and packet loss in the future via time-slot assignment?
- How to detect and resolve collision when happens?
- What is the impact of traffic density, distance between successive RSUs, and other parameters on the network performance?

4.3 Our solution: PTA-MAC

In the proposed PTA-MAC algorithm, each vehicle periodically broadcasts an FI message to its 1-hop neighbors through the control time-slot, like in VeMAC. Neighbor vehicles receiving all the FI messages during one time-frame can deduce the set of their 1-hop and 2-hop neighbors and the set of free and occupied time-slots in their 2-hop neighborhood. Then, instead of assigning a free time-slot randomly, as in existing solutions, we propose to assign the best time-slot that minimizes collisions in the future to an incoming node within a road segment. PTA-MAC works

in three steps: sojourn time prediction of new incoming vehicles within a road segment, time-slot assignment, and collision detection and resolution.

In the following subsections, we explain the time-slot assignment, collision detection, and resolution procedures, all necessary to facilitate the proposed preventive time-slot assignment scheme.

4.3.1 Assumptions

We define $t_{x,R}^e$ and $t_{x,R}^r$ as the entry and release time of a node x within a road segment. When a corresponding RSU R of a road segment receives a time-slot request from a vehicle, the latter will be considered an incoming vehicle for that road segment and an outgoing node for the previous one if it existed. We define $T(x)$ as the set of occupied time-slots by nodes in the 2-hop neighborhood of node x . We define $A(x)$ as the set of eligible time-slots for node x . We call eligible time-slot every time-slot that a node can occupy during its sojourn time within the coverage of an RSU without causing a collision with other nodes.

To simplify the analysis, the following assumptions are made:

- Each newly joining vehicle with no time-slot needs to listen to the channel first, then it can randomly choose an available one.
- Every vehicle broadcasts a message at every time frame, which contains information about all the occupied slots by itself and its one-hop neighbors.
- Every vehicle keeps the slot information about its one-hop and two-hop neighbors.
- Two nodes x and y are in collision if they occupy the same time-slot and the distance between them equals or is less than $2 * m_v$ ($distance(x, y) \leq 2 * m_v$).
- Every node keeps the same velocity within a single road segment. This can be explained by the fact that the road segment length is of the order of a few kilometers and the road structure nature (straight line without junctions).

4.3.2 Sojourn time prediction

The main purpose of this contribution is to propose an efficient time-slot assignment mechanism for vehicular networks based on a sojourn time prediction method that offers a high prediction accuracy. Unlike other methods in the literature which predict long-distance trips (dozens of kilometers: taxi trips, urban public transportation trips), our method requires the prediction of short-distance trips (few kilometers). Since the traveled distance is short, the environmental parameters greatly impact the accuracy of the predictions. In addition, many features must be considered for our target prediction. Therefore, machine learning (ML) will be the best candidate to solve this problem. Supervised learning is appropriate for our problem because a labeled dataset is available. Also, it is rapid and more accurate in this context than other types of ML.

When an incoming vehicle x comes within a road segment at instant t , the RSU R predicts its corresponding sojourn time $ST_{x,R}$. We propose a GPS-free ML model for regression that predicts the sojourn time of vehicles (target) within a road segment. The main steps of sojourn time prediction are:

- The corresponding RSU gets all the needed information about the incoming vehicle in its region.
- According to the communicated information, the RSU predicts the sojourn time of the vehicle within the road segment.
- RSU computes collected information and communicates the best time-slot to occupy the vehicle and other useful information.

To predict the sojourn time of a vehicle, the RSU exploits control data communicated by that vehicle and data collected from its environment. Instead of exploiting nodes' coordinates, velocity, and acceleration (GPS data), we use supervised learning to predict a vehicle's sojourn time within a road segment using historical data collected via inter-node and node-RSU interactions.

The set of features used to predict sojourn time is as follows:

- The node's minimum, maximum, and average sojourn time within the coverage of previous RSUs.
- The minimum, maximum, and average sojourn time of nodes within the coverage of the actual RSU.
- The current node density within the road segment.
- The presence of obstacles, slopes, etc., within the road segment.

4.3.3 Time-slot assignment

In what follows, we show how to construct $A(x)$ and make the best choice among eligible time-slots to minimize the probability of future collisions. Therefore, the network will be more stable and energy efficient. To find the set of eligible time-slot $A(x)$, the algorithm proceeds as follows:

Initially, to prevent collisions with vehicles located behind a x that have not yet entered the current road segment, x shares with the corresponding RSU information about the time-slots it has already allocated to its immediate neighbors and neighbors two hops away. This information allows the RSU to exclude those time-slots from their list of available time-slots, thereby avoiding potential collisions.

Then the RSU R tries to find the future neighbors of x within the current road segment. Indeed, it computes the approximate distance between each node within the road segment and x between the instants $t_{x,R}^e$ and $t_{x,R}^r$ based on their predicted sojourn time. Because velocities of the nodes are assumed to be constant within a road segment, the location of a node x at an instant t pos_x^t is calculated as follows:

$$pos_x^t = (t - t_{x,R}^e) * \frac{2 * m_{rsu}}{ST_{x,R}} \quad (4.1)$$

A time-slot $T_i \in A(x)$ if for every node y occupying T_i , the distance between x and y for the entire sojourn time of x must be greater than the distance $2 * m_v$.

$$distance(x, y) > 2 * m_v \forall t = t_{x,R}^e \leq t \leq t = t_{x,R}^r \quad (4.2)$$

The RSU R can calculate the $distance(x, y)$ for $t_1 = t_{x,R}^e$ and $t_2 = t_{x,R}^r$. Then, if Equation (4.2) is satisfied for both $t = t_{x,R}^e$ and $t = t_{x,R}^r$ and x is behind y ($pos_x^t \leq pos_y^t$), then $T_i \in A(x)$. If not, that means x and y cannot occupy the same time-slot because they will cause a collision.

Lemma 1 We can consider only the latest vehicles allotted distinct time-slots in the eligible time-slots search process.

Proof 1 Considering a set of nodes, $[x_1..x_n]$ that occupy the same time-slot T within the same road segment with corresponding RSU R such that $t_{x_1,R}^e > .. > t_{x_n,R}^e$. Following our proposed protocol, the distance between two nodes occupying the same time-slot must be greater than $2 * m_v$. For an incoming node x_{n+1} , if T is an eligible slot for x_{n+1} , that means that the distance between x_{n+1} and each node occupying the same time-slot within the road segment is greater than $2 * m_v$. Therefore, we can consider only x_n to find whether T is an eligible time-slot for x_{n+1} . Denoting \mathcal{S}_R the set of the latest incoming nodes occupying distinct time-slots and x an incoming node within the coverage of an RSU R at instant t , we can say from the above approaches that for every vehicle y in \mathcal{S}_R , if $\forall t_{x,R}^e \leq t \leq t_{x,R}^r$ $distance(x, y) > 2 * R$, $T(y)$ is an eligible time-slot for x .

Finally, for time-slot assignment, we will proceed as the following: If the current allotted time-slot of an incoming node x is in $A(x)$, it will keep it with a probability p to minimize the time-slot switching occurrence. Indeed, the network will converge toward a steady state in which the nodes will maintain their assigned time-slots for an extended period of time. If not, R will look for the best time-slot to minimize the collision probability. In detail, it will search through all the nodes within its coverage for the node \hat{y} that will have the highest distance between itself and \hat{y} . Then it allocated the latter's time-slot to the node x .

4.3.4 Collision detection & resolution

Like in VeMAC, in our proposed protocol, nodes deduce collisions with the help of the neighbors' packets. If at least one node within the two-hop neighborhood of node x accesses the same time-slot, then all the transmissions in the slot fail. Node x will determine whether its attempt was successful by observing the following time-slots. The message transmission of node x is

considered successful if the packets received from all its neighbors indicate that x is in the list of their neighbors. Otherwise, node x deduces that a collision has occurred.

If a node perceives a collision, it must give up its original slot and choose another available time-slot. The time-slot choice, here, will be based on $T(x)$ (the set of available time-slots in the node's neighborhood) and $A(x)$ (the time-slot list communicated by the last RSU the node has crossed). If the intersection set between the two sets is not empty, the node will choose a time-slot from this set. Otherwise, it randomly selects an available time-slot from $T(x)$.

4.4 Performance analysis

We compare PTA-MAC with VeMAC [83], Vector-based TDMA [77], and PTMAC [76] in terms of Root Mean Square Error (RMSE), the average number of collisions per vehicle and average overhead size (explained in the following subsections). To better understand the network performance, we vary the network traffic density, distance between RSUs, time-slots per time frame, and lanes per road direction.

To show the impact of GPS on network performance, we propose a GPS-based protocol for comparison purposes only. It uses a GPS-based model instead of the GPS-free model for sojourn time prediction. The model uses the following features in addition to those used by the GPS-free model:

- Vehicle's min speed in the latest Δ time duration
- Vehicle's max speed in the latest Δ time duration
- Vehicle's average speed in the latest Δ time duration
- Vehicle's actual speed when entering a new road segment

with Δ a predefined time duration.

4.4.1 RMSE for Sojourn Time Prediction

RMSE is the standard deviation of the residuals. It indicates the absolute fit of the model to the simulation data and provides average model prediction error in units of the variable (seconds). The *RMSE* values are negatively-oriented scores, which means lower values are better.

For an RSU R , the average *RMSE* is as following:

$$RMSE_R = \sqrt{\frac{1}{N} \sum_{i=1}^N (\hat{y}_i - y_i)^2}$$

with N the number of incoming vehicles within the RSU, \hat{y}_i and y_i are the predicted and actual values of the sojourn time of vehicle i within the road segment.

4.4.2 Average Number of Collisions per vehicle

During simulations, the total number of collisions is calculated, then divided by the total number of vehicles. Collisions are the main cause of packet loss. So, the average number of collisions per vehicle gives an idea about the Packet Loss Rate (PLR), an important performance parameter for wireless networks.

4.4.3 Overhead size

Packets transmitted on the control channel are composed of a header and high-priority short applications fields. The size of each field in a packet transmitted by a node x is estimated as follows: The main part of the header consists of announcing the set $N^1(x)$ and the time-slot used by each node in that set. The node sends the requested information to the RSU if it consists of a time-slot request packet. We denote N_{id} , the number of bits required to represent a node ID, and N_{ts} , the number of bits needed to identify a time-slot in a time frame. Therefore, the total packet size S (in bits) is:

$$S = |N^1(x)|(N_{id} + N_{ts}) + b_{req} + b_{app} + b_{extra}$$

where b_{req} is the number of bits for the information request field, b_{app} is the number of bits for the high-priority application field, and b_{extra} is the number of bits for all other information in the packet such as MAC addresses, priority fields, error correcting codes, and so on.

4.5 Simulation Results

To evaluate the performance of our protocol, we consider the SUMO simulator [78] to generate and simulate vehicular traffic scenarios. The parameters of each vehicle flow include the maximum number of vehicles, the flow's starting and ending roads, and the starting and ending times. We evaluate our proposed protocol on a two-lane highway with a total distance of $20km$. The road is divided into dkm segments, each containing an RSU at the beginning. The vehicles' speed is adjusted in response to traffic conditions and ranges from 25 to $43m/s$ as shown in figure 24.

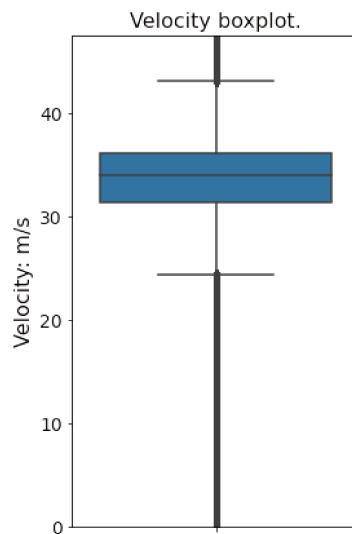


Figure 24. Vehicles' velocity box-plot.

We generate traffic traces by SUMO simulator and feed them to a network simulator developed with *Python*. We use a Random forest model with default regression values to predict vehicles' sojourn time within each road segment. The model is pre-trained using data from various mobility simulations. The number of time-slots per time frame for each traffic density is presented in Table 5 and is chosen so that all protocols can guarantee at least one available time-slot for every vehicle during the simulation.

Table 6 summarizes the simulation parameters.

Table 5. Number of time-slots per time frame.

Traffic density (veh/h)	Number of time TS per TF
400	20
600	30
800	40
1000	50
1200	60
1400	70
1600	80
1800	90

Table 6. Simulation parameters.

Parameter	Value
Simulation time	3600 <i>seconds</i>
Time frame duration	100 <i>ms</i>
Road length	20 <i>km</i>
Number of lanes per direction	2
RSU radius of coverage	100 <i>m</i>
Vehicle radius of coverage	100 <i>m</i>
Δ	3

4.5.1 Comparison between GPS-based and GPS-free PTA-MAC

In what follows, we compare the two versions of PTA-MAC (GPS-free and GPS-based) regarding sojourn time prediction accuracy and communication collision.

4.5.1.1 Impact of GPS on sojourn time prediction accuracy

Figure 25 shows the RMSE values for vehicles' sojourn time prediction for every RSU in a network with a traffic density equal to 1000*veh/h*. We can see that the first two RSUs have high RMSE values, which is explained by the lack or inaccuracy of information fed to the prediction model. Then, the RMSE values vary slightly according to the traffic conditions within a road segment.

Figure 26 shows the average RMSE for vehicles' sojourn time prediction with different traffic densities. We can see the average RMSE increasing when the network density increases. This is caused by the vehicles' behavior variation, which becomes less predictable for high traffic densities.

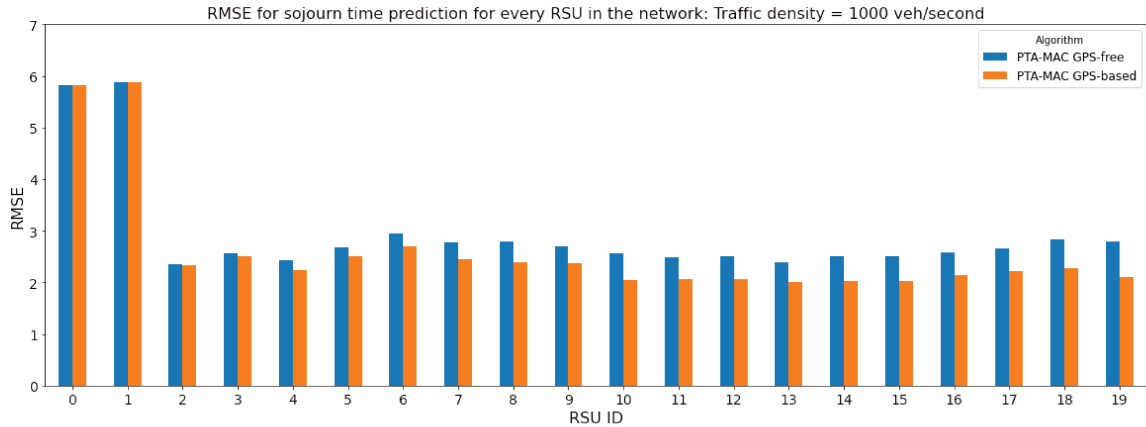


Figure 25. Average RMSE for every RSU in the network.

Furthermore, the GPS-based model demonstrates better performance compared to the GPS-free model. This is explained by the GPS-based model using more features for sojourn time prediction than the GPS-free model.

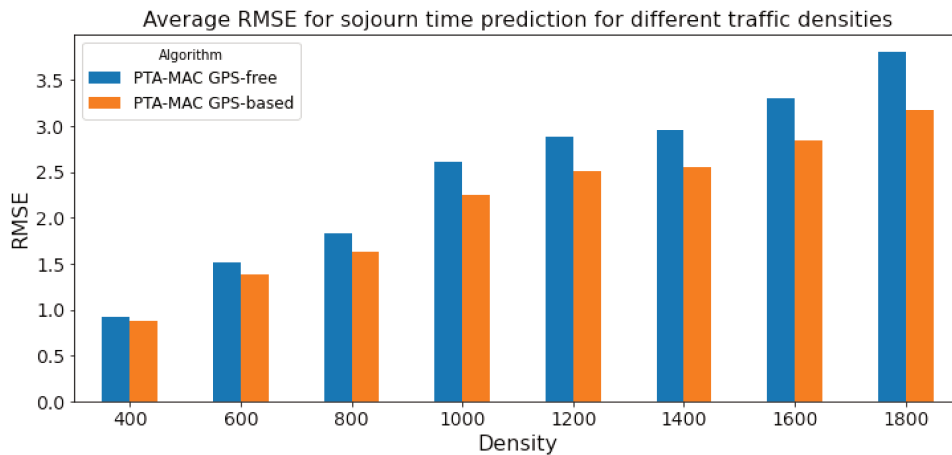


Figure 26. Average RMSE for different network densities.

Figure 27 shows the average RMSE for vehicles' sojourn time prediction for different numbers of lanes per road direction l with a traffic density equal to $1000veh/h$. The figure shows that the GPS-based model gives higher accuracy than the GPS-free model in all cases ($l = 2, l = 3$ and $l = 4$). However, the difference between the two models is inconsiderable for $l = 4$. Therefore, our proposed model, even without a GPS module, can predict the vehicles' sojourn time for wide roads with almost the same accuracy.

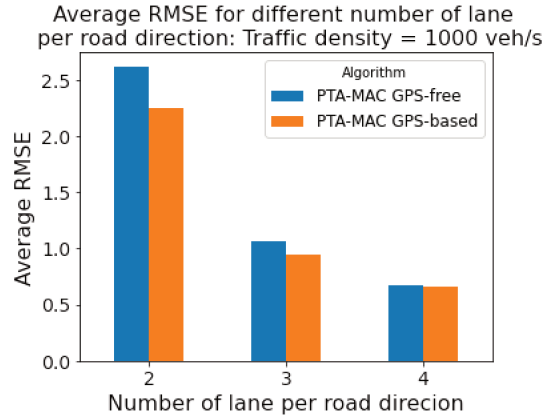


Figure 27. Average RMSE for different number of lanes per road direction.

4.5.1.2 Impact of Inter-RSU Distance

Figure 28 presents the average RMSE for vehicles’ sojourn time prediction for different inter-RSU distance d with a traffic density equal to $1000veh/h$. The RMSE seems proportional to the distance between RSUs.

Figure 29 shows the average collision per vehicle in the network for different RSU inter-distance d .

It can be seen that the number of collisions increases when d increases. However, the slope of the curve is low. It means we can increase the distance between RSUs and have almost the same number of collisions. Therefore, this leads us to the following advantages:

- Lower set up cost: Number of RSUs
- Few control data exchange between vehicles and RSU

4.5.2 Comparison between PTA-MAC and state-of-the-art protocols

In what follows, we compare PTA-MAC with VeMAC, Vector-based protocol, and PTMAC regarding communication collision and control overhead size. We also investigate the impact of the traffic density, time frame length, and number of lanes per road direction.

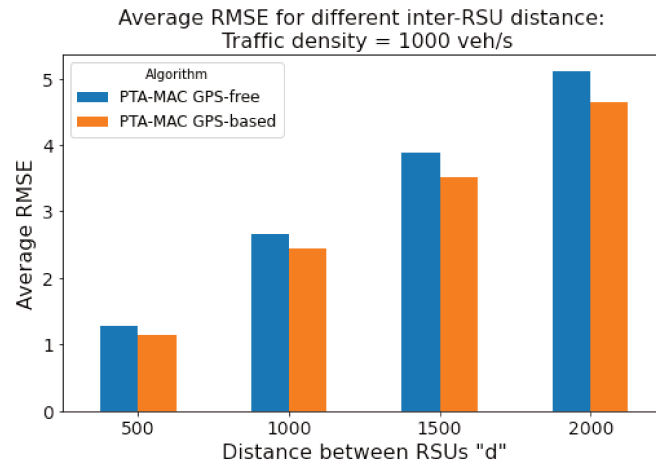


Figure 28. Average RMSE for different inter-RSU distance.

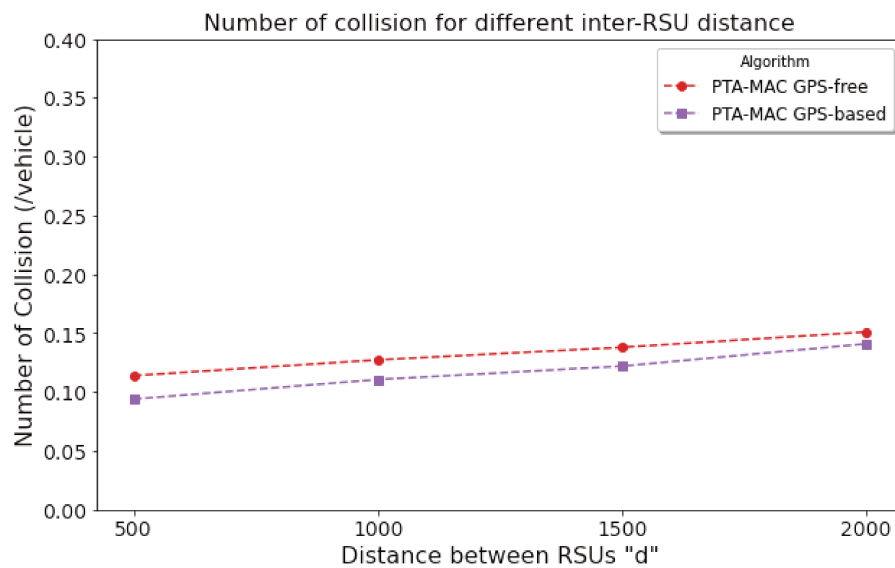


Figure 29. Number of collisions per vehicle for different inter-RSU distance.

4.5.2.1 Impact of traffic density

Figure 30 compares the studied and PTA-MAC in terms of the average number of collisions per vehicle in a network for different traffic densities.

For low network densities, PTA-MAC outperforms all other studied protocols for low and medium traffic densities. This can be explained by RMSE being low for low densities, so the proposed protocols can assign the best time-slot with high probability. PTMAC performs better than our proposed protocols for high densities since it can process an accurate and high quantity of control data.

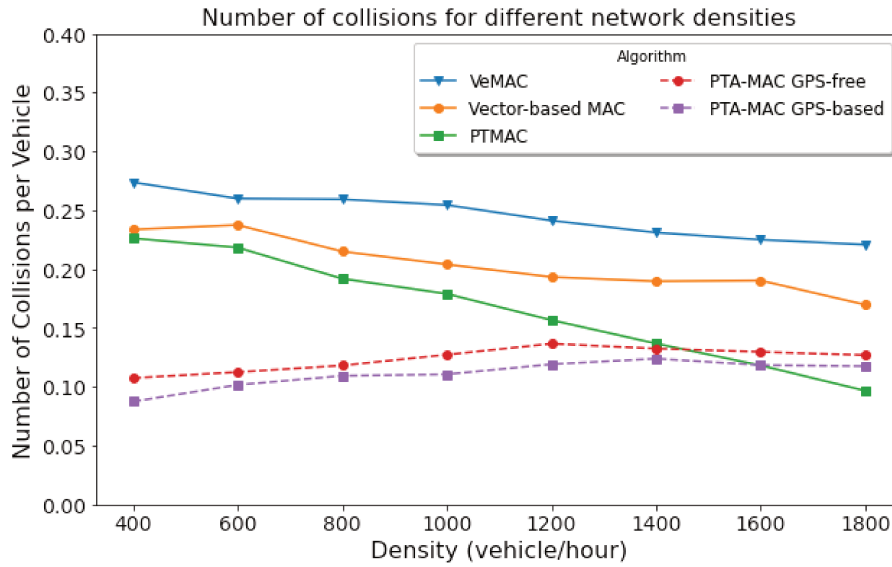


Figure 30. Average collision for the network with different traffic densities.

Figure 31 compares the studied and proposed protocols regarding average overhead size per vehicle in a network for variable traffic densities. The overhead size increases for higher traffic densities because the number of one and two-hop neighbors of vehicles increases. In Vector-based protocol, every vehicle must forward information about one- and two-hop neighbors. For the rest of the protocols, it must transmit information about their one-hop neighbors. We can observe that PTMAC and the Vector-based protocols require higher overhead than VeMAC. At the same time, our proposed protocols and VeMAC have low overhead sizes. The overhead is linear to the traffic density, with a greater slope for PTMAC and the Vector-based protocols than for our proposed protocols.

From the above observations, we conclude that PTA-MAC achieves, with a much smaller overhead size, better performance for low and medium traffic densities and close performance for high traffics than PTMAC.

4.5.2.2 Impact of number time frame length (number of time-slots)

Figure 32 compares PTA-MAC and studied protocols regarding average collision per vehicle in a network for different numbers of time-slots per time frame.

Collision decreases when the number of time-slots per frame is high. For the studied protocols, the vehicles will have more available time-slots to choose from when a collision occurs. Our

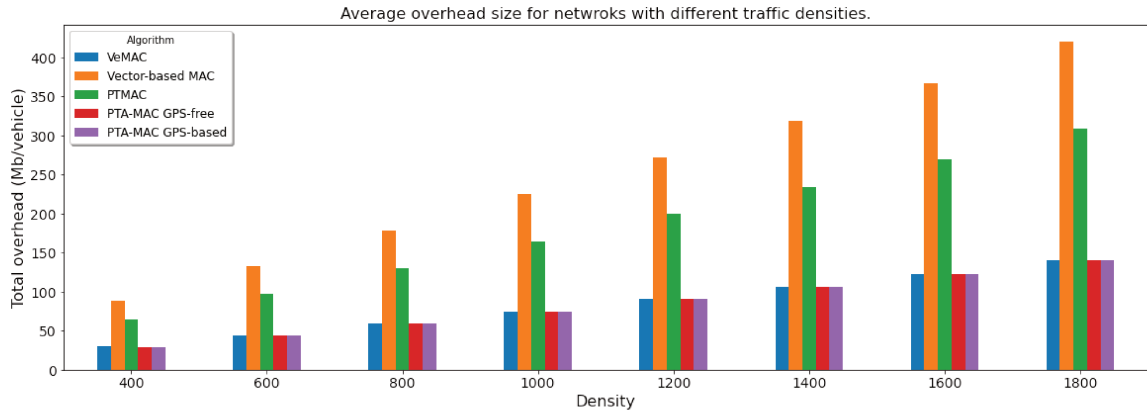


Figure 31. Average overhead size for the network with different traffic densities.

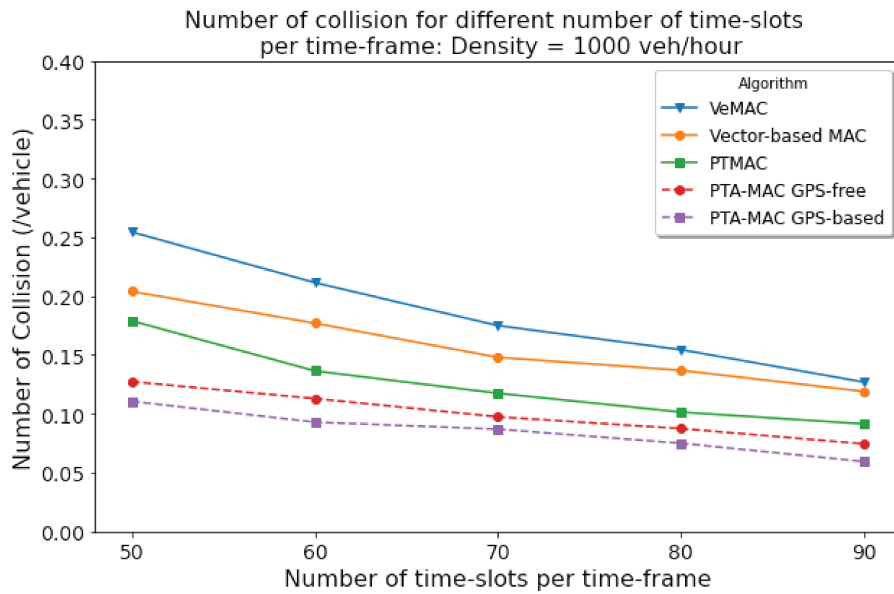


Figure 32. Average collision per vehicle for a variable number of time-slots per time frame.

proposed protocols benefit the same way from the availability of more time-slots and give better performance.

4.5.2.3 Impact of number of lanes per direction

Figure 33 compares PTA-MAC and the studied protocols in terms of the average number of collisions per vehicle for different number of lanes per road direction. We can see that collision varies in different ways compared to the number of lanes for different traffic densities. First, for low traffic density ($400veh/h$), collision is at its top for a three-lane road for the studied protocols. However, it remains constant with PTA-MAC. Second, for medium traffic density,

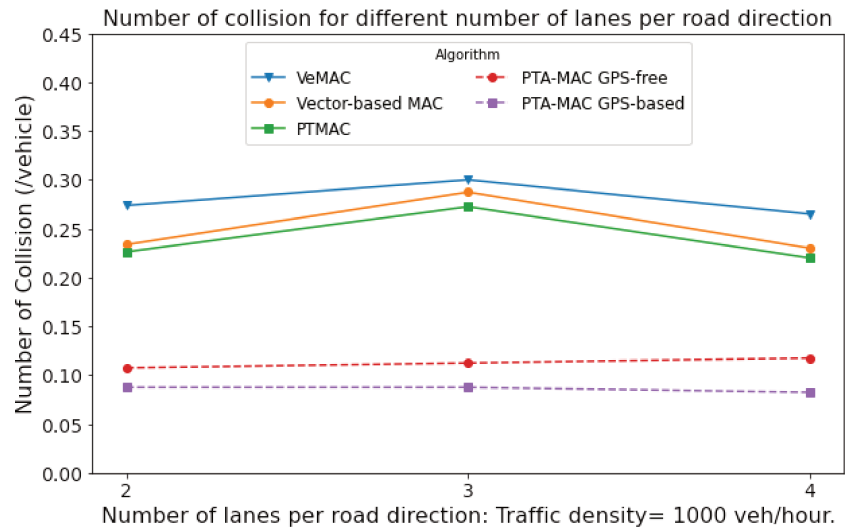
collision remains constant for almost all the studied protocols and PTA-MAC. Finally, for high traffic density, collision increases when the number of lanes increases.

The above observations demonstrate that the vehicles' mobility greatly impacts the network performance, and every MAC protocol has its way of responding to it. The important fact is that PTA-MAC is the most robust protocol for all traffic conditions and road width.

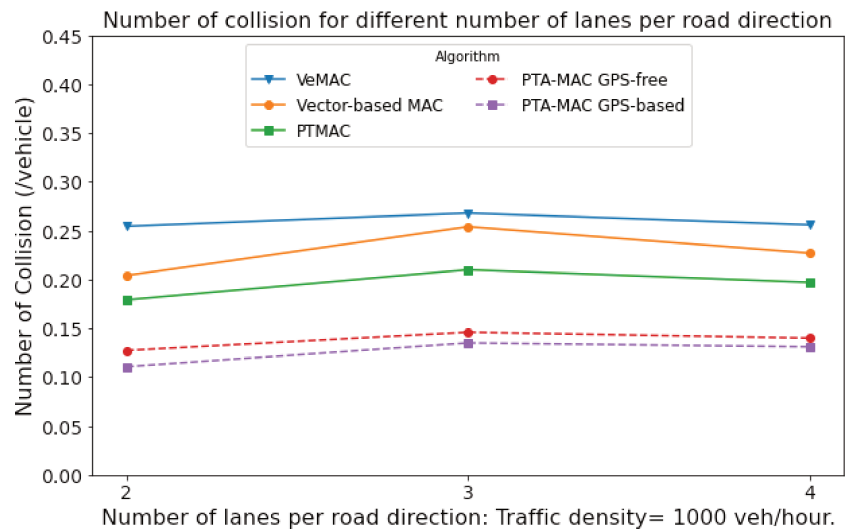
4.6 Discussion

The simulation results section confirms that PTA-MAC is a challenging protocol to recent and efficient state-of-the-art MAC protocols for vehicular networks. In effect, for low and medium traffic densities, PTA-MAC can reduce collisions by up to 50% compared to the most efficient protocol, "PTMAC". For high traffic densities ($> 1600veh/h$), PTA-MAC performs better than VeMAC and the Vector-based MAC protocol. However, it gives inferior (but not bad) results compared to PTMAC. From the point of view of overhead, PTA-MAC is among the protocols that require the least control overhead to work, unlike PTMAC. PTA-MAC works almost like VeMAC, with extra communication with every RSU only at the beginning of every road segment. That is not the case with PTMAC and Vector-based protocol, which require exchanging extra control information between vehicles at every time-frame. Therefore, we conclude that the good performance of PTMAC for high traffic densities comes with an extra cost (bandwidth efficiency).

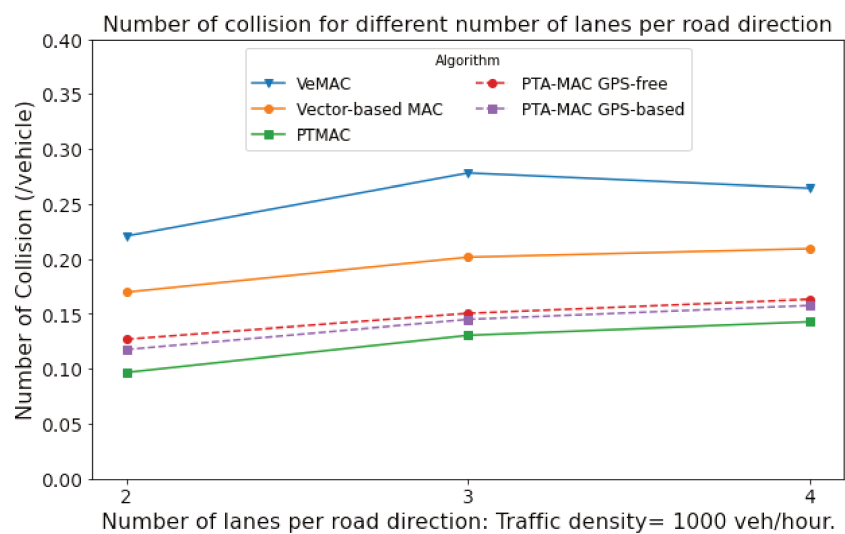
We proposed a GPS-based PTA-MAC to better observe the impact of using GPS in time-slot allocation. The use of GPS gives slightly better prediction accuracy. The prediction accuracy difference between the two models increases when the traffic density increases and decreases when the road is wider. In terms of collision, prediction accuracy has an important role in minimizing collision between vehicles. This is proved by the fact that GPS-based PTA-MAC causes fewer collisions in every case than GPS-free ones. Therefore, a better prediction model can perform better, but this is not the purpose of this work.



(a) traffic density = 400 veh/h.



(b) traffic density = 1000 veh/h.



(c) traffic density = 1800 veh/h.

Figure 33. Average number of collisions per vehicle for different number of lanes per road direction.

Conclusion

In this chapter, we proposed a new framework consisting of a preventive Time-slot allocation for a hybrid RSU-assisted vehicular network. For time-slot allocation protocol, an RSU predicts the sojourn time of an entering vehicle within a road segment and chooses the best time-slot that minimizes future communication collision in the network. Our solution proved to give good results compared to state-of-the-art protocols with low extra overhead.

In the future, we will focus on expanding our protocol's application to other types of networks with more complex mobility models (e.g., UAV networks).



Conclusion

In this thesis, we made three significant contributions:

Firstly, we comprehensively reviewed recent contention-free MAC Protocols proposed for wireless decentralized networks. We categorized these solutions based on the mobility degree of the network, specifically focusing on static, low/medium mobility, and high mobility networks. This classification has proven valuable in understanding the problem and solution spaces of mobility-related MAC algorithms. We also provided critical insights into the existing literature, offering guidance to researchers for exploring new research directions and addressing the mentioned problems. Additionally, we discussed the impact of mobility on MAC protocol design and the potential deployment of these protocols in different network types. This work provides a valuable resource for researchers guiding the development of more efficient and effective protocols for different types of networks through its understanding of mobility-related MAC algorithms' problem and solution spaces.

Secondly, we proposed a collision prediction model to detect possible collisions in dynamic networks within a predefined architecture. Our experimental results demonstrated that the collision prediction model exhibits high accuracy and precision. This paves the way for more reliable and collision-free transmissions in dynamic environments, leading to improved overall network efficiency.

Thirdly, we proposed a novel solution for preventive time-slot allocation in hybrid RSU-assisted vehicular networks. This solution involves an RSU predicting the sojourn time of an incoming vehicle within a road segment and selecting the optimal time-slot to minimize future communication collisions in the network. Our solution outperformed state-of-the-art protocols

with minimal additional overhead, showcasing its potential for enhancing the performance and reliability of vehicular networks. This solution has implications for various applications, including intelligent transportation systems, autonomous vehicles, and smart cities, where efficient and collision-free communication is crucial.

Overall, this thesis contributes to advancing knowledge and understanding of wireless decentralized networks, offering insights and solutions that can be applied to various network scenarios. The findings of this research hold significant practical implications for researchers, organizations, and policymakers interested in promoting efficient resource allocation and improving network performance in dynamic environments.

In future research, we plan to explore two additional aspects. Firstly, we aim to propose solutions to avoid collisions in general architectures by identifying more comprehensive features that characterize node movement direction and speed. We will focus on expanding the application of our protocol to other types of networks with more complex mobility models, such as UAV networks. Also, we intend to analyze the security issues and challenges specific to wireless decentralized networks, offering potential solutions to address different attack vectors.



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