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Dedication

I would like to dedicate this project to my family, who have been my constant source of love, support, and inspiration throughout my academic journey. Your unwavering encouragement and belief in my abilities have been invaluable, and I am grateful for the sacrifices you have made to help me pursue my dreams.

I would also like to express my gratitude to my professors, whose guidance and expertise have challenged me to grow and develop as a student. Your dedication to teaching and commitment to excellence have been a source of motivation and inspiration, and I am honored to have had the opportunity to learn from you.

Finally, I would like to acknowledge my classmates and friends, whose camaraderie and support have made this journey all the more fulfilling. Your encouragement, collaboration, and friendship have helped me to overcome obstacles and celebrate achievements, and I am grateful for the memories we have shared.

To my family, professors, classmates, and friends, thank you for being a part of my academic journey and for helping me to achieve my goals. This project is a testament to the power of collaboration, dedication, and perseverance, and I am proud to share it with you.

Summary

This master's dissertation explores the application of a metaheuristic algorithm called MRFO (Manta Ray Foraging Optimization) for optimizing routing protocols within mobile ad hoc networks (MANETs). MANETs are a type of decentralized wireless network consisting of mobile nodes that can establish temporary connections with each other, independent of any pre-existing infrastructure. Routing protocols, a critical component of MANET functionality, comprise a set of rules and algorithms that manage the forwarding of data packets across the network. The research proposes an improved routing protocol based on MRFO, called MantaNet, to identify optimal routes for data transmission. The thesis addresses routing in MANETs as an optimization problem and provides an overview of optimization problems and techniques, including the presentation of the MRFO method.

The application of MRFO in MANETs is then described, with various simulation results presented for different network scenarios. The simulation results demonstrate that the proposed method is capable of finding the optimal route and ensuring reliable and efficient data transmission in diverse network conditions, ranging from small to large scales, with reduced computational complexity. Overall, this research contributes to the understanding and enhancement of routing protocols in mobile ad hoc networks through the innovative application of the MRFO metaheuristic algorithm.

Key words: MANET; MRFO; optimization; metaheuristic; Routing protocol.

الملخص

تستكشف مذكرة الماستر تطبيق خوارزمية فوق متفوقة تسمى MRFO (التحسين بتجوال رايا المانتا) لتحسين بروتوكولات التوجيه ضمن شبكات ad hoc المتنقلة (MANETs) تعد MANETs نوعًا من الشبكات اللاسلكية اللامركزية المكونة من عقد متنقلة والتي يمكنها إنشاء اتصالات مؤقتة مع بعضها البعض، بغض النظر عن أي بنية تحتية سابقة موجودة. تُعد بروتوكولات التوجيه، وهي مكون فعال من وظائف MANET، مجموعة من القواعد والخوارزميات التي تدير إرسال حزم البيانات عبر الشبكة. تقترح هذه الأبحاث بروتوكول توجيه محسن مستند إلى MRFO، يُطلق عليه اسم MantaNet، لتحديد المسارات الأمثل لإرسال البيانات. تعالج الأطروحة التوجيه في MANET كمشكلة تحسين وتقدم نظرة عامة على مشاكل وتقنيات التحسين، بما في ذلك عرض طريقة MRFO ، ثم يتم وصف تطبيق MRFO في MANET، مع تقديم نتائج محاكاة مختلفة لسيناريوهات شبكية متنوعة. وتُظهر النتائج التجريبية أن الطريقة المقترحة قادرة على العثور على المسار الأمثل وضمان إرسال البيانات بموثوقية وكفاءة في ظروف شبكية متنوعة، تتراوح من صغيرة إلى كبيرة، مع انخفاض في التعقيد الحسابي. بشكل عام، تساهم هذه الأبحاث في فهم وتحسين بروتوكولات التوجيه في شبكات ad hoc المتنقلة من خلال التطبيق المبتكر لخوارزمية MRFO فوق المتفوقة.

الكلمات المفتاحية: شبكات المتنقلة ؛ التحسين بتجوال المانتا رايا ؛ تحسين ؛ فوق متفوقة ؛ بروتوكول التوجيه

Résumé

Cette mémoire de master explore l'application d'un algorithme métaheuristique appelé MRFO (Manta Ray Foraging Optimization) pour optimiser les protocoles de routage au sein des réseaux ad hoc mobiles (MANET). Les MANET sont un type de réseau sans fil décentralisé composé de nœuds mobiles qui peuvent établir des connexions temporaires entre eux, indépendamment de toute infrastructure préexistante. Les protocoles de routage, composante essentielle du fonctionnement des MANET, comprennent un ensemble de règles et d'algorithmes qui gèrent l'acheminement des paquets de données à travers le réseau. La recherche propose un protocole de routage amélioré basé sur MRFO, appelé MantaNet, pour identifier les itinéraires optimaux pour la transmission des données. La thèse aborde le routage dans les MANET comme un problème d'optimisation et fournit un aperçu des problèmes et techniques d'optimisation, y compris la présentation de la méthode MRFO. L'application de MRFO dans les MANET est ensuite décrite, avec divers résultats de simulation présentés pour différents scénarios de réseau. Les résultats expérimentaux démontrent que la méthode proposée est capable de trouver l'itinéraire optimal et d'assurer une transmission de données fiable et efficace dans diverses conditions de réseau, allant d'une petite à une grande échelle, avec une complexité de calcul réduite. Dans l'ensemble, cette recherche contribue à la compréhension et à l'amélioration des protocoles de routage dans les réseaux ad hoc mobiles grâce à l'application innovante de l'algorithme métaheuristique MRFO.

Mots-clés : MANET ; MRFO ; optimisation ; métaheuristique ; Protocole de routage.

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Abbreviations

MANETs : Mobile **A**d **H**oc **N**etworks

IETF : Engineering **T**ask **F**orce

IoT : Internet **o**f **T**hings

LANs : Local **A**rea **N**etworks

WANETs : Wireless **A**d **H**oc **N**etworks

WSN : Wireless **S**ensor **N**etwork

SPANs : Smartphone **A**d **H**oc **N**etworks

InVANETs : Intelligent **V**ehicular **A**d **H**oc **N**etworks

RSUs : Road **S**ide **U**nits

V2V : Vehicle**-to-V**ehicle

V2R : Vehicle**-to-R**oadside

VANETs : Vehicular **A**d **H**oc **N**etworks

PANs : Personal **A**rea **N**etworks

IPANs : Inter**-P**lanetary **A**rea **N**etworks

HANETs: Heterogeneous **A**d **H**oc **N**etworks

DSDV: Destination**-S**equenced **D**istance **V**ector

GSR: Global **S**tate **R**outing

OLSR: Optimized **L**ink **S**tate **R**outing

WRP: Wireless **R**outing **P**rotocol

DT: Distance **T**able

RT: Routing **T**able

LCT: Link**-C**ost **T**able

MRL: Message **R**etransmission **L**ist

AODV : Ad**-H**oc **O**n**-D**emand **D**istance **V**ector

TORA: Temporally **O**rdered **R**outing **A**lgorithm

DSR: **D**ynamic **S**ource **R**outing

RREQ: **R**oute **R**equest

RERR: **R**oute **E**rror

ZRP: **Z**one **R**outing **P**rotocol

MRFO: **M**anta **R**ay **F**oraging **O**ptimization

GA : **G**enetic **A**lgorithms

PSO : **P**article **S**warm **O**ptimisation

SA : **S**imulated **A**nnealing

TS : **T**he **T**abu **S**earch

ACO : **A**nt **C**olony **O**ptimization

TSP : **T**raveling **S**alesman **P**roblem

VRP : **V**ehicle **R**outing **P**roblem

General introduction

A mobile ad hoc network (MANET) is a wireless network composed of mobile devices that can establish a temporary network without relying on a fixed infrastructure. MANETs have diverse applications, including military operations, emergency response, disaster recovery, and ad-hoc collaboration in remote areas. The key advantages of MANETs are their flexibility and scalability, allowing for rapid deployment in situations where traditional infrastructure is unavailable or unreliable. MANETs also offer increased mobility, as devices can move freely within the network without the need for constant reconfiguration. Furthermore, MANETs enable peer-to-peer communication, efficient resource sharing, collaborative applications, and distributed computing. However, MANETs face challenges such as limited bandwidth, security concerns, and the need for efficient routing protocols to ensure reliable data transmission. Continuous research and development efforts are focused on enhancing the performance and routing protocols of MANETs in various applications. [1, 2]

A routing protocol is a set of rules and algorithms that determine how data packets are forwarded in a network. It enables efficient and reliable communication by directing data from a source node to a destination node through intermediate nodes. Routing protocols make decisions based on factors like network topology, available paths, and quality of service requirements. Their primary goal is to find the optimal path that minimizes delays, maximizes throughput, and ensures data delivery. Routing protocols are crucial in both wired and wireless networks, facilitating effective data transmission and enabling seamless connectivity between devices.[3, 4]

Metaheuristics are flexible problem-solving algorithms that aim to find near-optimal solutions for optimization and search problems. They explore different solution spaces using techniques like randomization and iterative improvement. While they don't guarantee the best solution, they provide efficient alternatives within a reasonable timeframe. Metaheuristics are widely applied in diverse fields to address complex problems where traditional methods are impractical or computationally intensive. [5]

In this master’s dissertation, our goal is to explore the application of the Manta Ray Foraging Optimization (MRFO) technique in the context of MANETs (Mobile Ad hoc Networks). The MRFO algorithm, inspired by the foraging behavior of manta rays, has shown promising results in various optimization problems such as engineering design problems, image processing and wireless communications. [6-8]

By adapting MRFO to MANETs challenges, we aim to enhance the routing performance and efficiency of the network. The objective is to develop a novel routing approach for MANET based MRFO, called MantaNet technique, that exploit the collective intelligence and adaptive search capabilities of MRFO to find the optimal route between the sender and receiver.

This manuscript is divided into three chapters organized as follows:

Chapter I: provides an introduction to MANET, its types, topologies, characteristics , application and routing protocols

Chapter II: begins with a general overview of the optimization problem, followed by the presentation of the principle of optimization by food search of Manta rays (MRFO). In the context of mobile ad hoc networks (MANET), we will address the use of the MRFO technique (Manta Ray Foraging Optimization) in the third chapter.

Chapter III: a novel routing approach based MANET is presented, the way to find the optimal route by MRFO is explained in this chapter.

Finally, we present our general conclusions and some perspectives.

Chapter I: Exploring MANET Network Principles

I.1. Introduction

In the domain of computer networking, "network" signifies an infrastructure that links multiple devices, facilitating communication and resource sharing among them. Networks can be structured, connecting devices via fixed infrastructure like routers and switches, or unstructured, such as in ad hoc networks.

An ad hoc network is a specific type of network wherein devices establish communication without the need for pre-existing infrastructure. In these networks, devices form temporary connections to spontaneously create a network. This decentralized method allows devices to exchange information even when fixed infrastructure is absent or impractical. A notable subset of ad hoc networks is the Mobile Ad Hoc Network (MANET).

MANETs are distinguished by their mobile nodes, which move independently and dynamically within the network. These nodes have the freedom to join or leave the network at any time, resulting in a continuously evolving network topology. The mobility of nodes introduces unique challenges to MANETs, including frequent link disruptions, limited resources, and the necessity for efficient routing protocols.[9]

This chapter delves into various aspects of ad hoc networks, with a particular emphasis on MANETs; covering their definitions, topology, and characteristics. It explores the applications of MANETs, the challenges they encounter, and strategies for overcoming these challenges. Furthermore, the chapter examines routing protocols within ad hoc networks, focusing on proactive, reactive and hybrid routing protocols.

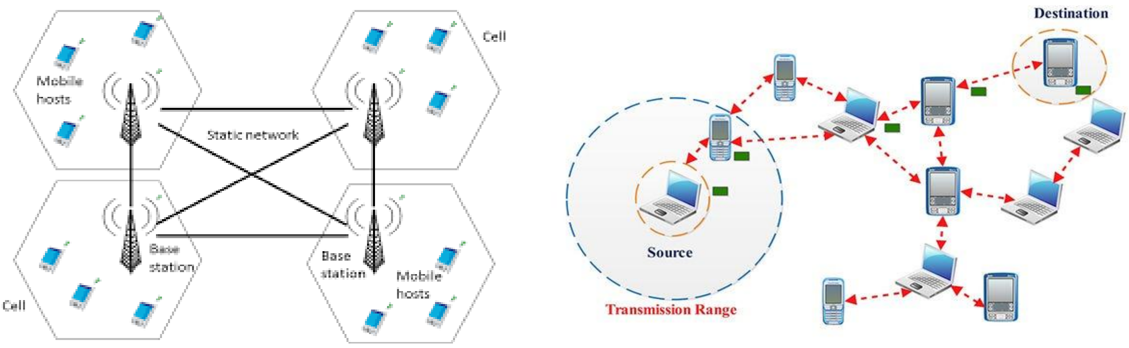
I.2. The Evolution of MANET: A Historical Overview

Mobile Ad Hoc Networks (MANETs) represent a class of wireless networks that boast a unique infrastructure-less and dynamically self-organizing capability, making them highly suitable for environments where traditional networking infrastructure is either unavailable or impractical to deploy. The concept of MANETs traces back to the 1970s, initially driven by military applications that required robust and flexible communication systems in battlefields. These early networks aimed to provide soldiers with reliable communication links that could withstand various physical and electronic challenges on the field.

Throughout the 1980s and 1990s, the development of MANETs gained momentum, paralleling advancements in wireless communication technologies. The invention of more efficient and compact wireless devices facilitated the exploration of MANET applications beyond military uses, expanding into emergency services, disaster relief operations, and even civilian recreational uses, where temporary networks could be rapidly deployed for specific events or purposes.

The official standardization efforts for MANETs began in the late 1990s, spearheaded by the Internet Engineering Task Force (IETF), which formed the Mobile Ad-hoc Networks (MANET) working group. This period marked significant research and development efforts that aimed to address the complex challenges associated with MANETs, including routing, network scalability, and security. As technology continued to evolve into the 21st century, MANETs found new applications in Internet of Things (IoT) devices and smart technologies, further cementing their role in the future of wireless networking by offering a versatile solution for creating dynamic, self-configuring networks. [10]

Wireless networks rely on centralized access points for communication, providing stable and structured connectivity. In contrast, ad hoc networks establish decentralized, spontaneous connections between devices without centralized infrastructure. Ad hoc networks are ideal for dynamic environments or scenarios where infrastructure deployment is impractical, such as disaster recovery or military operations. They prioritize flexibility and adaptability, enabling devices to communicate seamlessly without relying on pre-existing infrastructure. Figure I.1 compares Wireless network and Ad hoc network.



a) Wireless Network b) Ad hoc Network

Figure I.1 :**Comparison between Wireless network and Ad hoc network**

I.3. Type of Ad hoc Network

Ad hoc networks enable users to connect to the internet without relying on a dedicated router or wireless base station. Often termed as local area networks (LANs), these networks are temporary and swiftly deployable. Sometimes, ad hoc networks transition into more structured wireless networks. Their primary purpose is to facilitate communication among devices and individuals within a short duration. Wireless cards within the devices establish direct connections, although with intermittent connectivity. While multiple devices can join simultaneously, the network's capabilities may be constrained. Ad hoc mode denotes the spontaneous setup of such networks [11]. Various types of ad hoc networks are depicted in Figure I.2.

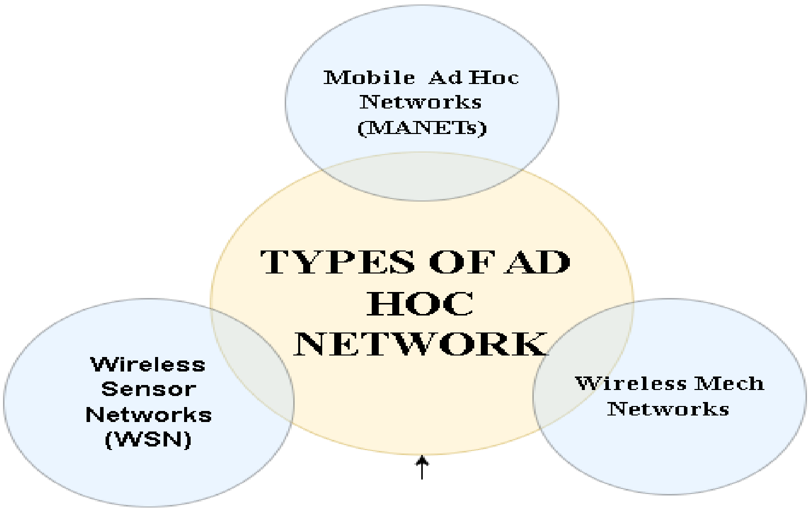


Figure I.2 **:Types of Ad Hoc Network**

1.3.1 Mobile ad hoc networks (MANETs)

Mobile ad hoc networks (MANETs) are built upon a link-layer network and a wireless ad hoc network, offering the capability to establish a mobile and adaptable network. As nodes move within the network, they establish wireless connections to exchange data, forming a group known as a network. MANETs are characterized by their self-configuring and self-healing nature, requiring no prior setup. The network structure changes dynamically, allowing nodes to move freely. These networks can be set up instantly and utilize mobile devices such as laptops, smartphones, or tablets, along with wireless devices, for connectivity and communication. The features of MANETs are depicted in Figure. I.3.

In MANETs, when a node sends a message, it selects specific nodes to receive the message. MANETs can be utilized either as standalone networks or as part of a larger internet infrastructure, adaptable to both scenarios. By incorporating different transceivers between nodes, MANETs become highly dynamic and autonomous, aiming to ensure smooth traffic flow and efficient communication among devices. Each device within the network must possess the necessary information to maintain operational efficiency.

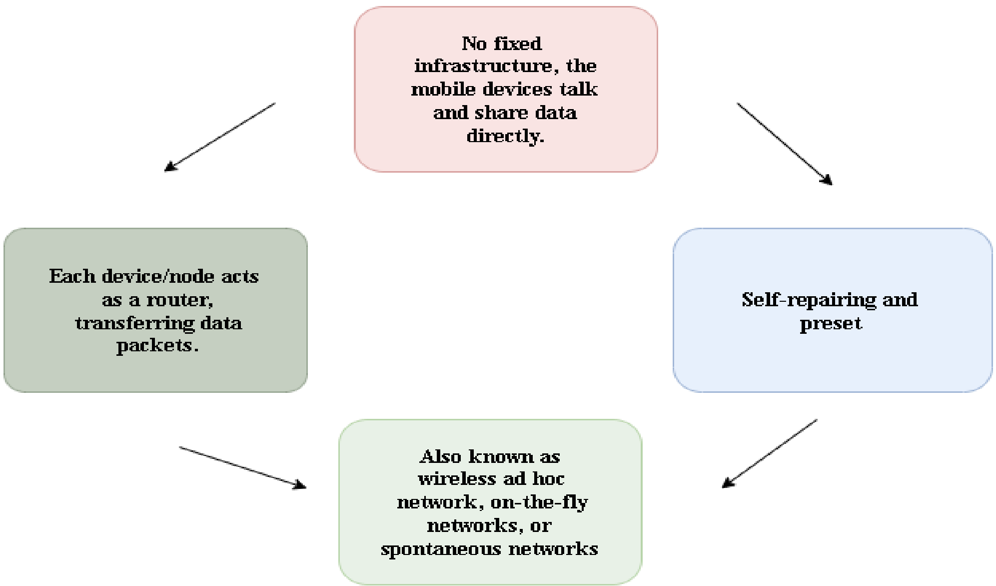


Figure I.3 : **MANET characteristics**

I.3.2. Wireless mesh network

Wireless mesh networks, also referred to as multi-hop wireless networks, comprise numerous interconnected wireless mesh routers forming a mesh-like backbone. Users can access the network via laptops or smartphones equipped with wireless capabilities, connecting to a router acting as a wireless access point that links to the mesh network. The backbone mesh network acts as the conduit for data transmission between users. Wireless mesh networks can connect to one or more routers, enabling connectivity to different networks, including the internet. These networks facilitate various functionalities within wireless mesh networks, also known as wireless ad hoc networks (WANET).

Wireless Ad Hoc Networks (WANETs) offer dynamic network formation and decentralized communication among devices without relying on fixed infrastructure. WANETs enable devices to self-organize and establish direct connections, allowing for flexible deployment and mobility.

Applications of WANETs include military operations, where soldiers can form a network on the battlefield for real-time communication and coordination. WANETs are also used in disaster scenarios, facilitating communication among first responders and aiding in search and rescue efforts. Additionally, WANETs find applications in Internet of Things (IoT) deployments, allowing devices to communicate directly and autonomously without the need for a centralized network.

I.3.3. Wireless sensor networks (WSNs)

A Wireless Sensor Network (WSN) is a self-contained network operating without infrastructure, enabling users to monitor environmental aspects using wireless sensors. WSNs are prevalent in specific locations for environmental management and monitoring. The base station of the WSN system connects to the internet, facilitating data sharing. Sensor nodes communicate wirelessly within the network, collectively forming the WSN. The insights gained from network data aid users in understanding their surroundings and making informed decisions.

WSN nodes, typically low-power devices, pose challenges in security implementation due to limited resources like memory and computing power. Risks include privacy breaches, control manipulation, and availability disruption by potential attackers, emphasizing the need for safeguarding encryption keys. A novel routing method for WSNs, considering energy usage, is mentioned. WSN integration is crucial for IoT advancement, where security becomes paramount as the ecosystem expands. Figure I.4 illustrates components and connectivity of a wireless sensor network

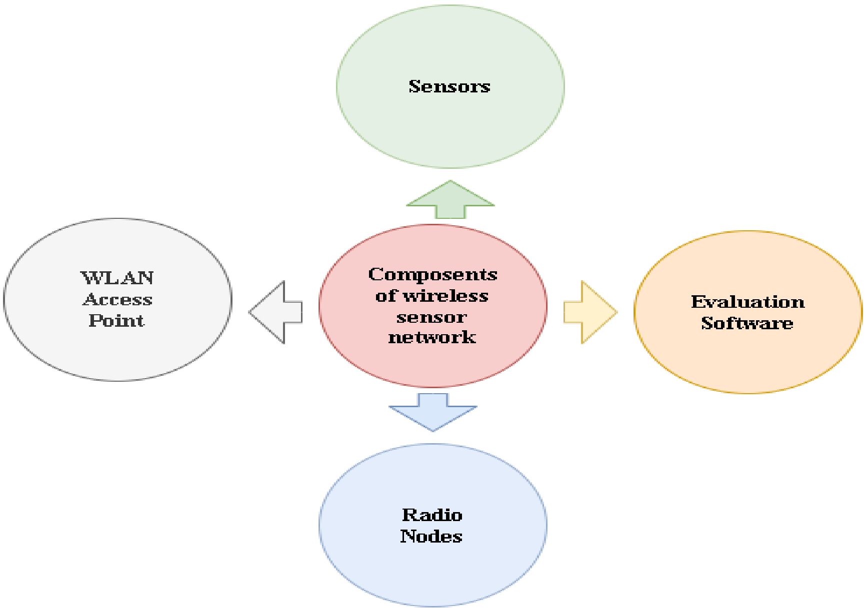


Figure I.4: **WSN components**

I.4. Mobile ad hoc networks (MANETs)

The shift towards multiple-network communication is rapidly occurring as people transition from traditional desktop computing. This new environment enables diverse platforms to communicate across various networks, catering to the needs of mobile workers and their teams. The upcoming wireless communication systems' next generation will feature a significant number of independent mobile users, necessitating swift integration.

Mobile Ad-hoc Networks (MANETs) consist of wireless mobile nodes that interconnect and establish a temporary network without relying on any infrastructure or centralized administration. The network's dynamics and unpredictability allow for nodes to join or depart at any time, often requiring multiple hops for message routing between nodes. Unlike cellular networks, MANETs lack fixed routers or designated locations, with all mobile nodes capable of acting as routers. MANETs provide a flexible and adaptable communication platform capable of accommodating large node counts and dynamic network topologies. [2]

MANETs offer the benefits of quick setup and flexibility, although their usage is still undergoing research and has not yet achieved widespread adoption. Efficient communication relies on proper routing protocols, necessitating unique methods to manage dynamic topology changes. While flat routing methods may suffice for smaller networks, larger networks require hierarchical or global routing. Protocol selection depends on factors such as node count, network size, and node mobility, as there is no universal protocol suitable for all networks. [1]. The working of MANETs is shown in Figure I.5

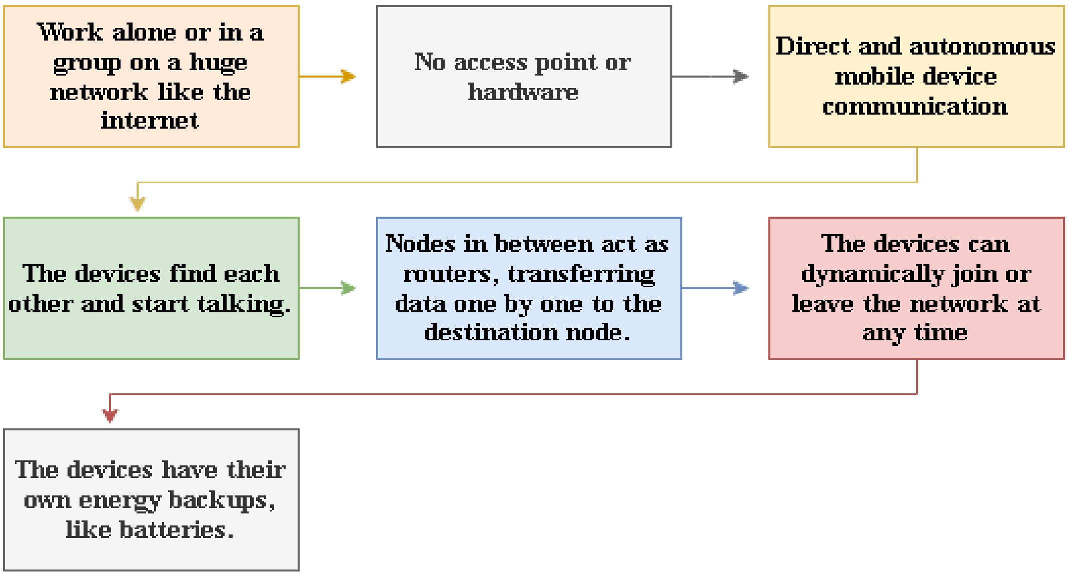


Figure I.5 : **Steps of MANET Working**

I.5. Topology

A Mobile Ad hoc Network (MANET) refers to a self-configuring network of mobile devices that operate without the need for a fixed infrastructure. The topology of a MANET is dynamic and constantly changing due to the mobility of nodes. Nodes in a MANET communicate directly with each other or through intermediate nodes, forming a multi-hop network. The topology of a MANET can vary based on the movement patterns of nodes, their transmission range, and the routing protocols employed. Common topologies in MANETs include: ***mesh***, ***cluster***, ***star***, and ***hybrid*** [11, 12]

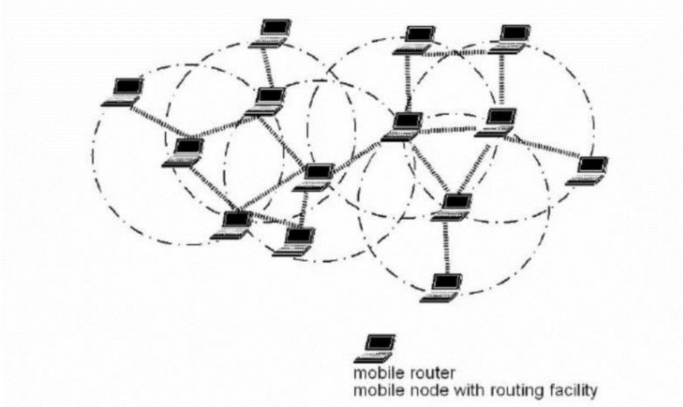


Figure I.6 : **Example Mobile Ad hoc Network**

Figure I.7depicts a scenario involving a sample Mobile Ad hoc Network (MANET) with four mobile nodes. In this scenario, nodes S, B, and C are within each other's transmission ranges. Consequently, nodes S, B, and C are considered neighbors and can communicate directly with one another. However, node D is outside the transmission range of node S. In such cases, an intermediary node, such as node C, acts as a router facilitating communication between nodes S and D. Before data can be transmitted from node S to node D, it must first be relayed through node C. This process may involve multiple hops along the route between the source and the destination. [12]

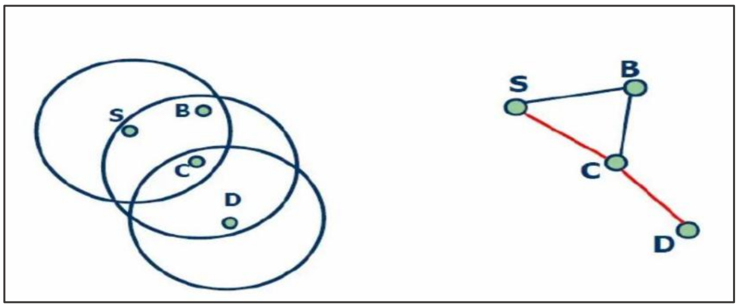
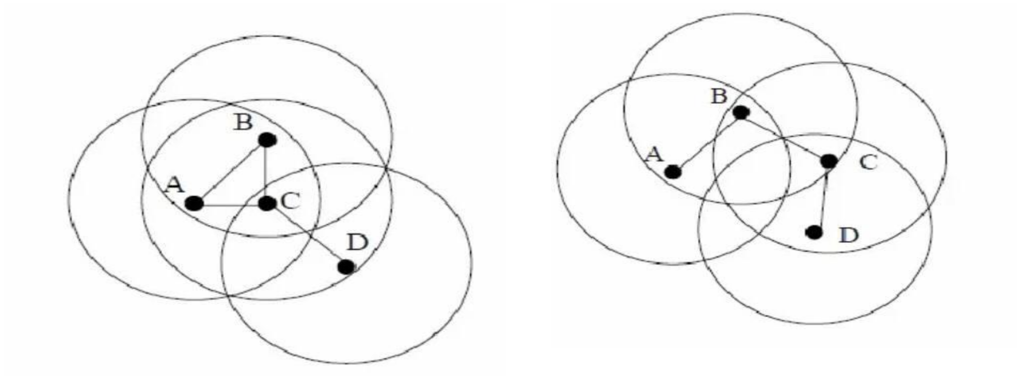


Figure I.7 : **Example for mobile ad hoc networks**

The movement of nodes in a Mobile Ad Hoc Network (MANET) significantly affects the network's topology:

- **Frequent Link Breakages and Formations:** As nodes move around, they constantly enter and leave the transmission range of other nodes. This results in frequent link breakages and formations between nodes. This dynamic nature makes it challenging to maintain stable connections.
- **Route Invalidation:** When nodes move, the established routes between them become invalid. Routing protocols in MANETs need to constantly adapt by discovering new routes or repairing broken ones. This overhead can lead to increased latency and packet drops.
- **Network Partitioning:** In extreme cases, if nodes move far apart quickly, the network can become partitioned into isolated segments. This can disrupt communication between nodes in different segments.
- **Scalability Challenges:** As the number of nodes in a MANET increases, the movement becomes more complex, leading to more frequent route changes and higher overhead on the network. This can limit the scalability of MANETs. [13, 14]



a) *A Mobile Ad-Hoc Network Before Movement*

b) *A Mobile Ad-Hoc Network After Movement*

Figure I.8 : **node movement example in MANET**

Hybrid Networks

Cellular networks and mobile ad hoc networks are combined in hybrid networks. A cellular network is present on one side, while mobile nodes with routing capabilities are present on the other.

This approach allows for the establishment of multi-hop routes between mobile nodes and the base station, resulting in an expanded coverage area for the base station. By leveraging existing infrastructure more efficiently, it becomes possible to cover larger areas with fewer fixed antennas and base stations, while also reducing power consumption. Enhancing cellular networks with ad-hoc technologies offers numerous benefits in terms of improved coverage, reduced infrastructure costs, and enhanced energy efficiency.

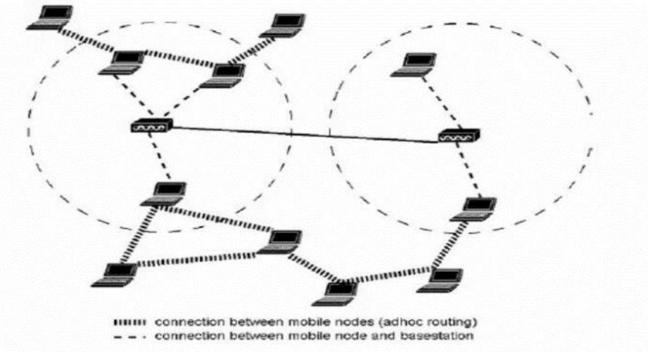


Figure I.9 : **Hybrid network**

I.6. Types of MANETS

Mobile ad-hoc networks (MANETs) are self-configuring networks consisting of mobile devices that communicate through wireless links. When a device in a MANET moves, its connections with other devices change accordingly. In a MANET, each device acts as a router, responsible for forwarding traffic that is not intended for its own use. To enable proper traffic routing, each device in a MANET is equipped with the necessary information. MANETs can either operate independently or be connected to the larger internet. [1 ,15].

Types of MANET include VANET, which facilitates communication among vehicles for intelligent transportation systems and cooperative driving. IVANET is a subset of VANET where vehicles communicate directly without relying on fixed infrastructure, enabling peer-to-peer communication and collaborative applications. SPAN, on the other hand, is a MANET type that utilizes smartphones as nodes to establish an ad hoc network, enabling direct communication and resource sharing in situations where traditional networks are unavailable or unreliable.

Figure I.10. illustrates the differences between VANETs (Vehicular Ad hoc Networks) and MANETs across various parameters.

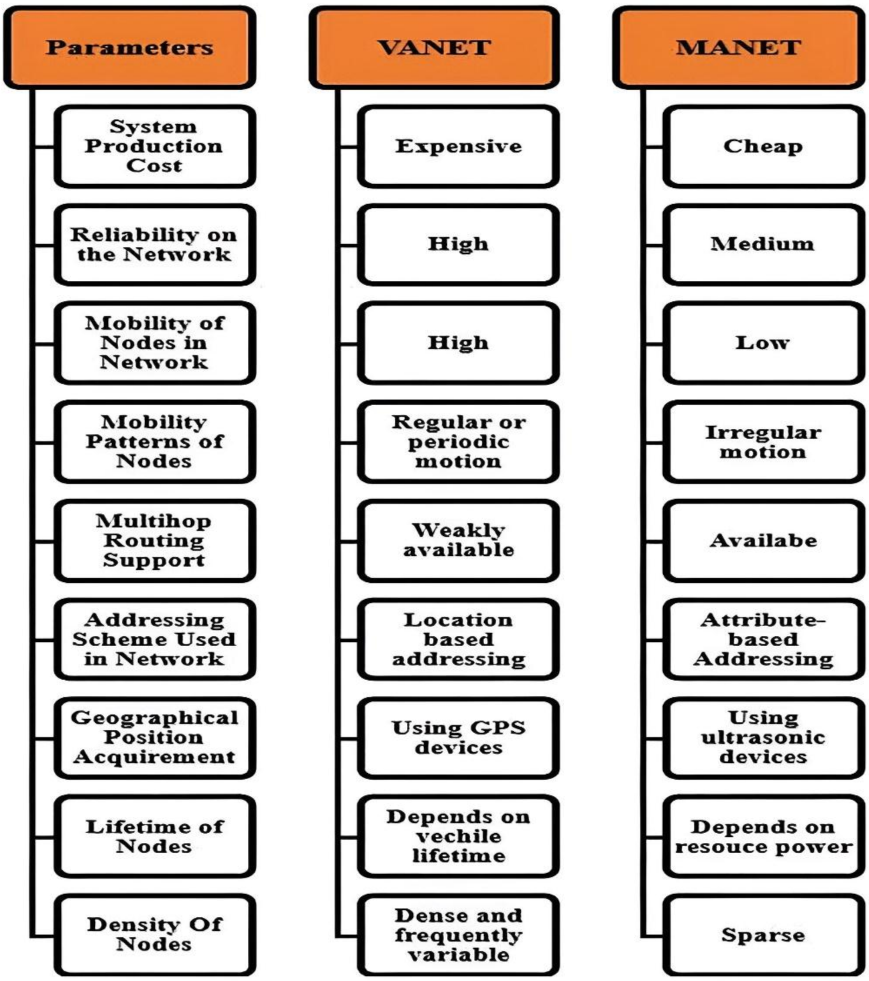


Figure I.10 : **Difference Between VANET and MANET**

I.6.1. Vehicular ad hoc network (VANET)

Vehicular Ad Hoc Networks (VANETs) represent dynamic networks comprising vehicles and connecting elements, such as bridges, formed spontaneously during operation. These networks, comprised of diverse vehicles and connecting devices, communicate wirelessly, facilitating the exchange of critical information. In VANETs, cars, phones, TVs, and other devices serve as nodes within a small network. Various wireless technologies, including cell phones, satellites, and WiMAX, enable seamless communication within VANETs.

VANETs, rapidly evolving networks primarily involving self-driving cars, encounter challenges due to their changing topology caused by highly mobile nodes. The proliferation of cars equipped with computers and wireless communication devices further contributes to this evolution. VANETs offer intervehicle communication, significantly enhancing pedestrian safety and mitigating accidents at blind intersections. They also play a pivotal role in traffic management during peak hours, potentially saving lives.

Although VANETs utilize specialized steering conventions, establishing reliable end-to-end paths poses significant challenges. Effective collaboration among hubs remains critical, with integration of mobile social networking into traditional VANET tools showing promise in enhancing participation. VANETs serve a crucial role in alleviating congestion and ensuring the safe passage of emergency vehicles (see Figure I.11) comparison of various characteristics and challenges associated with vehicular ad hoc networks (VANETs).

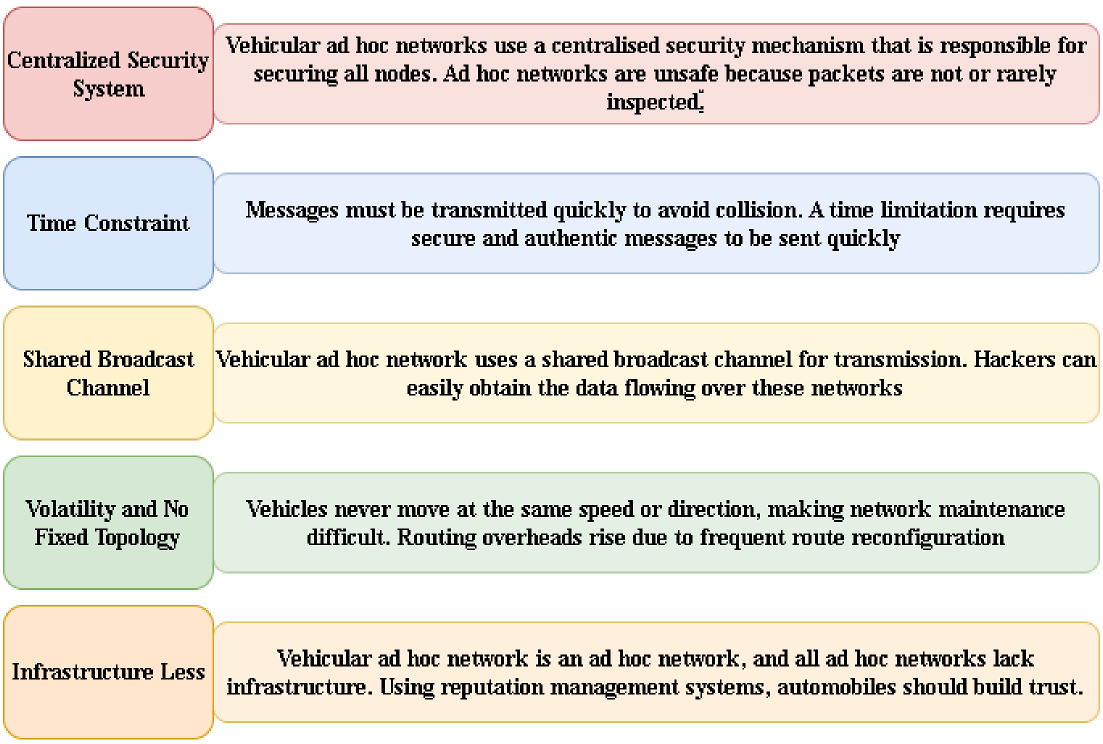


Figure I.11 : **VANET Features**

MANETs can also be broadly classified into two categories based on the number of hops between devices:

- **Single Hop MANETs:** These networks have a maximum distance of one hop between devices, like Bluetooth networks.
- **Multihop MANETs:** In these networks, devices are placed more than one hop apart

I.6.2. Intelligent vehicular ad hoc network

Intelligent Vehicular Ad Hoc Networks (InVANETs) offer additional functionalities, such as accessing car information on electronic maps and enabling efficient navigation. They complement rather than replace cell phones as the primary communication means. InVANETs employ WiFi-based navigation systems to pinpoint vehicle locations in vast areas like universities, airports, or cities, aiding users in selecting optimal routes with minimal congestion. Moreover, this approach serves as a city guide, assisting individuals in discovering and identifying points of interest.

Intelligent transportation systems entail vehicles communicating with each other and with roadside access points termed Road Side Units (RSUs). Vehicular communication enhances road safety, efficiency, and travel convenience by providing drivers with timely information. Vehicle-to-Vehicle (V2V) and Vehicle-to-Roadside (V2R) communication serve distinct purposes: V2R suits sparse networks and long-distance communication, whereas V2V allows direct contact over shorter to medium distances and in areas without roadside access points. By facilitating communication between vehicles and the infrastructure, intelligent transportation systems bolster safety and comfort.Mobile IPv6 is employed to ensure continuous internet connectivity on mobile devices. Solutions for mobile IPv6 in non-mobile networks exist, enabling seamless internet access.

I.6.3. Smart phone ad hoc networks (SPANs)

Smartphone ad hoc networks (SPANs) are a form of wireless ad hoc network that leverages the built-in Wi-Fi capabilities of smartphones to enable direct peer-to-peer communication without the need for traditional network infrastructure. SPANs allow smartphones to establish temporary networks on-the-fly, facilitating communication even in scenarios where cellular coverage or Wi-Fi access points are unavailable. In SPANs, smartphones dynamically form connections with nearby devices, creating a decentralized network where each device can serve as a node for relaying data to others. Unlike conventional Wi-Fi networks, SPANs operate in ad hoc mode, enabling devices to communicate directly with each other without the reliance on centralized access points. This flexibility makes SPANs particularly useful in emergency situations, disaster recovery efforts, or in areas with limited connectivity. Furthermore, SPANs can enable innovative applications such as peer-to-peer file sharing, collaborative gaming, or location-based services, enhancing the versatility and connectivity options of smartphones beyond traditional network infrastructures. [1]

An example of a Smartphone Ad Hoc Network (SPAN) could be a group of hikers in a remote area without cellular coverage or Wi-Fi access. Each hiker has a smartphone equipped with Wi-Fi capabilities. They activate the ad hoc mode on their smartphones, allowing them to establish direct connections with each other. By forming a SPAN, the hikers can communicate, share information, and coordinate their activities without relying on any external network infrastructure. The smartphones act as nodes in the network, relaying messages between devices as needed. This example demonstrates how SPANs can enable communication and collaboration in situations where traditional networks are unavailable or unreliable.

I.7 Characteristics

MANET has some qualities that have helped it become widely used throughout time. The following qualities are desired in Ad-Hoc Routing protocols [16,17]:

- **Distributed Operation:** The central management of network operations is not supported by a background network. Each node has a portion of the network's control. Each node in a MANET serves as a relay when necessary to carry out particular tasks like routing and security. Participating nodes should cooperate and communicate with one another.
- **Multi Hop Routing:** A packet must be resent through one or more intermediary nodes if a node wishes to communicate data to another node that is outside of its communication domain.
- **Autonomous Terminal:** In a mobile area network (MANET), every mobile node is a separate node that can serve as a host or a router.
- **Dynamic Topology:** Since nodes are free to move around, the topology of the network might consist of both bidirectional and unidirectional links and can change quickly and unpredictably at unanticipated periods.
- **Light-weight Terminals:** The MANET's nodes are often mobile, with low CPU capacity, low power storage, and tiny memory sizes.

- **Shared Physical Medium:** Any organization with the necessary tools and funds can use the wireless communication medium. Thus, it is not possible to limit access to the channel

I.8. Application

MANETs have gained popularity due to their versatility and find application across various fields in practical life. Here are the main applications of MANETs [18,19].

- **Military application**: In military operations, MANETs are heavily utilized when a resilient and adaptable communication network is needed in demanding and changing conditions.
- **Emergency services**: In an emergency, MANETs can be quickly installed to provide ad hoc communication networks, enabling emergency service providers to coordinate and exchange vital information.
- **Mobile conferencing:** Mobile conferencing applications can be made possible via MANETs, giving users the freedom to communicate and work together in real time while on the road without depending on permanent infrastructure.
- **Personal area networks:** Personal area networks (PANs) can be created with MANETs to facilitate data sharing and communication between devices that are close together.
- **Embedded computing applications:** Through the integration of MANETs into embedded computing systems, information sharing and communication between devices and sensors can occur in contexts with limited resources.
- **Mobile Satellite Earth-stations:** Mobile satellite earth-stations can communicate with one another using MANETs, providing mobile connectivity in isolated or disaster-affected areas.
- **Mars Proximity Network:** Mars Proximity Networks operate on a decentralized architecture akin to mobile ad hoc networks, where nearby nodes establish communication without prior configuration. Nodes within close range form the network participants, requiring mechanisms to identify neighbors and establish communication routes dynamically. Additionally, these networks must

exchange information on external connectivity, as specific nodes may act as gateways to other networks like the Internet.

- **Inter-Planetary Area Network (IPANs):** Inter-Planetary Area Networks, or IPANs, are networks that connect planets across vast distances and struggle with dependable information sharing, quick service delivery, and end-to-end connectivity. They employ interplanetary spacecraft and Mobile Ad hoc Networks (MANETs) to enable communication between smaller spacecraft orbiting nearby planets. IPANs are very useful for planetary exploration since they allow real-time data relay from a constellation of spacecraft to stations located on Earth.

I.9 Security

A security service's goal is to fortify a network before an attack occurs and make it more difficult for a malevolent node to compromise the network's security. The unique characteristics of MANET made it difficult to provide these services. A trade-off between these services is necessary for MANET security; if one service guarantees something without taking into account other services, the security system will not work. Network applications are responsible for offering a trade-off between various security services; however, delivering services individually in a MANET and offering a means of guaranteeing each service is a challenge. We talk about the following five significant security services and their difficulties [20, 21]

- **Availability:** All network data and services must be accessible to every authorized node in order for this service to function. Because of its open boundaries and changeable topology, MANET presents an availability difficulty. Since time is one of the security factors, access time—the amount of time required for a node to access network services or data—is significant. This service is ignored because it uses a lot of security and authentication levels and it takes time to pass security levels.
- **Authentication:** This service's objective is to provide reliable communication between two distinct nodes .Upon receiving packets from a source, a node needs to be certain of the identity of the source node. Key distribution and key management are problematic; certifications are used to deliver this service.
- **Data confidentiality:** Each node must be able to access only those services that it is authorized to access, according to this service. The majority of services that rely

on data confidentiality employ encryption techniques, however because MANETs lack central management, key distribution has been fraught with difficulties and occasionally is not feasible.

- **Integrity:** Only authorized nodes are allowed to create, amend, or remove packets, according to integrity security services. A Man-in-the-Middle attack, for instance, is directed towards this service. The attacker in this attack removes or alters every packet after capturing it.
- **Non-Repudiation:** Neither the source nor the destination may retract their data or activities by using this service. It implies that a node 1 cannot deny a packet it has transmitted to a node 2 after receiving it and replying to it.

I.10. Advantage of MANET

MANET enjoys several advantages which are summed up bellow [16]:

- Independent from central network administration.
- Self-configuring network, nodes also function as routers.
- Less expensive as compared to wired networks.
- Scalable, accommodating the addition of more nodes.
- Advanced flexibility.
- Robust owing to decentralized administration and lack of infrastructure.
- The network can be established at any place and time, easily and quickly without the need for wiring.
- Increased reliability due to multiple paths.
- Provides access to information and services irrespective of geographic position.
- Does not restrict access to channels.

I.11. Challenges in MANETS

Despite the MANET's advantages, there are still several obstacles that need to be solved. Over the past few years, MANETs have been a major area of study. Nearly every facet of the network has been examined in some capacity, at varying degrees of difficulty. The following list includes the MANET's top challenges [22, 23, 12]

a. Limited Resources: Because battery power is a rare resource, mobile nodes must rely on it. Power and storage capacity are also highly constrained.

b. Multiple Roles: Creating effective medium access protocols that enhance spectrum reuse and, consequently, aggregate channel utilization in MANETs is a critical concern.

c. Dynamic Topology: Nodes can be dynamically joined in any way and are mobile. The network's links change over time and are determined by how close two nodes are to one another.

d. Limited Bandwidth: The capacity of wireless links is still far smaller than that of infrastructure networks. Additionally, the actual throughput of wireless communication is frequently far lower than the maximum transmission rate of a radio after taking into consideration the effects of multiple access, fading, noise, interference circumstances, etc.

e. Heterogeneity: Heterogeneous Ad Hoc Networks (HANETs) are essential elements of the Internet of Things (IoT), a trend that will undoubtedly continue in future studies and implementations. Ad hoc networks have seen a surge in use in a variety of industries recently, most notably intelligent transportation, smart cities, armament control, and environmental monitoring.

f. Limited Survivability: Ad hoc networks' low resilience and susceptibility to security breaches are one of the main obstacles while utilizing them. Another risk associated with using a wireless channel for communication is the potential for link-level attacks, which can include message distortion, passive eavesdropping, and replay. Furthermore, the implementation of wireless ad hoc networks in various, frequently hostile environments (such as the military's quickly deployed battle-site network or sensor fields used to gather sensitive data in remote, unmanned locations) increases the vulnerability of these networks to network security attacks that result in the failure of network elements.

I.12. Routing Protocols for MANET

Routing protocols in Mobile Ad hoc Networks (MANETs) play a critical role in the establishment and upkeep of communication paths between nodes within a decentralized and dynamic network. These protocols serve to optimize data transmission by identifying the most efficient routes based on network topology and node mobility. Selection of an appropriate routing protocol is contingent upon various factors including network size, scalability, and adaptability requirements. Ad hoc routing is typically classified into proactive, reactive, and hybrid routing protocols [3, 4]. This classification delineates the fundamental approaches utilized in MANET routing strategies. For further clarity, refer to Figure I.12.

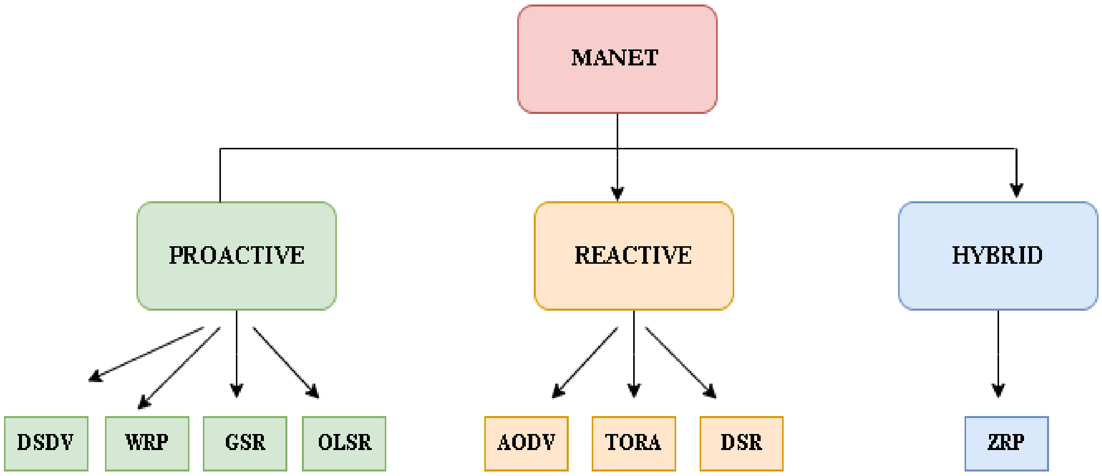


Figure I.12 : **Classification of MANET Routing Protocols**

I.12.1 Proactive routing protocol

Definition: Proactive routing protocols in Mobile Ad hoc Networks (MANETs) are designed to maintain up-to-date topology records by employing a distributed approach where each node maintains multiple tables. These tables are consistently updated and exchanged among nodes, which consequently leads to a significant increase in network overhead. The proactive routing protocols' methodology is comparable to that of the wired networks' routing protocols. Examples of such proactive routing protocols include Optimized Link State Routing (OLSR), Destination Sequenced Distance Vector (DSDV), Fisheye State Routing, and Distance Vector.

Challenges: In Mobile Ad hoc Networks (MANETs), nodes update topology information by disseminating messages across the entire network, a process that significantly impacts network throughput and results in heavy traffic. This dissemination of routing information leads to frequent changes in routing tables, which, in turn, consumes substantial bandwidth, energy, and memory resources. Despite the continuous update of routing information, a significant portion of this data remains unused due to the limited lifespan of routes within the network. Consequently, this approach poses challenges in terms of efficient resource utilization and overall network performance in MANETs.

Efficiency: Nodes within the network are tasked with continuously evaluating previously established routes and detecting any alterations in the network topology. Given that each node in the network possesses knowledge of the path to every other node, packets between nodes can be efficiently and promptly forwarded without the need to await further information, as the route is already predetermined. To facilitate packet forwarding, each node maintains up-to-date information including:

- The number of hops required for packets to traverse to reach the destination node.
- The latest sequence number generated by the destination node.
- The destination's address.

While this approach proves highly effective in networks with a limited number of nodes, its efficiency diminishes in larger networks. In sizable networks, the task of each node keeping track of the routing details of all other nodes becomes increasingly challenging.

Examples: The popular proactive protocols include Destination Sequenced Distance Vector (DSDV), Global State Routing (GSR), Wireless routing protocol (WRP), and Optimized Link State Routing (OLSR).

a. Destination-sequenced distance vector (DSDV)

The goal of this routing protocol is to prevent loop formation by extending the Bellman Ford method. In this instance, the shortest path algorithm is used to determine the route to the target. This routing protocol broadcasts updated routing tables to every node on a regular basis to ensure network consistency. One drawback of this routing technique is the high network overhead caused by the routing tables' periodic broadcasting. This protocol is limited to usage in small networks; it is not appropriate for use in big networks over 200 nodes due to the significant bandwidth required for the periodic transmission of update tables.

b. Global state routing (GSR)

This routing protocol makes use of the link state algorithm. Every node in the network initiates and maintains a link state table, which is periodically broadcast to all of the neighboring nodes. Thus, there are a lot less control messages overall. Due to the large size of the update packets, which will only increase as the network expands, enormous amounts of bandwidth are used.

c. Optimized link state routing (OLSR)

The link state algorithm serves as the foundation for this routing protocol, which is also known as the point-to-point routing protocol. Periodically, link state messages are exchanged to keep the routing data consistent across the network. A change in the network's topology will only be broadcast to a select few nodes, who are then in charge of rebroadcasting the change. The modification will be read by the nodes that do not get the update information;

they will not retransmit it to the other nodes. In this manner, the size of the control message will be kept to a minimum and the frequency of periodic transmissions will decrease.

d) Wireless routing protocol (WRP)

Wireless Routing Protocol (WRP) is a table-based protocol that incorporates the Bellman-Ford algorithm to calculate routes. It is similar to DSDV and aims to achieve loop-free routing and rapid convergence in the event of link failures. WRP employs four tables: distance table (DT), routing table (RT), link-cost table (LCT), and message retransmission list (MRL). These tables help nodes maintain accurate information about neighbors, network views, link costs, and pending message retransmissions. WRP ensures up-to-date routing information, eliminates loops by verifying predecessor consistency, and facilitates faster convergence during link failures. [24]

I.12.2 Reactive routing protocol

Definition: Reactive routing protocols in Mobile Ad hoc Networks (MANETs) differ from proactive protocols by not providing nodes with information about the entire network proactively. Instead, when a node requires forwarding a packet, it initiates contact with the destination node to acquire route information specifically for that destination. This on-demand route discovery mechanism results in lower network overhead but generally longer route discovery times compared to proactive routing protocols.

In reactive protocols, active routes are temporary and are stored in a cache for a limited time. These routes can be reused if packets need to be sent to the same destination within the specified timeframe. Examples of reactive routing protocols commonly employed in MANETs include Temporally Ordered Routing Algorithm (TORA), Location Aided Routing (LAR), Dynamic Source Routing (DSR), and Ad-hoc On-Demand Distance Vector Routing (AODV).

Challenges: The main drawback of reactive routing protocols is the time it takes to discover routes, especially for long distances. Compared to proactive routing protocols, reactive protocols consume less energy and generat e less overhead. To avoid heavy traffic, when the source node doesn't know a route, it checks neighboring nodes. If the necessary route information is not available, it spreads the search to other nodes in the network. This approach minimizes traffic by utilizing route maintenance schemes. However, the entire network is flooded during route determination in reactive routing protocols.

Efficiency: There is no need for continuous broadcasts with this routing technology. It is thought that reactive routing methods are bandwidth-efficient. Compared to proactive routing systems, reactive routing protocols are more widely used due to their low bandwidth consumption.

Examples: Some reactive protocols are Ad hoc On-Demand Distance Vector (AODV), Dynamic Source Routing (DSR), Temporally Ordered Routing Algorithm (TORA), Associativity-Based Routing[4].

a) Ad-hoc on-demand distance vector (AODV)

To reduce the transmissions, an ad hoc on demand distance vector was suggested. This protocol's primary goal is to only broadcast update packets when absolutely necessary. For emergency services, conferences, and communications on the battlefield, ad hoc on-demand distance vector protocol is a great option. Nodes that are not connected to active pathways will not actively send update packets or make an effort to keep their routing tables current in AODV. Unless another node is attempting to interact with this node, the nodes in a mobile ad hoc network utilizing the AODV protocol do not need to keep track of the expenses to each destination.

b) Temporally ordered routing algorithm (TORA)

The lightweight mobile routing protocol serves as the foundation for this routing protocol. The LMR protocol uses the same routing process. This routing protocol's key benefit is that it uses a lightweight adaptive multicast algorithm to facilitate multicasting. This routing protocol generates temporary routes that might be invalid, which could be a drawback. Unlike the other reactive routing techniques, this one is also utilized in extremely dynamic networks.

c) Dynamic Source Routing (DSR)

When using dynamic source routing, the starting node creates a Route Request (RREQ), which is transmitted via a data packet and includes the destination and source nodes. Subsequently, the packet is sent via the MANET flooding mechanism. Every node receives an RREQ packet; as it is unaware of the path to the destination, it adds its name to a list that is included in the packet's header before broadcasting the packet. A Route Error (RERR) data packet is generated and retransmitted on the route if any node in the MANET is unable to transmit the data packet to other nodes.

I.12.3 Hybrid Routing Protocol

Definition: The hybrid routing protocol combines the advantages of proactive and reactive routing. The network is divided into zones, with each node acting as the center of its own zone. Nodes are categorized as interior or peripheral based on their distance from the central node. This division into zones reduces congestion and facilitates optimal route detection.

If the source and destination nodes are in the same zone, packets can be delivered without delay due to the presence of routing tables with proactive routing information. However, if the source and destination are in different zones, there may be a delay as reactive routing is employed to search for routes on-demand.

Efficiency: The zone routing protocol minimizes the scope of proactive routing to individual zones, reducing routing information wastage. Proactive routing is used within a zone, while nodes outside the zone employ reactive routing to interact with more distant nodes. This approach eliminates the need to query all nodes in the network when route requests are received, as routing information is stored in all nodes using proactive routing. The zone routing protocol is designed to be flexible. This depends on how people behave as well as how the network is currently set up.

Examples: An example of hybrid protocols is Zone routing protocol (ZRP).

a. Zone routing protocol (ZRP)

Any node in this kind of routing system has a zone that is determined by its radius in hops. For routing inside the zone, proactive routing protocol is employed. Reactive routing protocol is used, however, for routing outside of the zone. This routing system functions by combining the benefits of proactive and reactive routing techniques. Zone routing protocols operate as proactive routing protocols for large networks and reactive routing protocols for networks with small routing zones.

Table I.1 : **Different MANET Routing Protocols**

Routing Protocol Class	Protocol	Routing Structure	Multiple Routes	Route Metric Method	Route Maintenance	Advantage/ Disadvantage
Proactive	Optimized link state routing (OLSR)	Flat	No	Periodic	Reduces control overhead using Multipoint Relay	Reduced control overhead and contention / hop neighbor knowledge required
	Global state routing(GSR)	Flat	No	Periodic and local	Localized updates	Localized updates/ High memory overhead
	Destination-sequenced distance vector(DSDV)	Flat	No	Periodic and as required	Loop free	Loop free / High Overhead
Ractive	Ad-hoc on-demand distance vector (AODV)	Flat	No	Freshest and shortest path	Route Table	Adaptable to highly dynamic Topologies / Scalability problems, large delays، hello messages
	Dynamic Source Routing (DSR)	Flat	No	Shortest path,or next available in route cache	Route Cache	Multiple routes, Promiscuous Overhearing / Scalability problems due to source routing and flooding, large delays
	Temporally ordered routing algorithm (TORA)	Flat	Yes	Shortest path,or next available	Route Table	Multiple routes/ Temporary routing loops
Hy brid	Zone routing protocol (ZRP)	Flat	No	Shortest path	Intrazone and interzone tables	Reduce retransmissions/ Overlapping zones

Table I.2 : **Comparison of routing protocols**

Parametres	Proactive routing Protocol	Reactive routing protocol	Hybrid routing Protocol
Routing Scheme	Table driven routing	On-demand routing	Combination of Proactive and reactive
Overhead	The routing overhead is high	The routing overhead is low	The routing overhead is Medium

Scalability	Scalability level is low	This protocol is not suitable for large networks	This protocol is designed for networks with up to 1000 nodes
Traffic	High	Low	High inside the zone and low outside the zone
Latency	Latency is low	Latency is high because of flooding	Latency is low inside the zone and is high outside the zone
Delay	Low	High	Low inside the zone and high outside the zone

Conclusion

In conclusion, Mobile Ad hoc Networks (MANETs) offer a decentralized and adaptable solution for dynamic communication scenarios. Their mesh, cluster, and hybrid topologies provide flexibility and resilience. However, security remains a concern due to their open nature.

Routing protocols like OLSR, AODV, and ZRP are essential for efficient data transmission, balancing between proactive, reactive, and hybrid approaches. However, routing protocols issue remain a persistent challenge due to the dynamic nature of node movements. In the following chapter, we propose a novel routing protocol for MANETs based on metaheuristics.

Chapter II

Optimization Techniques and MRFO Algorithm

II.1. Introduction

Optimization is a powerful process used to find the best solution among a set of possible options for a given problem. It involves either maximizing or minimizing an objective function, while adhering to specific constraints. Optimization plays a pivotal role in various fields, including engineering, economics, logistics, and computer science. Real-world problems often pose challenges due to their complex search spaces, non-linearity, high dimensionality, and the presence of constraints.

Traditional optimization methods, such as mathematical programming and gradient-based techniques, may struggle to handle these complexities effectively. This is where metaheuristic algorithms step in. Metaheuristics are versatile optimization techniques that offer efficient solutions to intricate problems. Unlike methods tied to specific problem structures or mathematical properties, metaheuristics draw inspiration from natural phenomena or problem-solving strategies. They excel at exploring and exploiting the search space, making them suitable for a wide range of domains. These algorithms have evolved alongside advances in computer science, operations research, numerical analysis, game theory, mathematical economics, control theory, and combinatory.

This chapter focuses on optimization problems and techniques, including metaheuristic approaches inspired by natural processes. It highlights the Manta Ray Foraging Optimization (MRFO) technique, elucidating its inspiration and mathematical model.

II.2. Optimization

Optimization is the process of finding the best solution or achieving the highest possible value for a given objective within a set of constraints. Mathematically, optimization problems can be formulated as mathematical models with an objective function to be maximized or minimized, subject to certain constraints or limitations.

The objective function represents the performance or quality to be optimized, while the constraints define the allowable range of values for the variables involved in the problem. The goal of optimization is to find the optimal values of the variables that satisfy the constraints and achieve the best possible outcome according to the objective function.

Optimization has wide applications across various domains, including engineering, economics, finance, logistics, operations research, and machine learning, where it is used to optimize resource allocation, production processes, scheduling, decision-making, and many other aspects of complex systems. [5]

Statement of an optimization problem

An optimization or a mathematical programming problem can be stated as follows [27].

$$\text{Find } X = \begin{Bmatrix} x1 \\ x2 \\ . \\ . \\ . \\ xn \end{Bmatrix}, \text{ which minimizes } f\ (X)$$

(II.1)

subject to the constraints

$$g_j\ (X) \leq\ 0, j\ =\ 1, 2, \dots, m \qquad \text{(II.2)}$$

$$l_j\ (X) =\ 0, j\ =\ 1, 2, \dots, p \qquad \text{(II.3)}$$

where X is an n-dimensional vector called the design vector, $f(X)$ is termed the objective function, and $g_j(X)$ and $l_j(X)$ are known as inequality and equality constraints, respectively.

The number of variables n and the number of constraints m and/or p need not be related in any way. The problem stated in (Eq. II.1) is called a constrained optimization problem. Some optimization problems do not involve any constraints and can be stated as

$$\text{Find X} = \begin{Bmatrix} x1 \\ x2 \\ . \\ . \\ . \\ xn \end{Bmatrix}, \text{ which minimizes } f\ (X) \qquad \text{(II.4)}$$

Such problems are called unconstrained optimization problems.

The resolution of an optimization problem consists of finding the local (or global) minimum (or maximum) points of the function f. Figure II.1 provides an example of local and global minima and maxima [27].

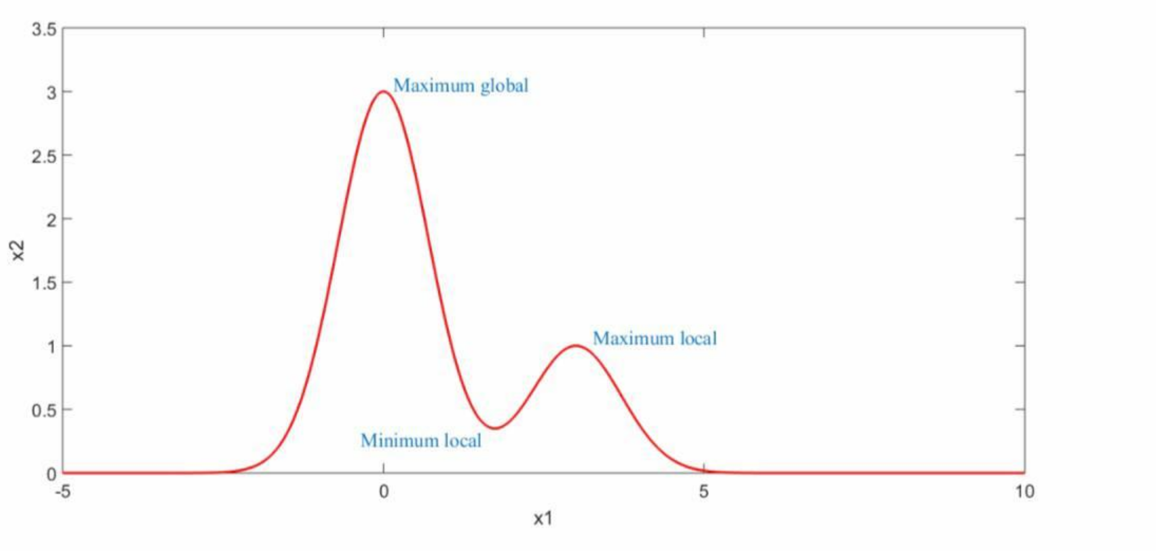


Figure II.1 : **Local and global minima and maxima of a function**

II.3. Classification of optimization problems

Various characteristics, such as the existence of constraints, the type of variables, the number of objective functions, the nature of the underlying equations, and so on, can be used to categorize optimization problems. This global classification makes it possible to comprehend the properties and structure of optimization problems better. [28-30]

- **Classification based on the existence of constraints**: This classification separates optimization problems according to the existence or non-existence of constraints on the decision-making variables.
- **Classification Based on the Physical Structure of the Problem:** This classification considers the problem's physical characteristics. For instance, problems related to networks, graphs, or permutations fall into specific structural categories.
- **Classification Based on the Nature of the Design Variables:** Here, we consider the type of variables involved. If the variables are continuous (e.g., real numbers), we deal with continuous optimization. Conversely, if the variables are discrete (e.g., integers), it falls under discrete optimization.
- **Classification Based on the Nature of the Equations Involved:** The equations governing the problem play a crucial role. We distinguish between linear optimization (where linear equations are involved) and nonlinear optimization (where equations are non-linear).

- **Classification Based on the Permissible Values of the Design Variables:** Some problems have specific bounds on the variables. If the variables must lie within certain limits, we encounter bounded optimization.
- **Classification Based on the Deterministic Nature of the Variables**: Deterministic optimization deals with fixed parameters. In contrast, stochastic optimization involves uncertain or probabilistic variables.
- **Classification Based on the Separability of the Functions:** When the objective function and constraints can be separated into simpler components, we have separable optimization.
- **Classification Based on the Number of Objective Functions:** Problems can have one or multiple objectives. If there's only one objective, it's a single-objective optimization. When dealing with multiple conflicting objectives, it becomes multi-objective optimization.

II.4. Optimization techniques

There are two main categories into which optimization techniques can be divided: The exact techniques and Approximate Techniques. [27, 31, 32]

II.4.1. The exact techniques

Exact methods are precise approaches used to solve optimization problems by determining the globally optimal solution without approximations or assumptions. In contrast to empirical techniques relying on heuristics and statistics, exact methods ensure the exact optimal solution.

These methods encompass various techniques categorized based on the nature of the variables involved. For instance, integer programming suits problems with discrete variables, while linear programming addresses those with continuous and discrete variables. However, both entail complex computational requirements and may not be feasible for highly complicated problems.

II.4.2. Approximate Techniques

Approximate techniques, also referred to as heuristic or metaheuristic methods, are employed when the complexity of the problem renders a comprehensive exploration of every possible solution impractical or only partially feasible.

These methods do not guarantee the search for the ideal solution, but they do provide practical and acceptable solutions in a reasonable amount of time. They are frequently based on guided research strategies that use probabilistic approaches, heuristics, or evolutionary algorithms to more effectively explore the space for solutions. These approaches are very helpful in solving difficult problems with a high number of variables or constraints.

II.5. The metaheuristics

Metaheuristics are stochastic optimization algorithms that aim to find an optimal solution that optimizes an objective function. They are designed to tackle complex optimization problems, in different domains by being applicable to both discrete and continuous problems. [33]

These methods share the following characteristics:

- ✓ They are, at least partially, ***stochastic***: This property allows them to handle the combinatorial explosion of possibilities.
- ✓ They do not rely on the often problematic calculation of objective function gradients.
- ✓ They are inspired by analogies with physics (such as simulated annealing, simulated diffusion), biology (such as evolutionary algorithms, tabu search), or ethology (such as ant colonies).
- ✓ They also share the same drawbacks: difficulties in tuning the method's parameters.

II.5.1. Classification of metaheuristics

Metaheuristic algorithms can be classified in several ways based on different criteria. Here are some common classifications [34]:

a). Nature-inspired vs. non-nature-inspired: Metaheuristics can be classified based on their inspiration from natural processes. Nature-inspired metaheuristics encompass algorithms like genetic algorithms, particle swarm optimization, and ant colony optimization. On the other hand, non-nature-inspired metaheuristics comprise algorithms such as simulated annealing and tabu search.

b). Single-solution vs. population-based: In addition, metaheuristics can be classified based on whether they operate on a single solution or a population of solutions. Single-solution metaheuristics consist of algorithms like simulated annealing and hill climbing. On the other hand, population-based metaheuristics encompass algorithms such as genetic algorithms, particle swarm optimization, and ant colony optimization.

c). Deterministic vs. stochastic: Metaheuristics can also be classified based on whether they employ deterministic or stochastic processes. Deterministic metaheuristics utilize deterministic processes to generate new solutions. Examples of such metaheuristics include hill climbing and deterministic annealing. On the other hand, stochastic metaheuristics employ stochastic processes to generate new solutions. Examples of stochastic metaheuristics include genetic algorithms and simulated annealing.

d). Local search-based vs. global search-based: Metaheuristics can be classified based on their emphasis on exploring either the local or global search space. Local search-based metaheuristics prioritize finding solutions within the immediate neighborhood of the current solution. Examples of local search-based metaheuristics include hill climbing and tabu search. On the other hand, global search-based metaheuristics focus on exploring the entire search space to discover optimal or near-optimal solutions. Examples of global search-based metaheuristics include genetic algorithms and ant colony optimization.

II.5.2. Some techniques of metaheuristics

There are many metaheuristic algorithms that have been developed over the years, each with its own strengths and weaknesses. Here are some of the most well-known metaheuristic algorithms, along with a brief description of how they work [35]:

a). Genetic Algorithms (GA): GA is inspired by the principles of natural selection and genetics. It starts by randomly generating an initial population of solutions, and then evolves the population by applying operators such as selection, crossover, and mutation. These operators simulate the process of natural selection, where individuals with higher fitness are more likely to reproduce and pass on their qualities to the next generation. GA has been widely used in optimization problems that involve finding the best combination of parameters or features.

b). Particle Swarm Optimisation (PSO): PSO is an algorithm for swarm intelligence that draws inspiration from the group behaviours of social creatures like fish schools and flocks of birds. A swarm of particles, each of which represents a potential solution to the optimization issue, is first generated at random. Based on its own position and velocity, as well as the best position the swarm has identified thus far, each particle travels in the search space. PSO has been extensively utilized in optimization tasks that entail determining the optimal neural network or other machine learning model weight configuration.

c). Simulated Annealing (SA): SA is a stochastic optimization approach that draws inspiration from the metallurgical annealing procedure. The system's temperature is progressively lowered after it first generates an initial solution at random. The algorithm is more likely to accept inferior solutions as it gets colder in order to break out of local optima. SA is frequently used to solve optimization issues including determining the ideal parameter configuration for complicated models or simulations.

d). The Tabu Search (TS): It is a metaheuristic that draws inspiration from the idea of memory in human decision-making. It generates an initial solution at random first, then uses operators like swapping and reversing to search the area around the solution. In order to remember recently visited solutions and prevent revisiting them, the algorithm makes use of a tabu list. TS has been extensively utilized in scheduling and routing optimization problems, which entail determining the optimal order of operations or decisions.

e). Ant Colony Optimization (ACO): This swarm intelligence method is based on how ants navigate their environment to find the quickest route between their colony and a food supply. The initial set of pheromone trails is created randomly to indicate the quality of the solutions found so far. Ants leave behind or follow pheromone trails based on the quality of the solutions they discover while foraging in the area. ACO is often applied to solve optimization problems involving determining the optimal paths or routes, such as those in transportation or logistics.

These represent a small selection of the numerous metaheuristic algorithms that have been created over time. The features of the optimization issue and the available computational resources determine which approach to choose. Each algorithm has advantages and disadvantages of its own.

II.5.3. Application of metaheuristics

Metaheuristics have been widely applied to various domains and problem types due to their flexibility and ability to find near-optimal solutions. Here are some common applications of metaheuristics [36-38]

Combinatorial Optimization: Metaheuristic algorithms are extensively used for solving combinatorial optimization problems such as the Traveling Salesman Problem (TSP), Vehicle Routing Problem (VRP), Knapsack Problem, and Graph Coloring Problem.

- **Scheduling and Timetabling:** Metaheuristics are employed to optimize scheduling and timetabling problems, including employee scheduling, project scheduling, course timetabling, and production planning.
- **Machine Learning and Data Mining:** Metaheuristic algorithms are utilized in feature selection, parameter tuning, and model optimization for machine learning and data mining tasks. They can enhance the performance of algorithms like neural networks, support vector machines, and decision trees.
- **Image and Signal Processing:** Metaheuristics find applications in image and signal processing tasks such as image reconstruction, image segmentation, denoising, and optimization of filter design.
- **Engineering Design and Optimization:** Metaheuristic techniques are used for engineering design optimization problems, including structural optimization, parameter estimation, and optimal control m
- **Portfolio Optimization:** Metaheuristics are employed to optimize investment portfolios by finding the best allocation of assets to maximize returns while minimizing risk.
- **Energy Optimization:** Metaheuristics assist in optimizing energy systems and resources, such as power generation and distribution, renewable energy integration, and energy-efficient routing in wireless sensor networks.
- **Bioinformatics**: Metaheuristics are applied to bioinformatics problems, including sequence alignment, protein folding, gene expression analysis, and DNA motif discovery.

These are just a few examples of the diverse range of applications where metaheuristics have proven to be effective problem-solving techniques. Their adaptability and ability to handle complex optimization problems make them valuable tools across various domains.

II.6. Manta ray foraging optimization (MRFO)

II.6.1. Inspiration

Manta rays are fascinating marine creatures known for their large size and graceful swimming. They have a flat body, pectoral fins, and cephalic lobes that aid in foraging. Manta rays feed on plankton by funneling water and prey into their mouths using their cephalic lobes and filtering the prey with modified gill rakers. There are two species of manta rays: reef manta rays and giant manta rays. They can reach impressive widths of up to 5.5 meters and 7 meters, respectively. Manta rays have evolved various intelligent foraging strategies, including chain foraging, cyclone foraging, and somersault foraging. These strategies allow them to efficiently gather plankton for sustenance. Researchers have developed a metaheuristic algorithm called Manta Ray Foraging Optimization (MRFO) inspired by these foraging behaviors for global optimization purposes. Manta rays play a vital role in marine ecosystems, although they face threats from fishing activities**.** Figure II.2 shows an example of a manta ray structure.

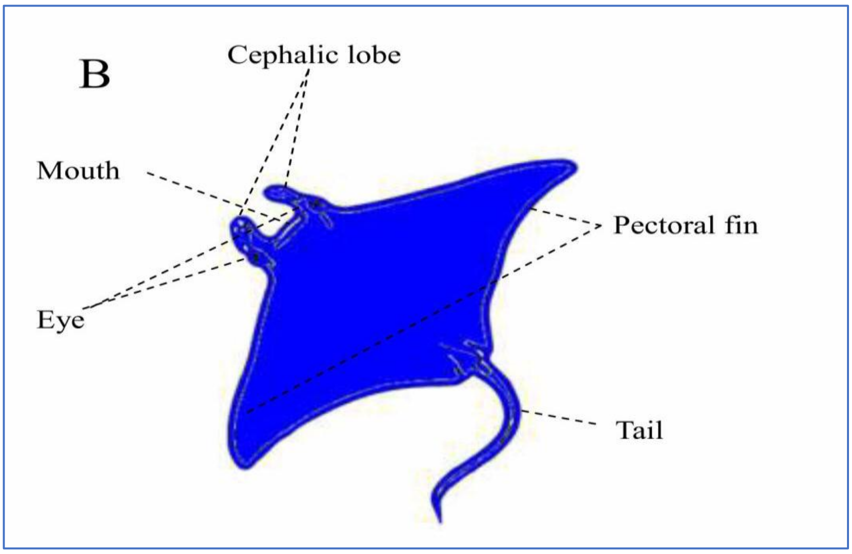


Figure II.1 **: structure of a manta ray**

II.6.2. Mathematical model

MRFO is inspired by three foraging behaviors including chain foraging, cyclone foraging and somersault foraging. The mathematical models are described below [39]:

a). chain foraging

MRFO is an algorithm inspired by manta ray foraging behavior. Individuals move towards positions with high plankton concentration, forming a foraging chain. Each individual updates based on the best solution found so far and the solution in front of it. The algorithm aims to optimize search for an unknown best solution**.**

$$x_i^d(t+1) = \begin{cases} x_i^d(t) + r.\left(x_{best}^d(t) - x_i^d(t)\right) + \alpha.\left(x_{best}^d(t) - x_i^d(t\,)\right) & i = 1 \\ x_i^d(t) + r.\left(x_{i-1}^d(t) - x_i^d(t)\right) + \alpha.\left(x_{best}^d(t) - x_i^d(t)\right) & i = 2, \dots, N \end{cases} . \quad (\text{II.5})$$

$$\alpha = 2.r.\sqrt{/\log(r)/} \quad (\text{II.6})$$

where, $x_i^d(t)$ is the position of i th individual at time t in d th dimension, r is a random vector within the range of [0, 1], α is a weight coefficient, $x_{best}^d(t)$ is the plankton with high concentration.

Figure II.3 depicts this foraging behavior in a 2-D space. The position update of the i th individual is determined by the position $x_{i-1}(t)$ of the (i-1) th current individual and the position $x_{best}(t)$ of the food.

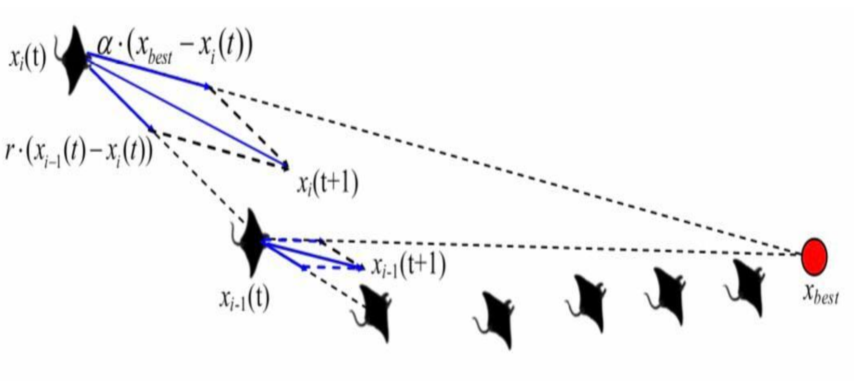


Figure II.2 : **Chain foraging behavior in a 2-D space**

b). Cyclone foraging

Manta rays employ a spiral foraging strategy, similar to the WOA algorithm [39], when they encounter an area of plankton. In cyclone foraging, manta ray swarms form a spiral line and move towards the food while following the individual in front. This behavior can be represented mathematically in a 2-D space using a specific equation.

$$\begin{cases} X_i(t+1) = X_{best} + r.\left(X_{i-1}(t) - X_i(t)\right) + e^{b\omega}.\cos(2\pi\omega).(X_{best} - X_i(t)) \\ Y_i(t+1) = Y_{best} + r.\left(Y_{i-1}(t) - Y_i(t)\right) + e^{b\omega}.\sin(2\pi\omega).(Y_{best} - Y_i\,(t)) \end{cases} \quad (\text{II.7})$$

where w is a random number in [0, 1].

This motion behavior may be extended to a n-D space. For simplicity, this mathematical model of cyclone foraging can be defined as follows:

$$x_i^d(t+1) = \begin{cases} x_{best}^d + r.\left(x_{best}^d(t) - x_i^d(t)\right) + \beta.\left(x_{best}^d(t) - x_i^d(t)\right) & i = 1 \\ x_{best}^d + r.\left(x_{i-1}^d(t) - x_i^d(t)\right) + \beta.\left(x_{best}^d(t) - x_i^d(t)\right) & i = 2, \dots, N \end{cases} \quad (\text{II.8})$$

$$\beta = 2e^{r1\frac{T-t+1}{T}}.\sin(2\pi r_1) \quad (\text{II.9})$$

where β is the weight coefficient, T is the maximum number of iterations, and r_1 is the rand number in [0,1].

N cyclone foraging, individuals perform random searches around the best solution found so far, combining exploitation and exploration. To enhance exploration, individuals are assigned new random positions throughout the search space as their reference positions. This mechanism promotes extensive global search in the MRFO algorithm. The mathematical equation representing this behavior is provided below.

$$x_{rand}^d = Lb^d + r.(Ub - Lb^d) \quad (\text{II.10})$$

$$x_i^d(t+1) = \begin{cases} x_{rand}^d + r.\left(x_{rand}^d - x_i^d(t)\right) + \beta.\left(x_{rand}^d - x_i^d(t)\right) & i = 1 \\ x_{rand}^d + r.\left(x_{i-1}^d(t) - x_i^d(t)\right) + \beta.\left(x_{rand}^d - x_i^d(t)\right) & i = 2, \dots, N \end{cases} \quad (\text{II.11})$$

where x_{rand}^{d} is a random position produced in the search space, $Lb^{d}$and Ub^{d} are the lower and upper limits of the d th dimension, respectively.

c). Somersault foraging

In this behavior, the position of the food is viewed as a pivot. Each individual tends to swim to and from around the pivot and somersault to a new position. Therefore, they always update their positions around the best position found so far. The mathematical model can be created as follows:

$$x_i^d(t+1) = x_i^d(t) + S.\left(r_2.x_{best}^d - r_3.x_i^d(t)\right), i = 1, \ldots, N \qquad (\text{II}.12)$$

where S is the somersault factor that decides the somersault range of manta rays and S = 2, r 2 and r 3 are two random numbers in [0, 1]. Algorithm II.1 outlines the main steps of MRFO algorithm.

Conclusion

In summary, this chapter has investigated into the domain of optimization problems, comprehensively exploring both exact and metaheuristic methodologies. While exact approaches prioritize precision, they often encounter difficulties when confronted with complex problem sets, primarily due to their intensive computational requirements. Conversely, metaheuristic strategies offer a more adaptable and efficient way for addressing such challenges. The chapter has provided a thorough clarification of the fundamental principles of metaheuristic algorithms, their classification, and their wide-ranging applications across diverse fields.

Furthermore, the chapter has introduced the MRFO technique, explaining its inspiration, mathematical model and algorithm.

In the next chapter, we will apply the MRFO technique to develop a novel routing protocol designed for MANET networks

Initialize the size of population N, the maximal number of iterations T and each manta ray

(t) = Lb + rand. (Ub − Lb) for i = 1, … , N and t = 1.

Compute the fitness of each individual $f_i = f(x_i)$, and obtain the best solution found so far x_{best}

/here Ub and Lb are the upper and lower boundaries of problem space, respectively.

WHILE stop criterion is not satisfied do

Algorithm II.1: MRFO Algorithm

FOR i=1 TO N DO

IF rand<0.5 THEN //Cyclone foraging

IF t/ $T_{max} < rand\ THEN$

$x_{rand} = Lb + rand.(Ub - Lb)$

$$x_i(t+1) = \begin{cases} x_{rand} + r.\left(x_{rand} - x_i(t)\right) + \beta.\left(x_{rand} - x_i(t)\right) & i = 1 \\ x_{rand} + r.\left(x_{i-1}(t) - x_i(t)\right) + \beta.\left(x_{rand} - x_i(t)\right) & i = 2, \dots, N \end{cases}$$

ELSE

$$x_i(t+1) = \begin{cases} x_{best} + r.\left(x_{best} - x_i(t)\right) + \beta.\left(x_{best} - x_i(t)\right) & i = 1 \\ x_{best} + r.\left(x_{i-1}(t) - x_i(t)\right) + \beta.\left(x_{best} - x_i(t)\right) & i = 2, \dots, N \end{cases}$$

END IF.

ELSE //Chain foraging

$$x_i(t+1) = \begin{cases} x_i(t) + r.\left(x_{best} - x_i(t)\right) + \alpha.\left(x_{best} - x_i(t)\right) & i = 1 \\ x_i(t) + r.\left(x_{i-1}(t) - x_i(t)\right) + \alpha.\left(x_{best} - x_i(t)\right) & i = 2, \dots, N \end{cases}$$

END IF.

Compute the fitness of each individual $(f\left(x_i(t+1)\right)$.

IF $f\left(x_i(t+1)\right) < f(x_{best})$ **THEN**

x_{best}=$x_i(t+1)$ //Somersault foraging

$x_i(t+1) = x_i(t) + S.(r_2.x_{best} - r_3.x_i(t))$

END IF

Compute the fitness of each individual$f\left(x_i(t+1)\right)$.

IF $f\left(x_i(t+1)\right) < f(x_{best})$ **THEN**

$x_{best} = x_i(t+1)$

END IF

END FOR.

END WHILE.

Return the best solution found so far x_{best}

Chapter III: An Improved Routing Approach for MANETs Using MRFO (MantaNet)

III.1. Introduction

Efficient routing protocols play a critical role in Mobile Ad hoc Networks (MANETs) to ensure reliable communication among nodes. MANETs are self-configuring networks of mobile devices without any centralized infrastructure, making efficient routing essential for establishing and maintaining communication paths. Traditional routing protocols face several challenges in this dynamic environment, including route discovery overhead, network congestion, and dynamic topology management.

The frequent topology changes and limited resources in MANETs result in high route discovery overhead and difficulty in maintaining stable routes. Additionally, network congestion caused by limited bandwidth and multiple nodes competing for resources hinders efficient communication. Moreover, the dynamic nature of MANETs, with nodes joining and leaving the network, presents challenges in managing the changing topology.

To address these challenges, there is a need for adaptive and efficient routing approaches capable of dynamically adapting to the network conditions and effectively managing routes. These advanced routing protocols can optimize communication, reduce overhead, and ensure reliable connectivity in MANETs.

This chapter introduces a novel routing approach for Mobile Ad hoc NETworks (MANETs) utilizing the Manta Ray Foraging Algorithm (MRFO). Various simulations have been conducted using MATLAB to assess the efficacy of this approach.

III.2. Presentation of our MANET network

For simulations, we designed a dynamic network comprising N nodes moving within a zone of dimensions $L \times H$. It is assumed that the sender is denoted as S, while the receiver is denoted as R. The zone under consideration for simulations can vary and may represent diverse environments such as roads, university campuses, or other scenarios.

The following figure illustrates an example of the network model considered in our simulations. It has 10 moving nodes. Their positions are marked by red squares, the blue arrows show the directions of the nodes' movement, and the routing is demonstrated by a black line.

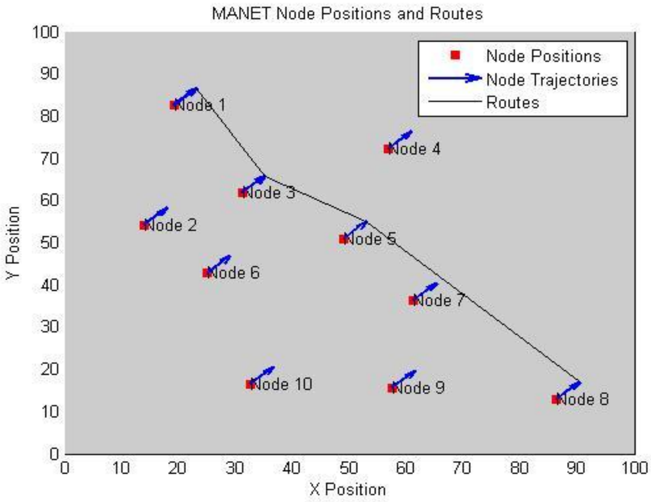


Figure III.1 : **Example of the MANET model used in our simulations.**

Each node is assigned a position NP in the two axes (x, y) within the zone and is capable of moving within this zone over time (t): $\left(NP_{i_x}^{t}, NP_{i_y}^{t}\right)$

Where: $i = 1,2, \dots N$ and $t = 1,2, \dots T$

Nodes positions can be represented in 3D matrix as follows:

$i = 1, \dots, N$

$t = 1, \dots, T$

$$\begin{bmatrix} NP_{1x}^{T} & NP_{2x}^{T} & \dots & NP_{ix}^{T} & \dots & NP_{Nx}^{T} \\ NP_{1y}^{T} & NP_{2y}^{T} & \dots & NP_{iy}^{T} & \dots & NP_{Ny}^{T} \end{bmatrix}$$

$$\begin{bmatrix} NP_{1x}^{t} & NP_{2x}^{t} & \dots & NP_{ix}^{t} & \dots & NP_{Nx}^{t} \\ NP_{1y}^{t} & NP_{2y}^{t} & \dots & NP_{iy}^{t} & \dots & NP_{Ny}^{t} \end{bmatrix}$$

$$\vdots$$

$$\begin{bmatrix} NP_{1x}^{2} & NP_{2x}^{2} & \dots & NP_{ix}^{2} & \dots & NP_{Nx}^{2} \\ NP_{1y}^{2} & NP_{2y}^{2} & \dots & NP_{iy}^{2} & \dots & NP_{Ny}^{2} \end{bmatrix}$$

$$\begin{bmatrix} NP_{1x}^{1} & NP_{2x}^{1} & \dots & NP_{ix}^{1} & \dots & NP_{Nx}^{1} \\ NP_{1y}^{1} & NP_{2y}^{1} & \dots & NP_{iy}^{1} & \dots & NP_{Ny}^{1} \end{bmatrix}$$

Our objective is to find the optimal route that allows data to be transmitted from the transmitter to the receiver with a minimum distance.

Table III.1 : **Parameters used of modeling the MANET**

Parameter	Value
N: Sensor node number	10
L: Length of the zone	100 m
H:Height of the zone	100 m
Rc: Communication range	30 m
T: Duration of mouvement	10 s

III.3. MantaNet: An Adaptive Routing Approach for MANETs Using MRFO

Our proposed routing approach for a Mobile Ad hoc NETwork (MANET), employing the MRFO metaheuristic method, named MantaNet, begins with a random initialization of candidate solutions. These solutions are subsequently evaluated using a fitness function. The updating process of MRFO is then applied to refine the candidate solutions through multiple iterations until a stopping criterion is achieved.

III.3.1 Initialization

The initialized populations can be represented by a matrix $(\mathrm{Ns} \times \mathrm{N} - 2)$, where the number of rows is equal to the number of solutions (Ns), and the number of columns is equal to the number of nodes in the zone minus 2 $(N - 2)$, we exclude the sender and the receiver.

$$P = \begin{bmatrix} p_1 \\ p_2 \\ \vdots \\ p_j \\ p_{Ns} \end{bmatrix} \tag{III.1}$$

Each solution p_j consists of a series of numbers indicating the node numbers traversed from the sender to the receiver.

Example: the following matrix presents an example of P, where the sender is S=1, the receiver is R=8, the number of nodes is N=10, and the number of solutions is Ns=3.

$$P = \begin{bmatrix} 4 & 9 & 3 & 0 & 0 & 0 & 0 & 0 \\ 2 & 5 & 3 & 10 & 6 & 4 & 0 & 0 \\ 10 & 3 & 5 & 4 & 9 & 2 & 7 & 6 \end{bmatrix}$$

The routing is :

- For the 1st solution: 4-9-3 mean: 1-4-9-3-8
- For the 2nd solution: 2-5-3-10-6-4-0-0 mean 1-2-5-3-0-6-4-8
- For the 3rd solution: 10-3-5-4-9-2-7-6 mean: 1-10-3-5-4-9-2-7-6-8

III.3.2 Fitness function

Our optimization problem involves minimizing the distance traversed by the data from sender to receiver. By minimizing the distance, we can also:

✓ ***Reduces energy consumption***: nodes typically rely on battery power for operation. Transmitting data over longer distances requires more energy, as nodes need to amplify their signals to reach farther destinations. By minimizing the distance traveled by data packets, nodes can conserve energy because they transmit data over shorter hops. This reduced transmission distance helps prolong the battery life of individual nodes and enhances the overall energy efficiency of the network.

✓ ***Alleviates overload and congestion:*** Overload and congestion often occur in MANETs when there is a high volume of traffic competing for limited network resources. When data packets traverse shorter distances, it reduces the likelihood of congestion at intermediate nodes or along communication paths. Shorter distances mean fewer hops and less contention for bandwidth and buffer space, thereby reducing the chances of packet collisions, queuing delays, and buffer overflow. Consequently, minimizing distance helps distribute traffic more evenly across the network, mitigating the risk of overload and congestion.

We should note that the nodes within the considered network are only permitted to transmit data to other nodes if the intended receiver falls within their transmission range.

Our objective function can be mathematically formulated as follows:

$$F(p) = F_1 + F_2 + F_3 \quad \text{(III.2)}$$

- F_1 calculates the distance between two successive nodes (k and $k+1$)

$$F_1 = \sum_{t=1}^{T} \sum_{k=1}^{(Ns-2)-1} \sqrt{\left(NP_{p(k)x}^{t} - NP_{p(k+1)x}^{t}\right)^2 + \left(NP_{p(k)y}^{t} - NP_{p(k+1)y}^{t}\right)^2} \quad \text{(III.3)}$$

- F_2 calculates the distance between the sender and the first node.

$$F_2 = \sum_{t=1}^{T} \sqrt{(S_x^t - NP_{P(1)x}^t)^2 + (S_x^t - NP_{p(1)y}^t)^2} \quad \text{(III.4)}$$

- F_3 calculates the distance between the last node and the receiver

$$F_3 = \sum_{t=1}^{T} \sqrt{(NP_{p(end)x}^t - R_x^t)^2 + (NP_{p(end)y}^t - R_y^t)^2} \quad \text{(III.5)}$$

III.3.3. Updating process:

Population is updating using the MRFO processes; chain foraging, cyclone foraging, and somersault foraging.

III.3.4. Parameters used for simulation

Table III 2 Parameters values

Parameter	**Value**
Ns : Population size	20
Iter_max: Maximun number of iterations	100
S : The sender	1
R : The receiver	8

The main flowchart of the proposed approach is shown in Figure III.2

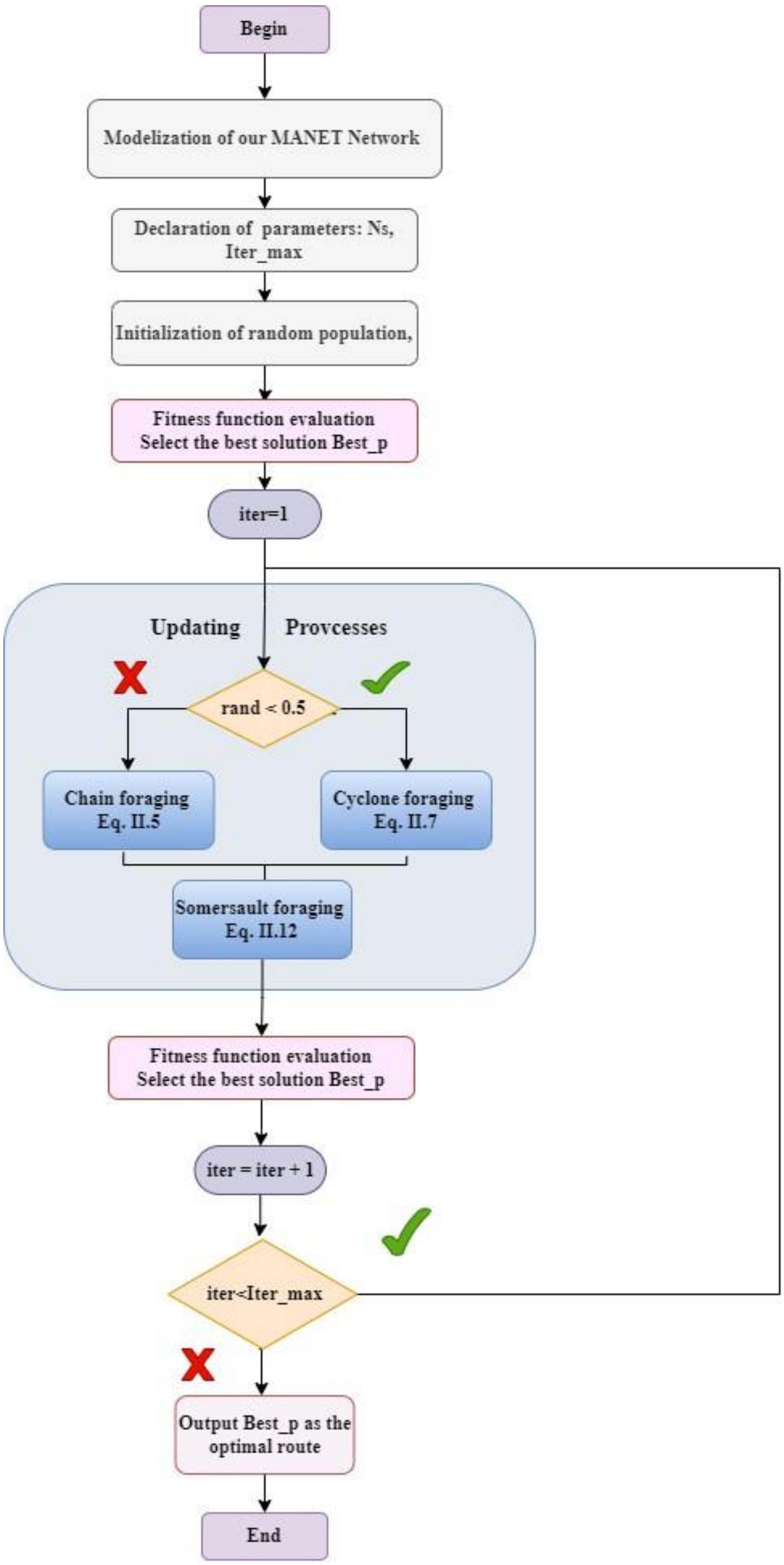


Figure III.2 : **Flowchart of our MantaNet**

III.4. Simulation results

To test the performance of our Manta Net approach, we will conduct several simulations by varying the distance between the sender and receiver, the number of nodes, the number of candidate solutions and the number of iterations. We will display the following figures:

- ***Network***: This figure represents the nodes positions and the optimal route found by MantaNet approach.
- ***Convergence Curve***: This figure plots the values of the objective function F (distance between nodes) over the iterations, with the goal of minimizing it.

III.4.1. Simulation 1

In simulation 1, we evaluated the algorithm with different distance between the sender and receiver nodes: short, medium and long. The objective is to verify the method's ability to find the optimal route even with long distances between the sender and receiver.

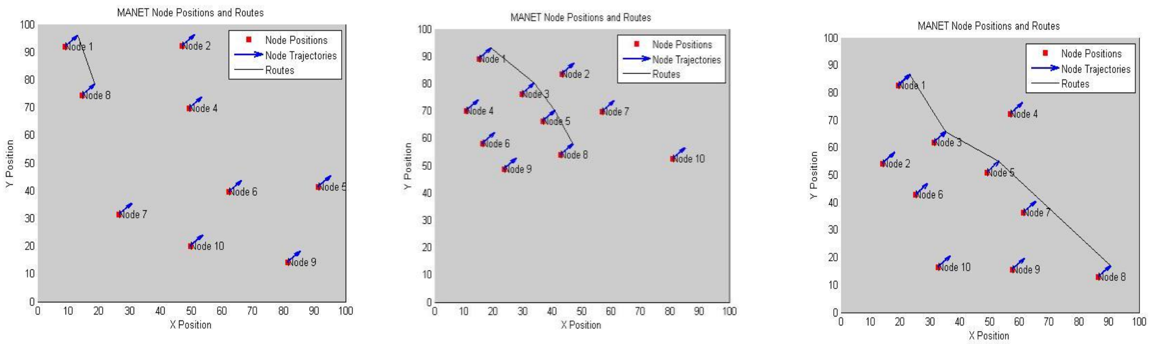


Figure III.3 : **Network with different distance between S and R**

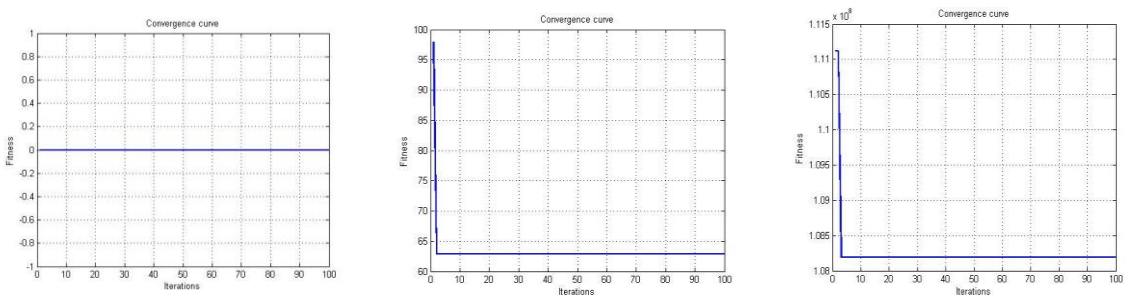


Figure III.4 **: Convergence curves with different distance between S and R**

Discussion 1:

Results illustrated in figures III.3 and III.4, indicate that:

- **Short Distance:** When the receiver node is within the communication range of the sender node, the need for optimization is minimal. The fitness value stabilizes quickly, indicating that the optimal route is inherently straightforward due to the proximity of the nodes.
- **Medium Distance:** For medium distances, where the receiver node is outside the sender node's direct communication range, the routing algorithm becomes crucial. The MRFO technique effectively identifies the shortest path, demonstrating the algorithm's ability to navigate through intermediate nodes efficiently.
  The convergence curve shows that while the algorithm initially explores various routes, it successfully converges to the optimal route with the shortest distance, as illustrated by the traversal through nodes 3 and 5 to reach node 8.
- **Long Distance:** At longer distances, the algorithm's efficacy remains robust, although it necessitates a higher number of iterations to find the optimal route. This is due to the increased complexity and number of potential paths. The algorithm’s ability to converge to an optimal route, even with longer distances, underscores its reliability and robustness in complex network topologies, as seen in the traversal through nodes 3, 5, and 7 before reaching node 8.

Conclusion 1 :

The proposed MantaNet routing method demonstrates a strong capability to adapt to different network distances. It consistently finds the optimal or near-optimal routes, ensuring efficient data transmission regardless of the initial sender-receiver distance. This adaptability is crucial for dynamic and large-scale networks where node distances frequently vary.

The convergence patterns observed in the simulations highlight the algorithm’s exploratory nature. Initially, it evaluates multiple potential routes with higher fitness values (longer distances or less optimal paths) before progressively honing in on the most efficient route. This behavior ensures comprehensive route evaluation and optimizes overall network performance by consistently identifying the shortest and most effective paths.

III.4.2. Simulation 2

In simulation 2, we evaluated the algorithm with different number of nodes; 10, 20 and 30. To ensure that the routing algorithm can efficiently determine the shortest route for data transmission from the sender to the receiver, even in networks with a high number of nodes.

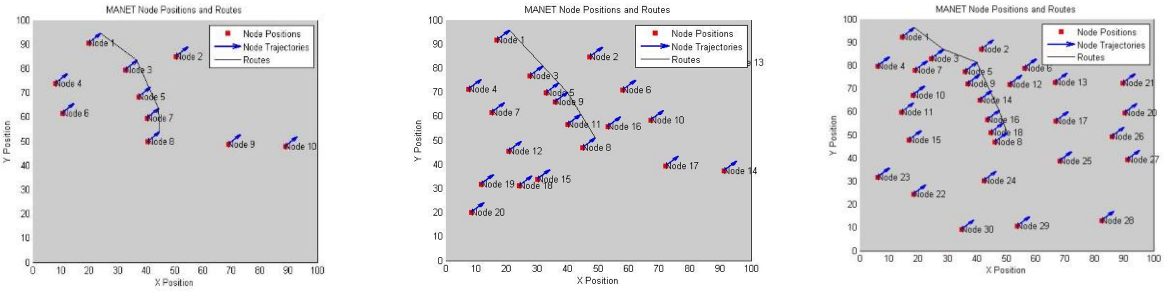


Figure III.5 : **Network with different number of nodes**

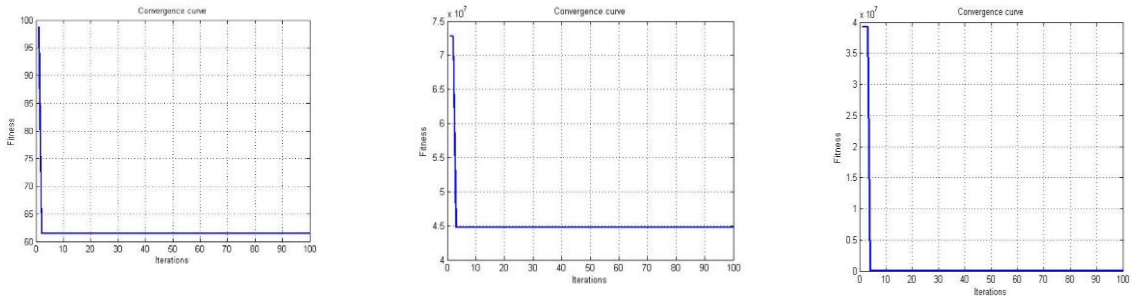


Figure III.6 : **Convergence curves with different number of nodes**

Discussion 2 :

Results illustrated in figures III.5 and III.6, indicate that:

- F**or N=10:** When the network consists of 10 nodes, the proposed algorithm effectively finds the shortest path, with data traversing through nodes 3, 5, and 7 before reaching node 8. This demonstrates the algorithm's capability to determine the optimal route even in small-scale networks.
- **For N=20:** In a network with 20 nodes, the routing technique efficiently identifies the shortest path, with data passing through nodes 3, 5, 9, and 11 before reaching node 8. This highlights the algorithm's effectiveness in managing increased network complexity and ensuring efficient data transmission.
- **For N=30:** As the number of nodes increases to 30, the complexity of finding the optimal route grows. The algorithm handles this complexity well, although the data

may traverse more intermediate nodes, such as 3, 5, 9, 14, 16, and 18, before reaching node 8. This underscores the robustness of the MantaNet-based routing method in large-scale networks, maintaining its ability to find efficient routes despite the increased number of potential paths.

Conclusion 2

- The proposed routing method demonstrates robust performance across different network sizes. It consistently identifies the optimal or near-optimal routes, ensuring efficient data transmission regardless of the number of nodes in the network. This adaptability is crucial for dynamic and scalable network environments where node density can vary significantly.

- The convergence patterns observed in the simulations highlight the algorithm’s efficiency. In smaller networks, the algorithm quickly stabilizes to the shortest path. As network size increases, the algorithm explores more potential routes but still converges to an optimal solution within a reasonable number of iterations. This behavior ensures comprehensive route evaluation and optimizes overall network performance.

III.4.3. Simulation 3

In simulation 3, we evaluated the algorithm with different number of candidate solutions: 20, 50 and 100. The objective of this simulation is to test if the performance of the method improves with the increase in the number of candidate solutions.

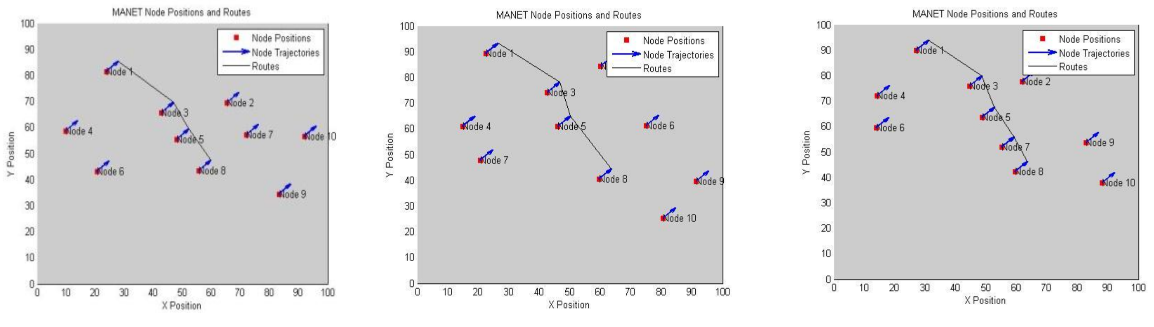


Figure III.7 : **Network with different number of candidate solutions**

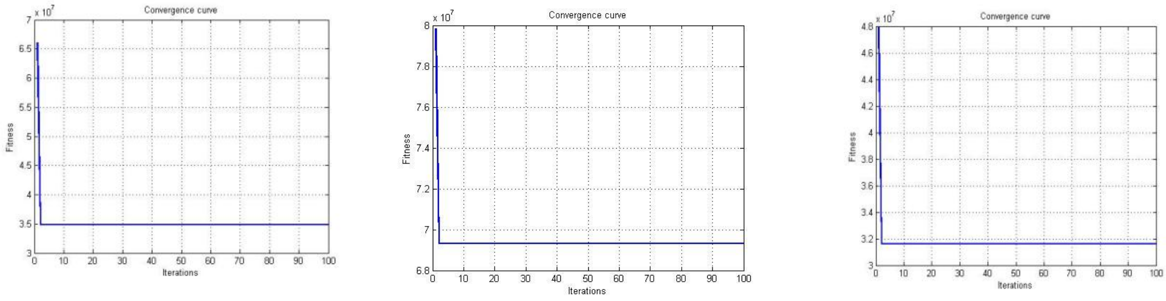


Figure III.8 : **Convergence curves with different number of candidate solutions**

Discussion 3:

Results illustrated in figures III.7 and III.8, indicate that:

The MantaNet-based routing algorithm consistently finds the optimal route with the minimum distance from the transmitter to the receiver across all tested scenarios. This demonstrates the algorithm's effectiveness in determining the shortest path regardless of the number of candidate solutions.

The convergence curves indicate that the algorithm reaches the minimum fitness value more quickly when initialized with a larger number of candidate solutions. Specifically, with 100 candidate solutions, the algorithm identifies the best route from the initial iterations. This suggests that increasing the number of candidate solutions enhances the algorithm's efficiency in finding the optimal solution faster.

Conclusion 3:

The algorithm maintains robust performance across different numbers of candidate solutions. It consistently identifies the optimal route, demonstrating its ability to find optimal routes even with a small number of candidate solutions, thereby decreasing computational time. The algorithm's performance can be enhanced by increasing the number of candidate solutions.

III.4.4. Simulation 4

In simulation 4, we evaluated the algorithm with different values for the maximum number of iterations: 100, 150, and 200. The objective of this simulation is to test if the performance of the method improves with an increase in the number of maximum iterations.

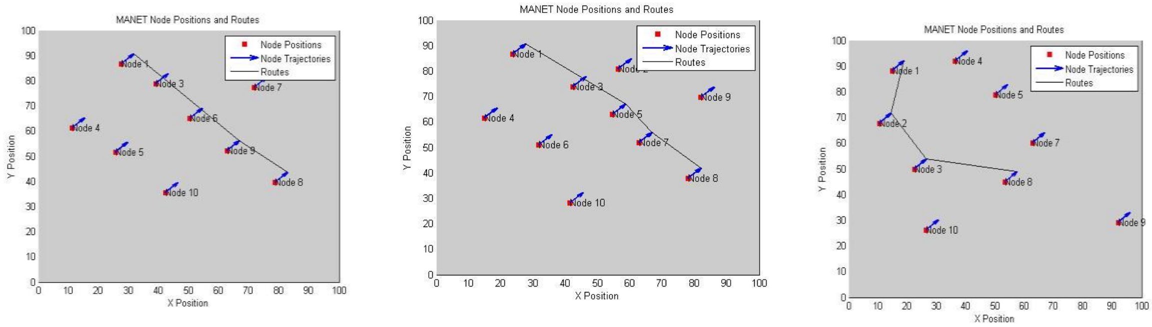


Figure III.9 : **Network with different number of maximum iterations**

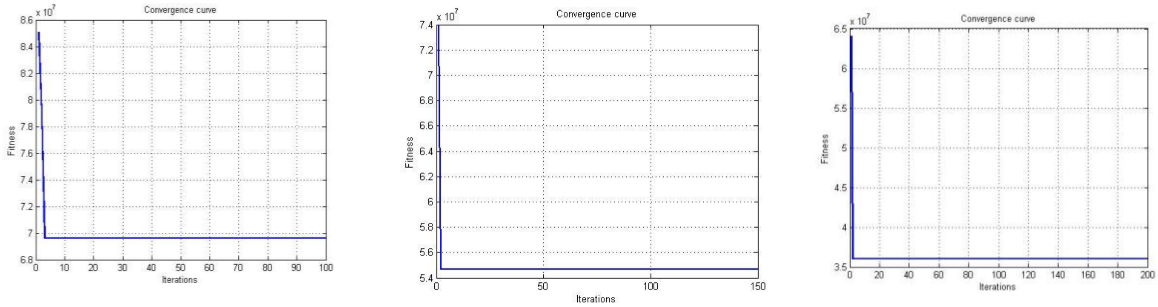


Figure III.10 **: Network with different number of maximum iterations**

Discussion 4:

Results illustrated in figures III.9 and III.10, indicate that:

- The MantaNet-based routing algorithm consistently identifies the optimal route with the shortest distance from the transmitter to the receiver across all tested scenarios. This demonstrates the algorithm's effectiveness in determining the shortest path.
- The convergence curves indicate that the algorithm stabilizes quickly from the initial iterations. This suggests that the algorithm is efficient and does not require a large number of iterations to find the optimal solution.

Conclusion 4 :

Increasing the maximum number of iterations does not significantly improve the performance of the algorithm since the optimal route is found within the initial iterations. This implies that the algorithm is highly efficient and effective even with fewer iterations, minimizing computational time while maintaining optimal performance.

III.4.4. General discussion

In summary, the proposed MRFO metaheuristic-based routing method proves to be effective across varying sender-receiver distances, maintaining optimal routing performance through its adaptive and robust convergence capabilities.

Our metaheuristic-based routing method is also effective across varying network sizes, maintaining optimal routing performance through its adaptive and robust convergence capabilities.

Additionally, it is highly effective and efficient across varying numbers of candidate solutions. The algorithm consistently identifies the shortest route for data transmission from the sender to the receiver, with faster convergence when initialized with a larger number of candidate solutions.

Furthermore, the algorithm quickly converges to the optimal solution within minimal iterations, indicating that increasing the maximum number of iterations does not notably enhance performance.

Conclusion

This chapter presents an enhanced routing protocol for MANET using the MRFO metaheuristic technique. The objective function taken into account is minimizing the distance between the sender and receiver passing through different nodes. Several simulations are carried out to evaluate the performance of the method.

According to the results obtained, our method is capable to find the optimal route and ensure reliable and efficient data transmission in diverse network scenarios, ranging from small to large scales, with reduced computational complexity.

General conclusion

In this master's dissertation, we studied the improvement of routing protocols using the MRFO (Manta Ray Foraging Optimization) technique. This optimization problem relies on the positions of the sender and receiver and the shortest path to deliver the information. For this reason, we initially studied MANET and its characteristics. Then, we presented the principle of the optimization technique used and finally, we presented our simulations.

We utilized the MRFO (Manta Ray Foraging Optimization) technique in our simulations to find the optimal and closest path. The iterative process started with random routes, gradually converging towards an optimal solution in general. To test our approach, several simulations were carried out on MATLAB, varying the distance between sender and receiver, increasing the number of nodes, candidate solutions, and iterations.

As a result, we can observe that the proposed routing algorithm (MantaNet) consistently identifies optimal or near-optimal routes across various network sizes. It quickly adapts to different network scales, evaluating and optimizing routes comprehensively. Additionally, the algorithm maintains strong performance even with a small number of candidate solutions and iterations, thereby reducing computational time. Overall, the MantaNet routing method offers a promising solution for efficient data transmission in networks.

From the results obtained, it can be concluded that MRFO has been successfully applied in the field of telecommunications, particularly in MANET routing protocols. The considered objective, the shortest path between sender and receiver, was effectively optimized in the proposed scenarios. This proves the efficiency and robustness of our MantaNet approach.

The perspectives of our work are:

- We propose the use of other metaheuristic techniques.
- Taking into account other constraints in the network.
- Additionally, the use of MRFO in other applications in the telecommunications field.

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