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Cross-Layer Design For Mobile Ad-Hoc Unmanned Aerial Vehicle Communication Networks

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CROSS-LAYER DESIGN FOR MOBILE AD-HOC UNMANNED AERIAL VEHICLE COMMUNICATION NETWORKS

by

Abdel Ilah Nour Alshbatat

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Abdel Ilah Nour Alshbatat, Ph.D.

Western Michigan University, 2010

Mobile Ad-Hoc network (MANET) is a popular type of wireless network that is formed by a collection of mobile nodes. Each node in such a network has the capability to communicate with its neighbors and non-neighbors through a wireless medium without using any existing network infrastructure. Due to the lack of infrastructure, all nodes in Ad-Hoc network are designed to act as an end system and a router for other nodes.

Traditionally, the dominant design methodology for network protocols was based on the open systems interconnection (OSI) reference model. This methodology divided the stack into seven layers in which each layer operates independently. Due to the dynamics of the Unmanned Aerial Vehicle (UAV) Ad-Hoc network, the conventional protocol stack is not sufficiently flexible to achieve certain quality of services (QoS) required by some applications. To overcome the limitations of the layering technique, cross-layering approach was implemented in this dissertation to adjust some key parameters in the first three layers of the OSI model based on the aircraft attitude variations (pitch, roll and yaw) and the variation of wireless links.

To that respect, directional antennas were used by the UAVs to extend the coverage area and reduce the number of hops between the source and destination. Meanwhile, since the traditional Medium Access Control (MAC) protocol assumed the use of Omni-directional antennas, we designed a new MAC scheme that adapts its parameters based on the channel Bit-Error-Rate (BER) which is affected by the new antenna system and aircraft attitude. As for the routing protocol, we modified the Optimized Link State Routing (OLSR) protocol in such a way that the decision for selecting the route will be based on a local profile that holds the gathered information from the first three layers.

UAV Ad-Hoc network was implemented by using a discrete event simulator called Optimized Network Engineering Tool (OPNET). We investigated the performance of the proposed techniques and compared them with the existing schemes. The simulation results showed that the proposed techniques improved the network performance and gave results better than the existing protocols in terms of throughput and End-to-End delay.

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CHAPTER I

INTRODUCTION

Recently, there has been an increasing interest in employing Unmanned Aerial Vehicles (UAV) in wireless communication networks, especially in Mobile Ad-Hoc Networks (MANET). UAVs have been primarily used for military applications. They have proven themselves in different applications, mainly in real-time surveillance and reconnaissance operations. The popularity of the unmanned aerial vehicle has been increasing dramatically with the advent of low-cost Commercial Off-The-Shelf (COTS) wireless equipment. By embedding this equipment in the UAV platform, UAVs can form a multi-hop cost-effective wireless communication network in the air.

There are several parameters that may have significant impact on the performance of the MANET system. Since MANET nodes generally have a limited power (in terms of milliwatts), the communication range is not large enough to cover those nodes that are fare away from the source node. Thus the need for multi-hop routes is essential if the target node is not directly reachable. Multi-hop routing has the capability to do so but adds more delay to the whole process. The problem may get complicated as soon as the UAV which implements the directional antenna gets involved in and be considered as the main node in the wireless network. New protocols for UAV MANET are frequently proposed, meanwhile, cross-layer design, which allows nonadjacent layers to share their information, has become very popular. Keeping these considerations in mind, Cross layer technique will be used in this dissertation for the goal of enhancing the network performance.

1.1 Unmanned Aerial Vehicle

Unmanned Aerial Vehicle (UAV) is defined as an aerial vehicle that does not carry a human crew, is powered by a jet or reciprocating engine, and can be piloted remotely or flown autonomously based on pre-programmed flight plans. Historically, UAVs have been primarily used for military applications. They have proven their use in different operations, mainly in real-time surveillance and reconnaissance operations [47, 48, 49]. Recently, UAV applications have been expanded to perform a wide variety of functions such as electronic attack, MANET node and hazardous site inspection. Moreover, UAVs are used nowadays in commercial applications, such as traffic monitoring and power line inspection.

Currently, there is a wide variety of acronyms that is associated with UAVs. Most of them are related to the functions performed by UAVs [50]. For example, the term Aerosonde refers to UAV whose primary role is to collect weather data (30 pounds, 9 foot wingspan aircraft). Another example is the Predator. Predator UAVs are used mainly by military, and are armed with missiles and used for hitting ground targets. Another acronym which is related to small UAVs is called Miniature or Micro UAVs (MAV). MAVs have the advantages of light weight and small size; they typically have less than 6 foot wingspan and weight less than 10 pounds, flying at low altitudes and using methanol as fuel. For example, the handheld UAV has a range of 2 km and has the capability to reach a low altitude of 600 m.

In general, Military UAVs are classified into three main categories: tactical, medium altitude and high altitude UAVs. Tactical UAV is small and inexpensive ($100,000), its Range is 160 km and it has the capability to reach altitude of 5000 ft. A medium altitude UAV costs around $1,000,000, its range is 200 km and it reaches altitude of 20,000 ft. On the other hand, high altitude UAV costs around $10,000,000 and it has the capability to reach distances higher than the medium UAV (>30,000 ft) [55].

Recently, the characteristics of the handheld low-altitude UAVs, for instance the Black Widow is a 6 inch wingspan aircraft, weighs 80 grams and it uses an electric motor, make them an attractive choice for communication application. Their small size, which simplifies the take-off and retrieval, presents many advantages in developing a fully functional Autonomous UAV. Autonomy, which is defined as self-decisions making, should be implemented by UAV's guidance system so that the vehicle is capable of moving from one location to another. Implementation of fully decentralized architectures in a UAV may provide higher level of cooperation in mobile Ad-Hoc networks and thus makes them equivalent to low altitude satellites. On the other hand, wireless links created by a UAV may experience rapid change in link conditions and thus result in poor quality of the communication channel.

A network of low-altitude UAVs is usually complex than the other types of wireless networks [51]. Wireless link created by a UAV may gain an alteration in link quality over time due to number of factors such as: Doppler effects, changes in communication distance, and blocking of line-of-sight by the aircraft body. Moreover, physical constraints imposed by low-altitude UAVs such as: size, weight and battery are other factors that may assist in the quality of wireless links. These factors degrade the network performance and thus they should be taken into consideration while developing UAV networking protocols. A key solution to the success of these protocols is their ability in adapting the UAV's constraints.

1.2 UAV Mobile Ad-Hoc Network

A Mobile Ad-Hoc Network (MANET) is a popular type of wireless network that is formed by a collection of self-organizing mobile nodes. Each node in such network has the capability to communicate with its neighbors over a shared wireless medium without using any existing network infrastructure. Due to the lack of central management, nodes in mobile Ad-Hoc network are designed to act as an end system and a router for other nodes.

MANET is created dynamically and does not rely on any pre-existing architecture. In MANET, Nodes are free to move independently and have the capability to deliver messages in a decentralized environment. One of the major challenges in mobile Ad-Hoc networks is how to route the packets over a network that changes its structure dynamically due to member mobility, especially when both the source and the destination are out of transmission range [52]. A new type of wireless network is raised in the sky: UAV Ad-Hoc networks which are used for communication among swarms of UAVs.

UAV Ad-Hoc Communication Network is another type of wireless network in which a collection of autonomous UAVs dynamically form a temporary multihop radio network without the aid of any centralized station. This new concept of networking enables UAVs to be equipped with a wireless transmitter and receiver for the purpose of data transmission [53]. Although this new approach of networking offers many advantages to wireless communications, it has brought many challenges. One of the greatest challenges to use UAV as a node in MANET is the effect of aircraft attitude on the wireless link quality.

In UAV MANET communication environments, due to the mobility of nodes, network topology may change rapidly and unpredictably. As a result, nodes are expected to act cooperatively in a friendly manner to establish network topology and to route data packets over multiple hops for long distances [54]. Such environments may introduce a new challenge to the use of miniature UAVs where the size is so small (light weight) when compared with the size of communication equipment required to transmit data over large distances. One of the key solutions to these challenges is the use of high gain directional antennas. Meanwhile, there is a need to develop efficient distributed algorithms to cope with the aircraft dynamics.

1.3 Cross-Layer Design

Recently, it has become clear that a traditional layering approach is not efficient for mobile Ad-Hoc wireless networks [15]. The inefficiency of this approach is clear; it cannot provide the communication services required by certain applications in an efficient manner and does not consider adaptations. For example, multimedia applications, which are sensitive to changes in networking conditions, require some changing in protocol's behavior to guarantee QoS such as end-to-end delay. Cross-layer design may satisfy this and yield significant improvement to the network performance by utilizing the valuable information shared among layers. This approach has increasingly attracted the attention of researchers and various structures have been suggested to deal with specific network conditions. It should be noted that cross-layering technique is not an alternative method to the original layering approach but it can be seen as an enhancement method.

Cross layer design is a promising approach in mobile Ad-Hoc networks and it is considered as one of the effective methods to enhance the performance of a wireless network by jointly designing multiple protocols. In contrast to layered architecture technique, cross-layering allows communication between non-neighboring layers as well as reading and controlling parameters of one layer from other layers [16, 17, 18, 19]. Cross-layering technique also allows parameters to be passed to the adjacent layers to assist them in determining the operation modes that will suit some requirements imposed by the nodes. In addition, it adapts the changes in wireless links. For example, the physical layer can adapt data rate, power and coding to meet application requirements and thus makes future networks work in an optimal way.

Today, there are many proposals for cross-layering design. Some of them focused on which layers should be coupled while others focused on how the layers are coupled. Those who focused on layers mainly coupled the physical and MAC layers. On the other hand, different method was presented to couple these layers. Creation of new interface between layers may help in information sharing. Meanwhile, the new interfaces are used to set parameters on the lower layer of the stack at runtime. Other methods involve coupling two or more layers at design time without creating any new interfaces between layers. Adjacent layers can also be merged to form a new layer that is capable of adapting the link variations or performing a new task that assists in performance enhancement.

Cross-layer design for improving the network performance has mainly focused on maximizing the lifetime of energy-constrained networks, in which nodes are typically powered by small batteries, and of delay-critical applications, such as real-time video, given certain network throughput requirements and delay constraints. In that respect, cross-layering technique is considered as a manager that coordinates layer parameters in which the knowledge of the wireless medium characteristics are shared among the associated layers.

1.4 Motivation and Objectives

Recently, there is a significant commercial and military interest in developing a communication system that enables UAVs to communicate directly at high distance. One of the key solutions to this problem would be the use of directional antenna; directional antenna can indeed decrease the number of hops, increase throughput and transmission coverage. On the other hand, the use of directional antenna in a UAV, under harsh conditions, is a great challenge in terms of wireless link stability. This requires a complete study of all conditions that will affect weak links and development of a new mechanism for establishing and enhancing these links.

The high mobility as well as the physical constraints which are imposed by a UAV may cause some degradation to the link performance. In addition, the three critical flight dynamics parameters known as pitch, roll and yaw may also cause the same degradation and have large implications on the network. Thus an effective MAC protocol should be designed to control the channel access and at the same time have the capability to sense any changes in aircraft attitude and automatically adjust the antenna system to maintain the best signal strength.

Variation of wireless links as a result of using UAVs that equipped with directional antenna may create several problems for network protocols that are implementing the framework of the layered architectures. In that respect, to integrate the directional antenna successfully into UAV Ad-Hoc networks and to realize its benefits within the MAC and network layers, Cross-layer technique is implemented in this dissertation so that the first three layers can inter-communicate the useful information and thus the transmission parameters are dynamically adjusted according to the variations in the channel quality. Cross-layer design allows the researcher to make better use of network resources and yields significantly improved performance.

The whole system is aimed to design an Ad-Hoc network of multiple UAVs that operate collectively and cover a wide area to support delay-critical applications. In addition, achieving the following sub-objectives:

1. Implementing the principle of cross-layer design so to solve the network issues imposed as a result of using unmanned aerial vehicle in the Ad-Hoc networks.
2. Design a new MAC scheme that has the capability to respond to the changes of the aircraft attitude by adapting system parameters and network services.
3. Modifying the Optimized Link State Routing (OLSR) protocol so to best benefit the UAV while using the directional antenna.

1.5 Contributions

My dissertation presents three main contributions. All are within the area of the first three layers of the OSI model. First, using directional antenna as part of the physical layer in the node that gained no mobility is not a challenging task, the most important challenge in using directional antenna for unmanned aerial vehicle Ad-Hoc networks is to design an antenna system that is capable of compensating for pitch, roll and yaw movements of the UAV by passing this information to the data link layer so that the beam will be formed opposite to the rotations of the UAV to maintain the antenna pattern in the desired direction. This process required a new mechanism that can adapt to the wide variety of conditions presented during the movement of the UAV. We presented this mechanism in our dissertation and we showed how it was compatible with the movement of the UAV and how it utilized the principle of cross-layering technique to achieve the optimal network performance.

Second, the location of the UAV is significant in Ad-Hoc networks; we developed a mechanism that is able to maintain the location of the UAVs and make it available as soon as other UAV require it. This was achieved by two methods; if there is some activity, the location will be embedded within the transmitted frames, otherwise a heartbeat message will be sent out to other nodes. In addition, IEEE 802.11 allows the node to retry the transmission seven times; this will add more delay to the network. To overcome this problem and to benefit the directional antenna we modified the MAC layer in such a way that it is capable of reducing the time as a result of the unsuccessful transmissions.

The last contribution is the routing protocol. Many protocols were designed for the Ad-Hoc networks; each one tries to solve certain issues regarding this type of network. In our dissertation, we modified the OLSR protocol and compared it with other protocols using directional antenna. OLSR protocol used a multipoint relay (MPR) to reduce the overhead packets. MPR is a node chosen by another node that is willing to transmit its data. This node is used to forward packets and flood the control messages. In addition, it's a one hop node and it is chosen so that it covers other two hop nodes. In this respect, we proposed a new mechanism that leads to the reduction in MPR numbers and thus reduces the overall end-to-end delay.

In that respect, we developed a new mechanism that is compliant with the concept of cross layer design; a global profile is constructed as a pipe through all of the layers (physical, MAC and network layers). This profile is used to hold the overall information gathered from the previous layers and from other UAVs. For example, bit error rate, retry counter (R), aircraft attitude, and antenna type in use will be available through the inter-communication between layers. Other information such as aircraft locations and multipoint relay will be available through the communication between UAVs.

1.6 Dissertation Layout

The rest of this dissertation is organized as follows: In chapter 2, we provide an overview of the research related to our dissertation and we classify them into four categories: MAC protocols using directional antennas, Unmanned Aerial Vehicle, cross-layer design and finally mobile Ad-Hoc routing protocols. Chapter 3 provides an overview of networking models, characteristics of mobile ad-hoc UAV communication networks and highlights cross-layering architectures along with the proposed system design for mobile Ad-Hoc UAV. Chapter 4 highlights our adaptive medium access control scheme for mobile Ad-Hoc UAV using directional antenna; provides an overview for the medium access control, physical layer and the modification of their protocols in cross-layer system; finally explains the proposed channel model, UAV mobility model, network model; and provides simulation results in OPNET 14.5. Chapter 5 describes our new Directional Optimized Link State Routing (DOLSR) protocol. Performance evaluation and comparison between OLSR and AODV were studied using OPNET Modeler14.5. Another comparison was conducted between OLSR and DOLSR using the same simulator. Meanwhile, we provide an overview for the Ad-Hoc routing protocols. Finally, in Chapter 6, we give our conclusion and discuss future work.

CHAPTER II

PERTINENT LITERATURE

This chapter provides an overview of the research that has been done so far for the four major components in our dissertation: MAC protocols using directional antennas, using Unmanned Aerial Vehicles (UAVs) as a node in MANET, cross-layer design and mobile Ad-Hoc routing protocols. We reviewed the related work for each field and examined how cross-layering approach has changed the OSI model so that it is capable of adapting its parameters to the varying link between the source and the destination.

2.1 MAC Protocols Using Directional Antennas

Recently, different MAC schemes have been proposed for MANET that is equipped with directional antenna. In general, most papers that discussed the directional antenna are focused on the modification of the medium access control protocols [28, 29, 30, 31}. Some researchers have suggested the use of switched beam antenna while others suggested the use of adaptive antenna. Nasipuri, et al. [56] proposed a directional MAC protocol that utilizes switched beam antenna. They showed that by using four directional antennas, the average throughput of the network could be improved up to 3 times over that of using Omni-directional antenna. They assumed that the gain of the directional antenna is equal to the gain of an Omni-directional antenna. In their mechanism, the transmissions and receptions involve Omni-directional antenna. The complete cycle starts by sending RTS packet using Omni-directional antenna. Receiver will respond with a CTS packet also using Omni-directional antenna. As soon as the transmitter receives the

CTS packet, it estimates the angle of arrival (AoA) of this packet and transmits data using directional antenna.

In [7], the authors assumed, as [56] did, that the directional gain equals the omni-directional gain and proposed two schemes: In the first scheme, Request-To-Send (RTS), acknowledgment (ACK) and data packets are sent directionally while Clear-To-Send (CTS) packet is sent Omni-directionally. Other nodes that hear the CTS should block the antenna on which it was received. In the second scheme, they proposed two types of RTS , Directional Request-To-Send (DRTS) and Omni-directional Request-To-Send (ORTS) based on the following rule: A) If none of the directional antennas of the node are blocked the node will send ORTS. B) Otherwise, the node will send a DRTS provided that the desired directional antenna is not blocked. The CTS, Data and ACK packets are the same as before. This assumption is simpler than that presented in [56] in which the node may transmit in directions that do not interfere with the ongoing transmissions.

Other researchers [57, 58, 59] studied the performance of MAC protocols with adaptive array antennas. Bao, et al. [59] developed a distributed Receiver-Oriented Multiple Access (ROMA) protocol for Ad-Hoc networks in which all nodes are equipped with a multi-beam adaptive array antenna. ROMA is capable of forming multiple beams and creating several simultaneous communication sessions. Another scheme was developed by the authors, neighbor-tracking, which is used to schedule transmissions by each node in a distributed way.

A caching mechanism is a new technique which was proposed to facilitate the operation of the MAC protocol for a node that is equipped with directional antenna [6]. The authors in [6], Takai, Martin and Ren present a new carrier sensing mechanism that is called DVCS (Directional Virtual Carrier Sensing). This mechanism needs information about AOA (Angle of Arrival) for each signal from the physical layer. They have proposed the use of a caching mechanism to store information about angular location of neighboring nodes. Whenever the MAC layer receives a packet from the upper layer, it will look in the cache to determine whether it has the information about the angular position of the destination node or not. If the angular position of the destination node is known, the packet is transmitted using the directional antenna, otherwise it will be sent using Omni-directional antenna.

The authors in [27] design another MAC protocol which uses multi hop RTSs to establish links between distant nodes; they call their protocol MMAC. In MMAC when any node receives RTS, it transmits CTS, DATA and ACK over a single hop. [27] and [6] have suggested the use of Directional Network Allocation Vector (DNAV). DNAV is similar to the NAV that is used in standard IEEE 802.11 except that the DNAV stores the angle of arrival of the RTS packets in any given direction. For each packet to be transmitted, the DNAV is consulted to see whether the angle of the packet to be transmitted is overlapped with any ongoing transmissions. If there are overlaps, the packet transmission is deferred; otherwise, the packet is transmitted.

In [4], the authors proposed a new scheme called Utilizing Directional Antennas for Ad-Hoc network (UDAAN). Their scheme involves new mechanisms such as neighbor discovery with beam forming, proactive routing and link characterization. They have shown in their research that employing directional antennas improves system performance.

Orientation handoff is another name for the mechanism that is created while integrating directional antenna with MAC protocol. This technique was invented to describe the process of switching from Omni-directional transmission to directional transmission. In [3], the authors proposed a novel preventive link maintenance scheme based on directional antennas. They aimed to extend the life of the link that is about to break. A warning is generated within a node when the received power is reduced below a certain threshold. A node then switches to the process of creating a directional antenna pattern to raise the received power so that the link will not break.

Although directional antennas offer many benefits to MANET, they also present new problems. In [5], the author proposed a new mechanism to solve different problems using directional antenna, for instance, hidden terminal problem and exposed terminal problem. All these problems are solved by building a MAC timing structure. In [25], the authors analyzed the performance of a wireless network using directional antenna based on a different coding scheme. In addition, they analyzed the effect of direction estimation error on the network performance. They derived the cumulative distribution function of the signal-to-interference-and-noise ratio (SINR) for a certain link and then they analyzed the outage probability of that link.

Locating and tracking nodes under mobility is a challenge in Ad-Hoc network. In most of the previous work, the authors assumed that the transmitter knows the receiver's location. This assumption may not be true due to the fact that offering nodes' positions may increase the overhead packets, thus the MAC protocol should offer a mechanism to locate and track node neighbors. Korakis et al [60] proposed the use of a circular RTS (CRTS) message to solve this problem. In their protocol, RTS/CTS packets are transmitted on every beam. By doing so, they achieve a higher range but at the cost of high control overhead.

In [41], the authors proposed a polling based MAC protocol that addresses the problem of neighbor discovery in the use of directional antennas. The proposed MAC protocol is based on the polling strategy wherein a node polls its neighbors periodically. Time is segmented into consecutive frames and nodes are synchronized with each other. By this technique each node is able to adjust its antenna weight in order to track its neighbors. Simulation results show how this protocol is efficient in terms of capacity enhancement.

Deafness problem is another challenge to Ad-Hoc network. This problem is created as a result of exchanging RTS/CTS directionally. In [62], the authors proposed a new protocol called Toned MAC. Deafness problem is addressed in this paper by using sub-band tones. Tones are sinusoidal signal that do not contain information bits and thus do not require demodulation. They are only detected through energy estimation and thus notify the neighbors of a communicating node. The channel in a node that implements this protocol must be divided in two sub-channels: the data channel and the control channel. The data channel is used for transmitting the four way handshaking while the control channel is used for transmitting the tone signal. Each tone-frequency is identified by a unique code to assist nodes in determining the sender of a given tone.

In [61], the authors proposed a MAC protocol called Adaptive Beam-Forming Carrier Sense Multiple Access/Collision Avoidance (ABF-CSMA/CA) by using smart antenna. This protocol, as others, employs the RTS/CTS/DATA/ACK access mechanism to manage node communications. In this protocol, training sequences are transmitted before applying directional Request-To-Send (RTS) and Clear-To-Send (CTS) packets. Training sequences are mainly used to estimate the behavior of the wireless channel.

In spite of these previous efforts, there are still significant problems that arise with the deployment of directional antennas in UAVs. For example, effects of aircraft dynamics. Aircraft dynamics are represented by three parameters: pitch, yaw and roll. Any variation in these parameters could lead to an intermittent channel between the sender and the receiver. The problem with the above approaches is that none of them considers the effect of aircraft dynamics while implementing directional antenna.

2.2 Unmanned Aerial Vehicle

Integrating wireless equipment into a small UAV has been studied recently, especially in the context of MANET where communication is required between nodes that would not be able to communicate because of line-of-site obstructions. In [8], the authors showed that by integrating small low-cost commercial off-the-shelf 802.11b equipment into a UAV, a powerful networking node can be created in the air. They also showed that UAVs provided shorter routes that had better throughput than a similar ground-based network. To understand the performance of such a network, the authors in [9] built a wireless network test bed using IEEE 802.11b; the test bed gave detailed data on network throughput, delay, range, and connectivity under different operating regimes.

In [10], the authors have addressed the issue of configuring 802.11a antennas in UAV based networking and presented a set of field experiments (test bed) to the wireless link between UAVs and ground station. They measured the link-layer throughput based on various antenna orientations and communication distances. They conclude that both the UAV and the ground station should use Omni-directional dipole antennas to get high throughput. In addition, they showed that the path loss in an airfield environment is roughly proportional to the square of the communication distance.

In [37], the author describes an intelligent flight system to be used as a test bed for future development. All UAVs fly under control of autopilot and onboard computer. Onboard computer is used to provide mission control and runs Intelligent Controller(IC) software. Communication between ICs (i.e. between UAVs) is via 802.11b Ad-Hoc network. Any order from ground station is sent to the UAV IC via 802.11b. The next generation of such UAVs will work as a collaborative autonomous unit where each UAV is receiving high level mission commands from the ground station [38] to accomplish a set of objectives. Communication between UAVs should be established without significant setup so there is a need for future plans to enhance communication architecture with strong support by new transport layer protocols.

Applications with UAV have specific requirements to reduce the overhead under heavy transmission load. In [40] the authors presented a new contention-based medium access control protocol for wireless Ad-Hoc networks of unmanned aerial vehicles. They called their protocol a Receiver-initiated Access Control with Sender Scheduling (RACSS). The RACSS MAC protocol uses the concept of contention-based protocol where the receivers have the power to decide which node to transmit. In mobile Ad-Hoc network, data transmission can be performed by one of three methods: direct transmission, multi-hop relaying through intermediate nodes, and data ferrying through a node that physically moves between sources and destinations [26]. Implementation of these methods is restricted by the nature of the UAV and the application.

Another application of networked-UAVs is a cooperative search system. The authors in [68] present such a system in which a swarm of UAVs search and monitor the ground for enemy targets. They are communicating cooperatively to locate the targets and then send the target's coordinates to another platform. The authors investigate the effect of the realistic wireless communications upon a group of UAVs conducting a distributed global-search algorithm; their results indicated that communication ranges and number of UAVs have a significant impact on the group's ability to search an area for locating targets.

Flying a UAV over a wireless Ad-Hoc network may help to optimize the performance of the network for better quality of service (QoS). In such scenario, the UAV acts as a node and generates, receives, and forwards data packets to other nodes in the network. In [69], the authors introduced an Ad-Hoc wireless mobile network that employs a hierarchical networking architecture. They incorporated the use of unmanned aerial vehicle to enhance the operation of the network, and to achieve a more stable backbone system. In addition, they presented a new MAC layer power control algorithm for efficient utilization of the MAC resources through the use of time slot allocations, and through the use of CSMA/CA protocol.

In [70] the authors studied the problem of UAV placement over ground nodes with the end goal of improving network connectivity by applying flocking algorithm. Flocking algorithm for UAV placement can provide good coverage, connectivity and load-balance to the underlying mobile nodes by using local information in making decisions about where to move and thus keeping the overhead packets very low. The authors assumed that there is no direct connectivity between ground nodes and only

UAVs are responsible for connecting the ground nodes. Simply, by applying flocking algorithm, UAVs should maintain safe distance from each other, maintain connectivity among themselves and track the motion of ground nodes so that overall network connectivity is maintained.

To improve the range and the reliability of Ad-Hoc ground based networks. The concept of using UAV as a communication relay was presented in [63]. The authors studied the performance of the Ad-Hoc ground network using UAV as a relay node and the effects of UAVs' positions and velocities on Bit-Error-Rate (BER). In [66], the authors presented the load-carry-and-deliver (LCAD) networking paradigm to relay messages between two distant ground nodes. This paradigm, LCAD, is designed for maximizing the throughput of UAV-relaying networks by having a UAV load from a source ground node, carry the data while flying to the destination, and finally deliver the data to a destination ground node. They compared their paradigm against the conventional multi-hop and they claimed that the proposed LCAD paradigm can be used to provide high throughput between ground nodes.

In [67], the authors investigate the properties of relay-enabled networks as a function of the number of relays in the network. Three basic communication modes were taken into consideration: 1) direct communication, 2) relay communication with one transmission at a time (single transmitter case), and 3) relay communication with multiple simultaneous transmissions at different relays (parallel transmitter case). They summarized their finding as follows: When multiple packets are sent at a time (the second packet is generated while the first packet is still in its path to the destination), the performance depends on the separation in hops between simultaneous transmissions in the relay chain and doesn't depend on the distance and noise. On the other hand, when packets are sent one at a time (packet is forwarded completely from source to destination before the next packet is forwarded), the performance depends on the number of relays.

Movement pattern of UAVs has significant impact on networking performance. In [54], the authors presented algorithms for determining a desirable mobility model for UAVs in reconnaissance operations. Two mobility models were provided: in the first one, the UAVs move independently and randomly while in the second one the pheromone model guide their movement. Based on their conclusion, the random model is simple and it achieves good results. The pheromone model achieves good result, but it has problems with respect to network connectivity. In addition, their study shows that coverage and connectivity of communication are two conflicting objectives.

A lot of software tools are used to simulate the UAV Ad-Hoc networks such as OPNET. OPNET is a simulation tool that includes hundreds of pre-built models to study the performance of communication networks [64, 65]. In [39], the author enhanced OPNET models to provide a means of evaluating the communication link between UAVs. They created a movement module that incorporates actual flight position data into an OPNET scenario. The process model of the UAV movement is responsible for setting UAV attitude (pitch, roll and yaw). Their module operates in two modes: rounded rectangle and trajectory. In rounded rectangle, the node follows a user defined rectangle centered around the node position (latitude, longitude and altitude), while in trajectory, the node moves according to the trajectory file that contains a list of aircraft position and attitude.

Although the above approaches showed tremendous advantages for the use of UAVs in communication systems, we think that the impact of the UAV node on Ad-Hoc network still needs more investigation. In other words, using UAVs in Ad-Hoc network requires a mechanism to modify the standard OSI model.

2.3 Cross-Layer Design

As a result of the rapid progress in technology, some applications experience a number of constraints that result in low Quality of Service (QoS). For example, multimedia applications are characterized by the sensitivity to the packet delays. Another constraint is the nature of the wireless channel in which multi-path signals fades and there is interference from neighboring transmissions. All the above factors have led the researchers to develop and propose a number of new approaches targeted at reducing delay during the transmission of multimedia data through a large network. Cross-layer design is the most attractive approach for researchers in which all layers share knowledge with each other about the specific application characteristics and the instant network conditions. Most of the available research has proven that physical (PHY) and MAC layers are very important especially in wireless networks and should be designed jointly [71]. As for the UAV Ad-Hoc network, previous research suggests that UAV node requires an integrated design to the OSI reference model [11, 12].

Other researchers have shown that cross-layer design of different protocols is essential to meet application requirements. In [13], the authors presented cross-layer design to address some problems observed in wireless networks such as mobility, packet losses and delay that cannot be handled well by strictly layered architectures. They propose the use of cross layer manager in which it is responsible for setting the protocol internal state that exposed by protocol layers. In [15], the authors focused on the limitations of energy resources in Ad-Hoc network and how it affects application requirements. They showed that the link layer, the MAC layer, and all other higher layers should be jointly designed to minimize the total energy consumption.

In [2], the authors proposed a new mechanism to enhance the routing protocols by location prediction. Cross-layering information is gathered by their technique and stored in a separate profile so that other layers can access this profile during the decision making. In their mechanism, they applied the principle of cross-layer design to the routing and middleware layers to facilitate data accessibility for various applications at the end-systems. The shared data comprises information such as location, mobility, and transmission range. These data are abstracted from each necessary layer, updated periodically and stored again in the local profile. One disadvantage for this mechanism is that the network is relatively highly loaded due to information exchange among nodes.

In [14], the authors have studied the problem of multi-hop real-time video streaming over wireless Ad-Hoc networks under a variety of scenarios. They presented cross-layer design approach in order to adjust lower layer parameters such as packet size, number of retransmission, modulation and symbol rate according to the video traffic characteristics and channel conditions. It is shown that the improvements of the data link layer techniques such as scheduling and rate allocation are very significant to enhance link throughput, which in turn improves the achievable capacity region of the Ad-Hoc network.

A joint cross-layer approach of application layer and MAC layer was proposed in [75] to improve the video quality under the constraints of bandwidth and delay. Unlike the author in [14], the authors in [75] have shown that by partitioning the packets into different priority classes and correspondingly adjusting the transmission strategies for each class, significant improvements can be obtained. In addition, they developed a real-time greedy algorithm that is capable of correctly determining the number of times needed for the current packet to be retransmitted based on the actual number of times that the previous packets have been transmitted. However, this algorithm guaranteed the packet until it is received or expired, it does not consider possible future changes in channel condition.

In [76], the author addressed the issue of crossing the first three layers where the physical layer knowledge of the wireless medium is shared with higher layers in order to improve network performance. In network layer, he constructed a multi-hop route taking into his account the channel noise in the vicinity of the nodes and continuously evaluated the routes based on the potential retransmissions over links. In MAC layer, he developed a mechanism that improves the IEEE 802.11 binary exponential backoff with a capability of differentiating between different types of unsuccessful transmissions. In physical layer, he showed that network capacity can be increased significantly by capturing the strongest frame regardless of wither it comes before or after the weaker frame. In addition, he proposed the use of directional antennas and developed the MAC protocol, in which the location of the node is embedded in the transmitted frames.

The author in [77] proposed a jointly optimal design of the first three layers of the OSI model. In contrast to the author in [76], the goal of the optimization in [77] is to achieve proportional fairness. Proportional fairness is achieved by considering a joint optimization of rates, transmission power, medium access and routing. His finding for the optimal solution can be summarized as follows:

- Any node intents to transmit. It should transmit with the maximum power.
- Nodes that are located around the destination node should keep silent during data transmission. Other nodes outside this region can transmit at any time.
- The source node should adapt transmission rate based on the level of the interference at the destination node.
- Relaying the message along loss route is better than using longer hops or sending directly.
- Selection of the routing protocol is independent of the design of the optimal MAC protocol.

To the best of our knowledge, there is no existing standard or generic cross-layering architecture that has guaranteed a specific aspect of network performance. Many researchers have published different architectures for wireless networks. Most of them are based on the categories mentioned in [43]. The authors in [43] are presenting a survey for the area of cross-layering design. They noted that the layering architecture can be modified in one of the following ways:

- Creation of new interfaces.
- Merging of adjacent layers.
- Design coupling without new interfaces
- Vertical calibration across layers.

In [44], the authors focus on the interaction between protocols in terms of energy constraint and security. They proposed a new architecture that is called MobileMan. MobileMan divides functionalities and responsibilities between layers and seeks to expand the cross-layering all over the stack through the data sharing. They aimed to optimize network performance by increasing interaction among source protocols and at the same time decreasing remote communications. The core of this architecture is based on a local profile (Network Status) that functions as a repository for the gathered information. The Network Status is responsible for storing and managing the data to be shared. Then each protocol accesses the Network Status to share its data with other protocols.

Another architecture was presented in [45]. They called their architecture CrossTalk. CrossTalk aims for achieving global objectives with local behavior and is capable of creating two profiles: one is local while the other is global. Local profile is responsible for organizing the information that is provided locally by each layer. Such information could be the velocity, current battery, location information, neighbor count, signal-to-noise ratio, or transmit power. To create the global profile, CrossTalk adds the data that is available within the local profile to the outgoing packets. As soon as the node receives the packet, it extracts that information and adds it to its global view. In this way, CrossTalk architecture minimizes the overhead packets and thus enhances the network performance.

Many researchers have summarized cross layer design benefits in their papers [72, 73, 74], others have shown that modification of the layered architecture should be done with a high level of care. They believed that cross layer design should be viewed as an alternative method for designing an adaptive wireless network. In [46], the authors highlighted the importance of cross-layer design and discussed some problems that might occur as a result of crossing the OSI model. They showed that direct optimization of link and physical layer may create problems if higher layer protocols are not able to benefit from it. Furthermore, uncoordinated cross-layer designs may lead to loss of transparency and scalability and thus researchers should consider the totality of the design and the long-term architecture value of the suggestion. Otherwise Cross-layer design should be kept to a minimum.

To this end, Cross layer design for performance optimization has received much attention over the past few years, mainly the means of information sharing among OSI layers, information about environment and information about the applications. The two types of information are considered independently of each other. Thus as shown above, the effectiveness of the adaptation mechanism is to combine both types and consider their effects to the whole stack.

2.4 Ad-Hoc Routing Protocol

Due to the limited transmission range of the Ad-Hoc members, other nodes may be needed to exchange data with others across the network. Recently, a lot of protocols targeting specifically the issue of how to route the data across the network have been developed. In [78, 79, 80], the authors presented a survey and comparison of current routing protocols for mobile Ad-Hoc networks. All classified the protocols into three types: flat routing, hierarchical routing, and geographic position assisted routing. Flat routing protocols uses a flat addressing scheme, hierarchical routing protocols require a scalable addressing system and geographic position assisted routing assumes that each node is equipped with the global positioning system. They conclude that the flat routing protocols, mainly the OLSR, are producing less control overhead than the others and they are more efficient than classical algorithms when networks are dense.

Other researchers classified the routing protocol according to the routing strategy. In [81, 82, 83], the authors classified the routing protocols into proactive (table-driven) and reactive (on demand) protocols. Proactive routing protocols update the route periodically while reactive routing protocols maintain the routes that are currently in use. In terms of high mobility, they claimed that proactive protocols have the capability of producing higher routing efficiency than reactive protocols. As an example, OLSR, which forces the updates of the link state only at MPR nodes, reduces both the size of the routing packets and the number of nodes that is needed for forwarding such packets.

Two conventional methods are used by the above routing protocols for the purpose of routing data across the networks: Link-state and distance-vector. The link-state routing (LS) algorithms maintain the information about network topology at each router and make route decision based on this information. Moreover, they periodically allow flooding of this information to their neighbors [84]. On the other hand, the distance-vector routing (DS) algorithms operate by maintaining a table (vector) at each router in which the best known distance to all destinations and the route to follow are available [85]. Generally speaking, DS routing algorithms are suffering from creating a loop in mobile environments. This problem is solved by the use of LS, even though the overheads are relatively high.

The majority of the research is focusing on building routing protocol using omni-directional antenna. A limited number of routing protocols have been proposed to take the advantage of directional antennas [34, 86, 35, 36]. In [34], directional antenna is used to improve the efficiency of the on-demand routing protocols. The main idea is to utilize the directional antenna in order to reduce the routing overhead by reducing the number of routing packets transmitted during route discovery. In contrast, the author in [86] focused on reducing the overhead of route maintenance by modifying the Dynamic Source Routing (DSR) protocol and on-demand routing protocol.

In [35], the author addressed the issue of routing in mobile Ad-Hoc networks using directional antenna. He used the directional antenna to improve the performance of the network in two situations. The first one is the use of directional antenna during the process of route repair as result of node movement. The second issue is the use of directional antenna in the case of dynamic network partitioning as a result of node mobility. The same issue was addressed in [36]; they optimized the reactive protocol, DSR, to be used in Ad-Hoc using directional antenna. If the source does not receive a reply from the destination, the source will send hello message in order to update the location information of the destination node. By this process, the directional antenna has been shown to find the route with fewer hops.

The authors in [87] evaluated the impact of directional antennas on the performance of routing protocols. They proposed a routing strategy that adapts the routing protocol to the use of directional antenna. Simply, they presented a sweeping mechanism that avoids forwarding request in the direction where the channel is busy. As a result of the deafness problem that is created while using directional antenna, the authors concluded that the advantage of using directional antennas will not be satisfactory, thus in some scenarios it would be better to use Omni-directional antennas rather than the directional antenna.

Due to mobility of nodes in MANET, network topology may change rapidly and unpredictably, thus it is difficult to provide quality-of-service (QoS) routing in an Ad-Hoc network. A number of studies have been proposed to provide quality-of-service in MANETs. The author in [88] discussed how to support QoS routing in OLSR by developing heuristics that allow this protocol to find the maximum bandwidth path. He proposed three algorithms for MPR selection: In the first algorithm, the node will select the one-hop neighbor that reaches the maximum number of uncovered two-hop neighbors as MPR. In the second algorithm, the node will select the best bandwidth neighbors as MPRs until all the two-hop neighbors are covered. Finally, in the third algorithm, the node will select the MPRs in such a way that all the two-hop neighbors have the optimal bandwidth path through the MPRs to the current node. He showed that the above three heuristic algorithms are increasing the opportunity to find a path that is optimal under a bandwidth constraint. Moreover, he proved that algorithms two and three are indeed optimal for the Ad-Hoc network.

Optimized Link State Routing Protocol (OLSR) was proposed in [92]. OLSR is an optimization for link state routing protocol in which it periodically exchanges topology information with other nodes in the Ad-Hoc network. The key point in OLSR is the selection of the Multi Point Relays (MPRs). The MPRs are selected in such a way that they cover all nodes that are two hops away from the source node. The authors in [92] proposed a heuristic approach for MPR selection as follows:

- The source node should start with an empty MPR set.
- For each node X in the one-hop neighbors, calculate the number of X's neighbors [A,B,C ------]
- Select the MPRs from the X's neighbors in which they provide only one path to some of the two-hop nodes [a, b, c -----].
- To cover the remaining nodes of the set [a, b, c -----], select the MPR which covers the maximum uncovered node.
- Process each node X that is found in the MPRs set , if it does not cover all nodes in the set [a, b, c--], remove X from the MPRs set

In addition, he summarized the OLSR protocol in three steps as follows:

1. Neighbors sensing: Nodes are capable of sensing each others by exchanging HELLO messages.
2. Topology Control (TC) dissemination: Each node in the network advertises its link information to all other nodes through the MPRs.
3. Routing table calculation: Each node is capable of computing the shortest path based on TC messages received from other nodes.

In OLSR, the multipoint relay (MPR) selection has an important effect on the routing protocol's performance. MPRs are used to minimize the routing messages and limit the effects of the broadcasting in the Ad-Hoc network. Each node implementing the OLSR selects a set of MPRs in its neighborhood which are responsible for retransmitting flooding packets. In [90], the author analyzed the performance of the OLSR routing protocols. In particular, they focused on the size of the MPRs in the network. They showed that the size of the MPR set has a significant effect on the diffusion of the information over the network.

The authors in [91] were also interested in the performances of the Multipoint Relay selection. They analyzed the mean number of the selected MPR per node and their spatial distribution by providing two bounds (lower and upper) as a function of the network density. They also gave analytical results on the performance of MPRs and their implications on the efficiency of broadcasting and on the reliability of OLSR.

In [89], the authors compared two Ad-Hoc routing protocols: Ad-Hoc On Demand Distance Vector (AODV) and Optimized Link State Routing (OLSR) protocols. They have shown that AODV and OLSR are the most attractive protocols for multimedia transmission. Based on this paper, AODV performs well in the networks with static traffic and thus it can be used in environments with critical resources. On the other hand, OLSR is more efficient in high density networks and it can be used to reduce the overhead load.

CHAPTER III

CROSS-LAYER DESIGN

3.1 Introduction

Cross-layer design is a promising approach in mobile Ad-Hoc networks and it is considered as one of the effective methods to enhance the performance of a wireless network by jointly designing multiple protocols. In contrast to layered architecture technique, which is not efficient for Ad-Hoc wireless networks [15], cross-layering allows communication between non-neighboring layers as well as reading and controlling the parameters of one layer from other layers [16, 17, 18, 19]. Cross-layering technique also allows parameters to be passed to the adjacent layers to assist them in determining the operation modes that will suit some requirements imposed by the nodes. In addition, this technique adapts the changes in wireless links and network topology and thus makes future networks self-behaving.

Due to the mobility and delay problems which were observed in Ad-Hoc network, development of a new mechanism for improving communication performance and efficiency in such a network is essential nowadays. Cross-layer optimization approach may provide a more flexible solution and enable an efficient communication path among OSI layers. This approach indicates that adjacent layers can communicate with each other by creating new interfaces and then using the concept of adaptation. Adaptation in our case study means that network, data link, and physical protocols should have the capability of observing network changes and then responding accordingly.

3.2 Networking Models

Layering model is the best way of organizing a network. Regardless of the type of network, most networks are designed as a series of layers, starting with the physical layer and ending with the application layer. Each layer implements a set of protocols in which they carry out a sequence of operations, together layers and protocols form the architecture of the network. In the following subsections we will introduce the two most important models, the open systems interconnection (OSI) model and the TCP/IP model.

3.2.1 Open System Interconnection Reference Model

In 1977, the open systems interconnection (OSI) reference model was developed by the International Organization for Standardization (ISO). In its basic architecture, OSI has two major components: a seven-layer model and a set of specific protocols. The model divided the network architecture into seven layers which are Application, Presentation, Session, Transport, Network, Data-Link, and Physical Layers. Figure 3.1 presents the OSI model. In this model, each layer provides services to the layer above it and receives service from the layer below it. Sets of specific protocols were developed and gathered as specifications for different networks. As an example, IEEE 802.11 standard, which represent the specifications for wireless networks, works on the two lowest layers of the OSI model (Data-Link Layer and Physical Layer).

In OSI model, layers are logically stacked one over another. Each node in the network should stick to this hierarchy and communicate with other nodes by maintaining the same level without knowing the inner working at the lower layers. For example, data link layer, say at node (1) should work with that data link layer at node (2). Below is a brief description of the whole stack.

1. Physical Layer: Mainly, physical layer defines the electrical and physical specifications of the devices. For example, cables, cards, and physical aspects (pins, voltages). This layer provides the hardware means of sending and receiving data by telling one device how to transmit and the other device how to receive. Moreover, it shows how to establish and terminate the connection to the wireless medium. This layer participate in the process of contention, flow control and finally modulation issues.
2. Data-link Layer: The main objective of the OSI data link layer is to handle physical layer errors, flow control and channel access. For example, in IEEE 802.11 data link layer consists of two sub-layers: Medium Access Control (MAC) layer and Logical Link Control (LLC) layer. MAC layer is interfaced directly with the physical layer and it controls how the node on the network gains access to the medium and gets permission to transmit its data. On the other hand, LLC provides the logical aspects such as flow control and error checking.
3. Network Layer: Network layer is responsible for determining the logical path between the source and the destination. In addition, it performs many functions such as network addressing, congestion control, error handling and packet sequencing. One of the most important protocols in this layer is the internet protocol (IP).
4. Transport Layer: This layer provides reliable data transfer between end users. It controls the reliability of a given link between source and destination through error recovery and flow control. Error recovery retrieves lost data if it is dropped while in transit from source to destination, while flow control ensures complete data transfer from

sender to receiver. The most important protocols used in this layer are Transmission Control Protocol (TCP) and User Datagram Protocol (UDP).

5. Session Layer: The session layer controls the connection between hosts. It establishes and terminates the virtual connection between local and remote applications. In other words, the session layer starts and stops communication sessions between network devices.

6. Presentation Layer: Presentation layer transforms data into the form that the application layer can accept. For example, it converts a string of data into a recognizable file format, such as .doc or .jpeg. In addition, it translates the user data into a format that can be carried by the network.

7. Application Layer: The application layer is the top layer in the OSI protocol stack. It defines how an application running on one system can communicate with an application running on another system. It provides services to application programs outside the scope of the OSI model.

Advantages of the OSI model:

1. Easy to modify layers.
2. Reduce complexity of the task.
3. Easy to standardize and deploy new protocols.

Limitations of the OSI model:

1. Not flexible to adapt to wireless applications.
2. Transmission parameters can't be adjusted to the variations in channel quality.
3. Direct coupling between layers is unavoidable.
4. No joint optimum performance for the whole system.

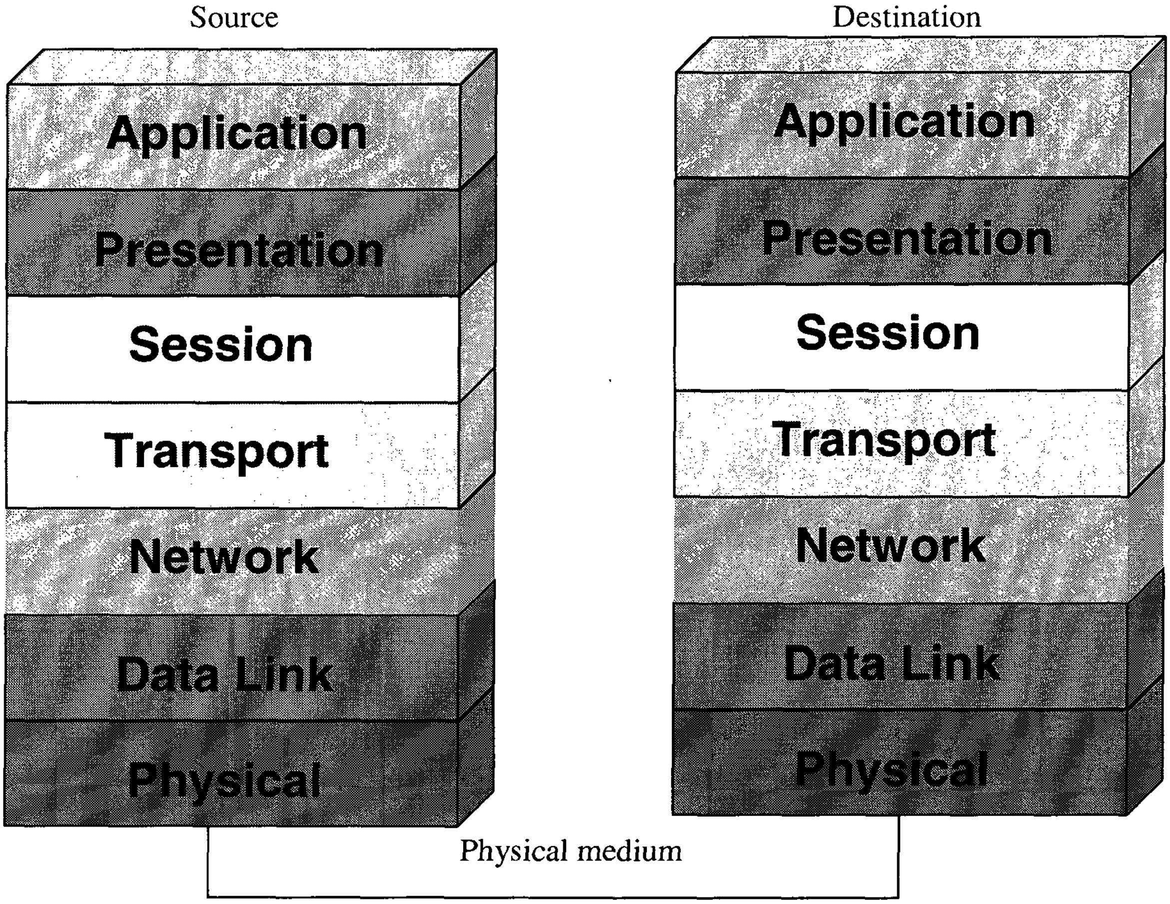


Figure 3.1: Open System Interconnection Reference Model

3.2.2 TCP/IP Model

TCP/IP model was developed by the U.S. Department of Defense Advanced Research Projects Agency (DARPA). The purpose of the TCP/IP was to connect a number of devices to the Internet with a high-speed communication link. As shown in figure 3.2, TCP/IP has four layers: Application, Transport, Internet and Network Access layers. Each layer in the TCP/IP model corresponds to one or more layers of the seven-layer open systems interconnection model. Below is a brief description of each layer.

1. Network Access Layer: This layer is responsible for delivering data to the other devices on the attached physical network. In addition, it performs different duties such as: checks for errors, acknowledges of received frames and converts the data into electrical pulses.

2. Internet Layer: This layer is responsible for addressing, packaging, fragmentation, error detection and routing. The most important protocols operate in this layer are Internet Protocol (IP) and Address Resolution Protocol (ARP).

3. Transport Layer: This layer is responsible for the end-to-end flow of data and for providing the application layer with session and datagram communication services. Two primary protocols operate in this layer: Transmission Control Protocol (TCP) and User Datagram Protocol (UDP).

4. Application Layer: By this layer, the user applications (as an example: web browser) can access the services of the other layers. Hypertext Transfer Protocol (HTTP) and File Transfer Protocol (FTP) are two examples operate in this layer.

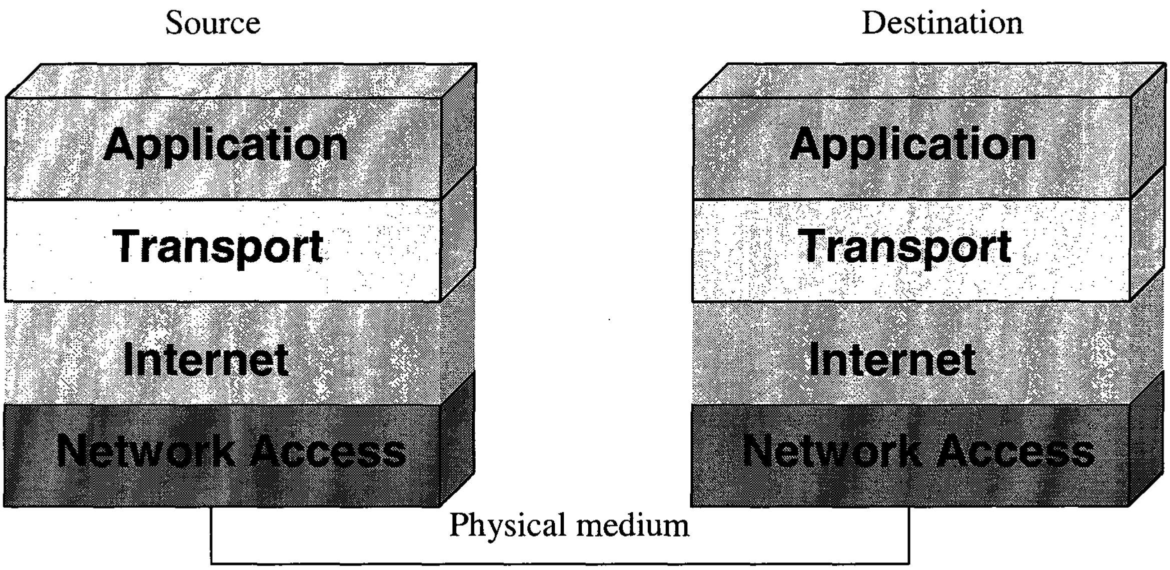


Figure 3.2: TCP/IP Model

Table 3.1 shows a comparison between the two models. Both models have an application layer. As shown in the table, TCP/IP application layer performs the functions of the OSI application, presentation and session layers. While TCP/IP network access layer carries out the functions of the OSI data link and physical layers.

Table 3.1

Comparison between OSI and TCP/IP Models

OSI Number	**OSI Layer**	**TCP/IP Number**	**TCP/IP Layer**
7	Application	4	Application
6	Presentation		
5	Session		
4	Transport	3	Transport
3	Network	2	Internet
2	Data Link	1	Network Access
1	Physical		

3.3 Characteristics of Mobile Ad-Hoc UAV Communication Networks

Mobile Ad-Hoc UAV communication networks have some characteristics that may differ from other types of wireless networks. In addition to the characteristics of the wireless networks (limitation in radio range, bandwidth and energy), UAV adds new characteristics such as high mobility, antenna blockage and attitude effects. These characteristics are categorized as small-scale because the channel state is changed within a short period of time. Other characteristics that depend on the interference coming from the surroundings are called large-scale because their effects on the channel state are slow.

In the following subsections we will focus on the following small-scale important characteristics: aircraft attitude and antenna blockage.

3.3.1 Effect of Aircraft Attitude on MANET Performance

The impact of aircraft attitude pitch, roll, and yaw on the MANET performance is significant. In particular, aircraft attitude affects end-to-end delay and throughput. These effects increase the retransmissions overhead and thus reduce the overall throughput and increase the end-to-end delay. In order to reduce the impact of aircraft attitude, there is a need for designing an antenna system and protocols that compensate for these effects and be largely unaffected by changes in aircraft attitude.

Generally, Antenna system is classified into two types: directional antenna and Omni-directional antenna. In directional antenna, the signal propagates in a certain direction while in Omni-directional antenna; the signal propagates in all directions. A blade antenna, one type of Omni-directional antenna, is often used on aircraft. The impact of aircraft attitude on this type of antenna is extremely clear; as the aircraft changes its attitude, the radiation pattern of the blade antenna is rotated with respect to aircraft axis, and thus, its gain starts to fluctuate. This fluctuation affects the range of the communication link between aircrafts. Therefore, there is a need for creating a mechanism that is able to track the aircraft attitude and isolate antenna system from the rolling, yawing and pitching movements of the UAV and at the same time providing better gain than Omni-directional antenna.

3.3.2 Effect of Aircraft Body on Antenna System

Due to the light weight and small size of the UAVs, antenna system presents unique challenges in terms of electrical performance. All antenna used by a UAV should offer the advantages of reduced size and light weight. Those advantages may result in degradation in electrical performance, and thus reduction in communication range. Another challenge is the location of the antenna with respect to aircraft body, the antenna may be mounted on the top or bottom of the fuselage and for a certain time during data transmission, the aircraft body may be located in between the antenna and the destination. This results in a complete blockage which creates an intermittent link.

3.4 Revolution of Cross-Layer Design

Traditionally, network protocols have used the layered architecture defined by the ISO open systems interconnection model. Under this model, all protocols function in a certain way and communicate only with other protocols that belong to the same layer. In other words, each layer communicates with the corresponding layer at the other end of the network through the layers below it. To be more specific, OSI model describes how data is transferred from one node to another through the existing medium (either wired or wireless). In addition, the OSI model divides the stack into seven layers to reduce the complexity of the protocols.

Although, there are some functions in a network that are existing by nature such as cooperation and security, it has recently become evident that the strict layering architecture is not efficient enough for the performance optimization in the Ad-Hoc wireless networks. Strict layering architecture has served extremely well for wired networks and it contains some adaptive mechanisms, such as: updating routing tables, success or failure notification. However these adjustments are not enough to cope with the dynamics of the Ad-Hoc network. This is mainly due to the fact that this type of networks restricted to certain resources. To be more specific, layer boundaries should be broken. This can lead to more efficient performance of the transmission stack in which all layers share knowledge with each other about the specific application characteristics and the network conditions.

3.5 Cross-Layer Architectures

In recent years, many researchers have published different designs for cross-layering architecture. The majority are targeting to design architectures that satisfy the network in terms of self-configuration and self-optimization. Self-configuration and self-optimization require high level of information to attain the best performance in a network. In general, there is no existing standard or generic cross-layering architecture that guarantees a certain QoS. Most of the proposed designs for cross-layering are based on one of the categories mentioned by the author in [43]. In a UAV scenario, the situation is somehow different, both the source which generates the packets and the recipient have significant effects on the link, thus, in our cross layering architecture we will consider the network as one unit for data sharing. To that respect, cross-layering architectures can be divided into two categories: those which depend on the local information gathered by node's protocols and those which depend on the global information gathered by the remote destination and source node. In the following subsections we will present two architectures that are published for the Ad-hoc network.

3.5.1 Architectures Based on Local Profiles

As shown in figure 3.3. The MobileMan [44] architecture presents the Network Status as a repository for information that uniformly manages the interaction between layers. The proposed architecture introduces some modification for protocol stack using 802.11. At the MAC layer, they enhanced the concept of the back-off and developed a new forwarding scheme. As for the network layer, routing information that is restricted to this layer can be used by other layers. Meanwhile, transport protocols utilize information reported by the lower layers in the created Network Status to provide upper layers with reliable services. The new architecture emphasizes cooperation between layers by sharing Network Status while maintaining the layer separation in the protocol design. The authors claim that their reference architecture offers the following advantages:

- Cross-layer optimization for all network functions such as energy management
- Improved local and global adaptation (reduces network congestion)
- Full context awareness at all layers
- Reduced overhead, avoids data duplication at different layers.

On the other hand, the new architecture includes energy management, security and cooperation. Energy management, security and cooperation are cross-layered by nature. These parameters along with Network Status will offer complete state information through the stack so that protocols will use all of the information to adapt their behaviors and thus maximize throughput and minimize end-to-end delay.

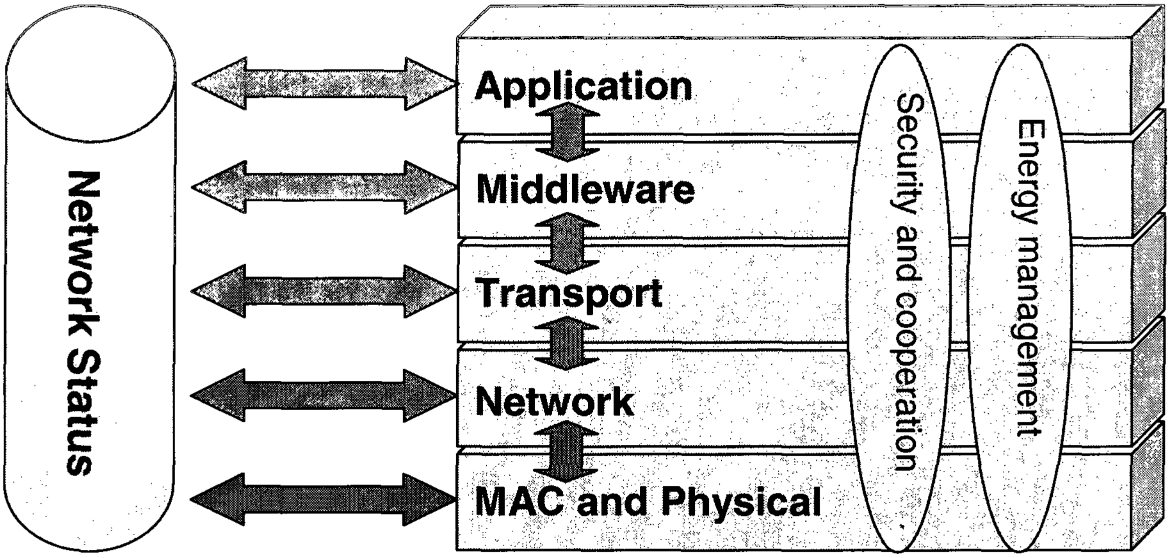


Figure 3.3: MobileMan Cross-Layering Architecture

3.5.2 Architectures Based on Global and Local Profiles

CrossTalk architecture [45] is shown in figure 3.4. It consists of two data management entities. The first one is responsible for organizing the information that is provided locally by each layer. Such information could be the velocity, current battery, location information, neighbor count, signal-to-noise ratio, or transmit power. All protocols running within the node can access this information and utilize it for local optimizations. The other entity is similar to the first one in terms of the type of information collected in the local view. CrossTalk adds the data that is available within the local profile to the outgoing packets. As soon as the node receives the packet, it extracts that information and adds it to its global view. In this way, CrossTalk architecture minimizes the overall overhead packets and thus enhances the end-to-end delay.

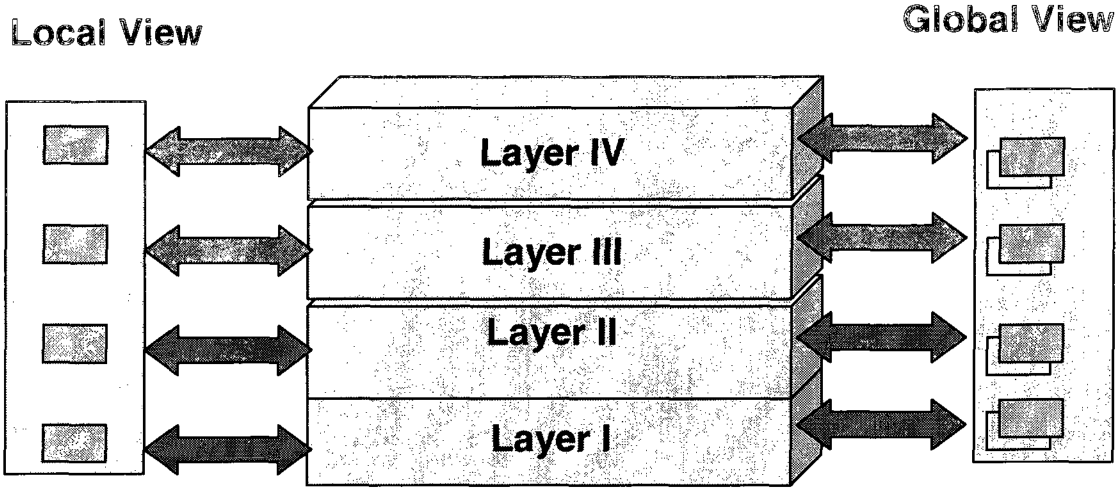


Figure 3.4: CrossTalk Architecture

3.6 Cross-Layer Design for Mobile Ad-Hoc UAV

Our design to the Ad-Hoc UAV communication network will be compatible with the IEEE 802.11 standard. IEEE 802.11 was developed using direct-sequence and frequency-hopping techniques in the 2.4 GHz and infrared technique. The coverage area for IEEE802.11 is limited to hundreds of meters. In my research, cross-layer optimizations have only incorporated the following layers: physical Layer, data link layer and network layer. Both data link and network layers will be measured by throughput and delay, while physical layer will be measured by Bit-Error-Rate (BER). Layer protocols should be adjusted to satisfy our goal and to adapt UAV constraints. Our design mainly for the physical layer will be restricted to the antenna system so it can be expanded by using radio frequency less than that specified by the standard in order to provide large signal coverage.

3.6.1 Physical Layer Design

The physical layer of the UAV system will perform a direct sequence spread spectrum to provide wireless connection to the Ad-Hoc network. Generally speaking, a spread spectrum modulation technique generates a signal that has a bandwidth much larger than the original signal. The bandwidth of the transmitted signal is determined by the message to be transmitted and by an additional signal called pseudo-noise (PN) code. Spread spectrum systems are classified into different types based on how the original data is modulated by the PN code. Basically, there are two types of Spread Spectrum modulation techniques: Frequency Hopping (FHSS) and Direct Sequence (DSSS).

1. Frequency Hopping Spread Spectrum (FHSS): In FHSS, the signal energy is spread over a wider bandwidth than the information bandwidth. The available bandwidth is divided into a large number of frequencies that are spaced to prevent interference. The spreading code in FHSS is the list of frequencies to be used for the carrier signal which is periodically modified as a result of using a digital frequency synthesizer. A digital frequency synthesizer is driven by the PN to hop among the previous frequencies. FHSS is defined in IEEE 802.11 to cover 79 frequencies ranging from 2.402 GHz to 2.480 GHz with a channel width of 1 MHz.
2. Direct Sequence Spread Spectrum (DSSS): In DSSS, the data signal is multiplied with a pseudo-noise (PN) code. It uses a technique called chipping in which the modulated data is spread across the spectrum. The information to be transmitted is divided into small pieces. Each bit of signal data is spread at the transmitter into L chips, and then the chips are transmitted at a rate equal to L × bit rate of the data. DSSS can also be used as a multiple access technique; this multiple access technique is called code division multiple

access (CDMA). DSSS is divided by IEEE 802.11 into 14 possible carriers that are 22 MHz wide and covers the range from 2.402 GHz to 2.480 GHz.

The performance of physical layer is mainly affected by the interference as a result of sharing one channel. DSSS will be used in our system since the transmission capability of the wireless channel can be maximized by using variable data rate. The performance is determined based on the following parameters: transmit power, modulation, coding rate, and antenna beam. Bit error rate (BER) is the key factor to measure the performance of physical layer. Adaptation of these parameters to achieve the target BER is the key solution to the Ad-Hoc network. Usually, the BER is calculated by Signal-to-Noise Ratio (SNR). Increasing SNR in the Ad-Hoc network can improve the performance and reduce the BER. To satisfy this goal, directional antenna will be used so that the total gain is responsible for the improvement of the whole system.

3.6.2 MAC Layer Design

As a result of sharing the same channel in Ad-Hoc network, the MAC layer exists to schedule the transmissions and allocate channels between nodes. The result that may be gained by scheduling and allocation is to reduce the interference between nodes and stop concurrent transmissions. On the other hand, the effect of the previous MAC mission may add a delay to the packet transmission. Thus, designing MAC layer in such systems brings a high competition between researchers. Meanwhile, The MAC layer needs a new mechanism to adjust its parameters and to coordinate the available resources that may be shared by network members. Our system will minimize the time taken as a result of scheduling by switching the transmission between the two types of antenna used by the UAV.

3.6.3 Network Layer Design

The responsibility of the network layer is to divide the data into small packets and then add a logical address of the source and the destination. Based on the added address, the process will continue by acquiring the route that will carry the data packets according to these addresses. The decision in selecting the route between source and destination differs from one protocol to another, and thus, the performance of the MAC and physical layer will be affected [42]. In a UAV Ad-Hoc network, the OLSR routing protocol is implemented with a slight modification to serve the directional antenna. The decision in selecting the route will be based on the MPRs that are selected by the UAVs.

3.6.4 System Design

Due to the nature of the UAVs, the local adaptability of the OSI model can not achieve a certain application requirement, thus, a global adaptability is required where information is exchanged between layers. In addition, the dynamic state of our network required a comprehensive adaptation to the aircraft attitude.

As shown in Figure 3.5, our proposed cross-layer design is based on the interactivity between protocols and the sharing of the following information: Bit-Error-Rate (BER), aircraft attitude, aircraft locations, retry counter (R), multipoint relay (MPR) locations and antenna type in use. All of the information is shared and accessed by the first three layers of the OSI model. The upward-downward arrows indicate that the two layers affect the session during packet transmission, while left-right arrows indicate that each layer has the capability to fetch and store the needed data. BER will be read as a result of CTS reception. During the use of Omni-directional antenna, the MAC layer will switch to directional antenna if the BER gets worse. In addition, it will keep transmission on Omni- directional as the UAVs are getting close to each other.

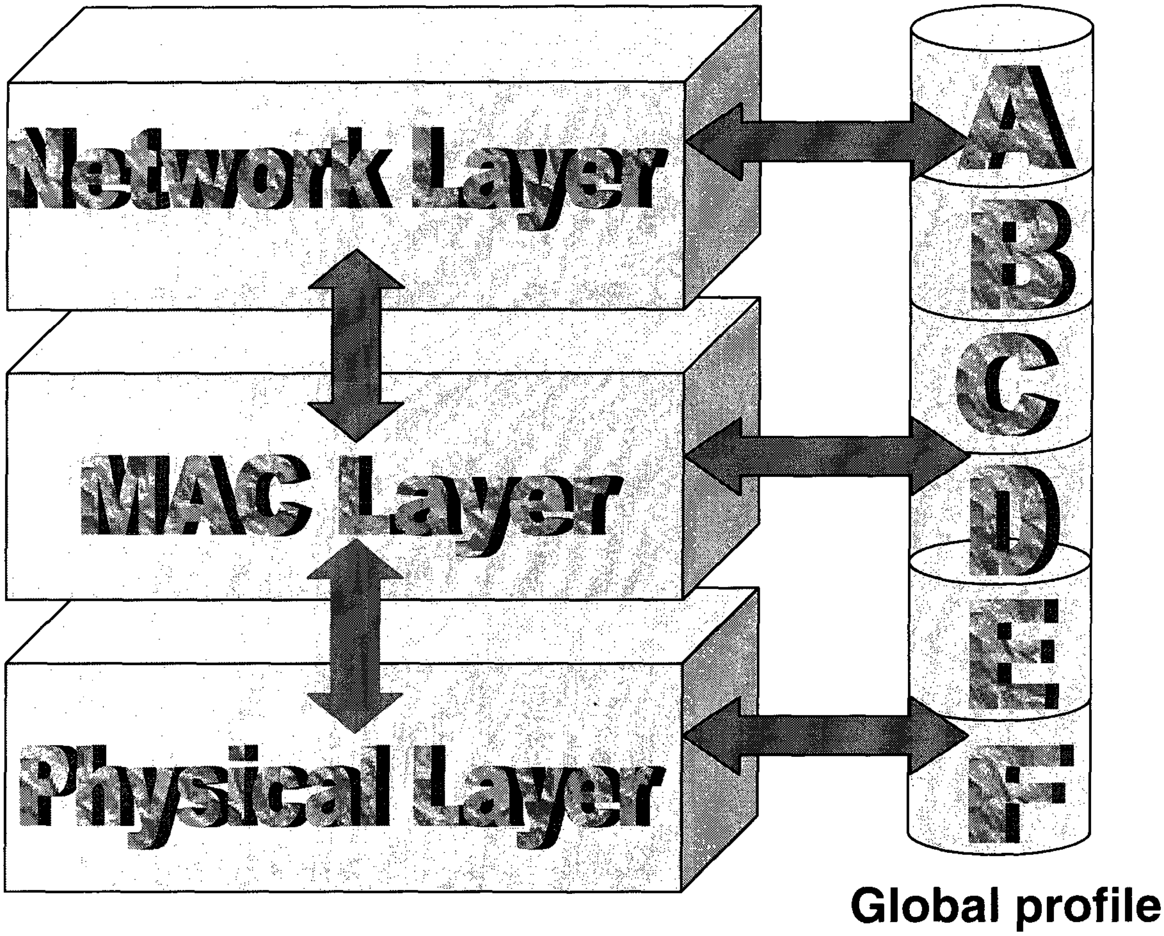


Figure 3.5: Target-Source Based Architecture

3.7 Summary

It is evident that the impact of the aircraft attitude on the performance of the Ad-Hoc network during the use of directional antenna will be significant. To reduce this effect, the first three layers in the OSI module should exchange information about the state of the wireless link. By implementing cross-layer technique in such network we can make this information available as requested. At the beginning of this chapter, we gave a brief description for the two most important models used in networking; the open systems interconnection (OSI) model and the TCP/IP model. Then we discusses some characteristics that UAV network posses and differs from other networks, such as the effect of aircraft attitude on the MANRT performance and the effect of the aircraft fuselage on the antenna system. These characteristics are making the models mentioned above inefficient and not effective in such networks. At the end of this chapter, we present two architectures that are published for the Ad-hoc network, those are architectures that based on local profiles and architectures that based on global and local profiles; last we present our new architecture that is called Target-source Based Architecture.

CHAPTER IV

MAC SCHEME FOR MOBILE AD-HOC UAV USING DIRECTIONAL ANTENNA

In this chapter, we address the effect of using directional antenna on the Medium Access Control (MAC) layer. With directional antenna, higher gain allows UAV to communicate with other UAVs located at higher distance in fewer hops. On the other hand, the high mobility as well as the physical constraints imposed by a UAV may cause the use of directional antenna to be less beneficial and meaningless. In this respect, we have designed a new scheme that has the capability of benefitting from the directional antenna and at the same time is capable of handling the above issues. Our scheme is based on the following two performance goals: maximizing network throughput and minimizing End-to-End delay.

4.1 Introduction

Recently, UAV has been used in military applications as well as civilian [21]. It shows great advantages and importance in search and rescue, real time surveillance, reconnaissance operations, traffic monitoring and range extension. Moreover, UAVs are suited for situations that are too dangerous for direct human monitoring. In general, UAVs have the potential to create an Ad-Hoc network and greatly reduce the hops from source to destination. On the other hand, UAVs are characterized by high mobility and attitude variations.

It assumed that in all of the UAVs used in communication networks, each node is equipped with Omni-directional antenna in which signal is transmitted to all directions.

As a result, the capacity of the network and the range of the UAVs are common problems for UAV mobile Ad-Hoc networks. These problems can be largely eliminated by using directional antenna [6, 7, 22, 23, 24]. In this chapter, we considered a collection of UAVs that communicate through a wireless link such as MANET using directional antenna. The current MAC protocol (IEEE 802.11) that implements the Omni-directional antenna may not be suitable while using directional antenna. Thus, a new adaptive medium access control protocol is required to adapt the new technique as well as the constraints imposed by the UAV. To be more specific, we introduced a new mechanism that is called target information table (global profile) to work with our new MAC scheme during the switch from Omni-directional to directional antenna.

The primary challenge to use directional antenna in such network is the errors in UAV position; this leads to the reduction of the directivity in the desired direction. Therefore, a combination of more than one navigation system is the central requirements for a practical solution to the UAV communication system. As is known, GPS provides position information at (1) second interval, this interval will not benefit our scheme since our scheme needs a higher update rate for the position of the UAV. As a result, each UAV should be equipped with a GPS and an Inertial Measurement Unit (IMU) to offer the positions of other UAVs [1, 20, 33]. The benefit of using an IMU with a GPS is that the IMU may be calibrated by the GPS signal, and thus, it can provide position and angle at a quicker rate than GPS.

4.2 Medium Access Control (MAC) Layer Description

The IEEE 802.11 standard [100] specifies the parameters for the medium access control as well as those for the physical layer. It assumes the use of Omni-directional antenna and provides the functionality required to guarantee a reliable data transmission over a wireless media. In the following subsections we will focus on the mechanisms that are used by the MAC layer for the purpose of channel allocation, frame formatting, error checking and fragmentation. Meanwhile, we will study the effect of directional antenna on the performance of this layer.

In IEEE 802.11 standard, wireless MAC protocol is supported by a Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA). CSMA is a technique used by wireless/ wired network for performance improvement. To summarize CSMA, A node wishing to send a data packet should first listen to the medium to see if there is any activity. If the medium is sensed as idle for a Distributed Inter-Frame-Space (DIFS) interval, the node has the right to use the medium and start sending data. On the other hand, if the medium is sensed as busy or it becomes busy during the DIFS time interval, the transmission will be deferred for a certain time (random) until no other node occupies the medium.

Two different network architectures are specified by IEEE 802.11 standard: Ad-Hoc and infrastructure networks. In an Ad-Hoc network, there is no fixed infrastructure such as base station or access point (AP). Nodes in Ad-Hoc network are communicating directly via a wireless link, while in infrastructure network they are communicating through the access point. In addition, IEEE 802.11 standard specifies two access methods (MAC protocols): Distributed Coordination Function (DCF) and Point Coordination Function (PCF). DCF is considered as the basic access method and it is used in Ad-Hoc network while PCF is used in an infrastructure network.

4.2.1 Distributed Coordination Function (DCF)

DCF is considered as one of the main access mechanism in IEEE 802.11 MAC layer. This mechanism determines when and how to access the wireless channel and it has been used to support asynchronous data transfer. DCF employs the Carrier Sense Multiple Access / Collision Avoidance (CSMA/CA) with a random backoff and it specifies two mechanisms for channel sensing: physical carrier sense mechanism and virtual carrier sense mechanism. Physical carrier sensing is performed at the physical layer while virtual carrier sensing is performed at the MAC layer in which Request-to-send (RTS) and Clear-to-send (CTS) frames are exchanged between source and destination. Also DCF specifies a positive acknowledgment scheme that is transmitted by the destination to notify the source node of the successful reception.

Physical carrier sensing is used in Ad-Hoc network to mitigate the interference between nodes. A node wishing to transmit a packet should first assess the current channel by comparing the measured received energy against a predefined threshold. If the node detects that the value of the comparison is below a certain threshold, the node will start packet transmission. Otherwise, transmission will be deferred. As we will see later, OPNET simulator allows the node to generate an interrupt whenever it transmits a packet. This interrupt tells other nodes when transmission started and finished.

Virtual carrier sensing is performed by exchanging request-to-send and clear-to-send frames between source and destination. In DCF, Each node should embed the period of transmission in the header of the RTS and CTS frames. Upon receiving either of these two control packets, the node should extract the duration and store it in a local variable named Network Allocation Vector (NAV). This value shows that the channel is busy and the node couldn't access the medium. By this mechanism, the transmission should be deferred for the duration of the data frame that will follow.

As soon as the node senses that the channel has been idle for a period of time that exceeds the DIFS interval, the node starts packet transmission. Otherwise, packet transmission will be deferred for a period of time named Backoff. The length of the Backoff period is calculated by equation (4.1). The random number in the equation is selected randomly between zero and the contention window value size (CW) [0: CW]. Initially, the size is set to its minimum value (CWmin). If a collision has occurred, the size will be doubled. Table 4.1 shows the values for both the CW and slot time.

$$\text{Backoff time} = \text{Random number X (slot time)} \tag{4.1}$$

In wireless network, a collision is considered if the node does not receive an acknowledgment (ACK) packet from the destination node. As a result, contention window size is doubled for the next transmission attempt. It continues to increase to the CWmax. In DCF, transmission attempt is bounded by a certain number, if the attempts reach this number, the packet will be dropped. Meanwhile, if the medium has been sensed as idle for a DIFS, the timer will be decreased by one. As soon as the backoff timer becomes zero, the source node transmits the packet. The destination node will respond with an ACK message to the source node after a period of time called Short Inter-Frame Space (SIFS) interval. Figure 4.1 shows the IEEE 802.11 DCF Mechanism.

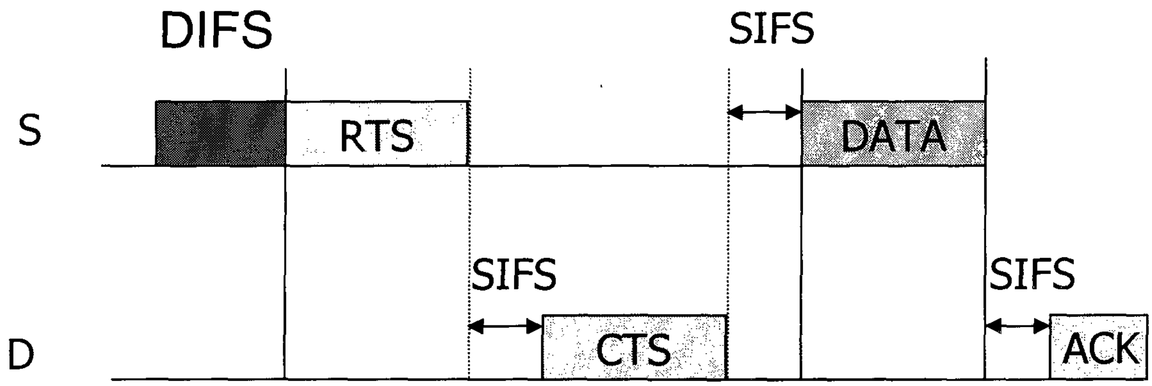


Figure 4.1: IEEE 802.11 DCF Mechanisms

4.2.2 Point Coordination Function (PCF)

Point coordination function is the second MAC technique specified by IEEE.802.11 standard. It is implemented by the point coordinator (PC) to coordinate the communication between the nodes within the network. Accessing wireless channel in PCF is a centralized method. PC sends a contention-free (CF-Poll) frame to the node giving it the permission to transmit a frame. If the polled node does not have any frames to send, null frame is transmitted. The period used by the access point to grasp the channel is called Point Coordination Function IFS (PIFS). PIFS period is smaller than DIFS because the AP always has the priority to access the channel.

As stated above, there are two modes of operations supported by the IEEE802.11 standard: infrastructure and Ad-Hoc. PCF is supported by the infrastructure mode of operation. Nodes in this technique are allowed to send their data only when they receive the polling frames from the point coordinator. In contrast to the DCF technique, nodes in

PCF are able to transmit without contending for the channel access. The point coordinator determines which station should be polled and which station has the right to transmit. PCF has its location above the DCF in MAC layer, and it is an optional access method.

4.2.3 Inter-Frame-Space (IFS)

In DCF, the gap in time between frames is called Inter-Frame-Space (IFS). Each station should determine if the medium is idle through the use of the physical carrier sensing mechanism for the intervals specified in table 4.1. In this table, four different periods are defined to provide priority levels for accessing the wireless channel: Point Coordination Function IFS (PIFS), Distributed Coordination Function IFS (DIFS), short IFS (SIFS) and extended IFS (EIFS).

1. PIFS: This interval should be used only by those nodes implementing the PCF mechanism to gain the access to the medium at the start of the contention-free period (CFP).
2. SIFS: It is considered as the shortest of the inter-space intervals. IEEE.802.11 standard has specified this period as the end of the last symbol of the previous frame to the beginning of the first symbol of the preamble of the next frame. This interval prevents other nodes from attempting to use the medium during the whole phase of exchanging data between two nodes, and thus giving priority to the source and destination to complete the exchange of their data.
3. DIFS: This interval should be used only by those nodes implementing the DCF technique. In the basic access method, as soon as the station senses the channel is idle,

the station waits for DIFS period and start sending their data. DIFS is calculated as shown in equation (4.2).

$$\text{DIFS} = \text{SIFS} + 2 \text{ X } (\text{slot time}) \tag{4.2}$$

4. EIFS: This interval should be used by the DCF whenever the physical layer has indicated to the MAC layer that there has been an error in frame transmission. EIFS is not used to control access to the radio link. But, if previously received frame contains error, the node has to defer for EIFS duration instead of DIFS before transmitting a frame.

$$\text{EIFS} = \text{Transmission time of (Ack) frame at lowest basic rate} + \text{SIFS} + \text{DIFS} \tag{4.3}$$

Table 4.1

Inter-Frame-Space Intervals

Frequency hopping (FH)	**Direct-Sequence Spread Spectrum (DSSS)**	**Infra red**
Tslot=50 us	Tslot=20 us	Tslot=8 us
SIFS= 28 us	SIFS= 10us	SIFS= 10 us
CWmin= 15	CWmin= 31	CWmin= 63
CWmax=1023	CWmax=1023	CWmax=1023

4.3 Physical Layer Description

As shown in table 4.2, The IEEE 802.11 standard defines the physical layer specifications that are mainly comprised of modulation type, frequency, channel bandwidth and transmission power. It specifies three physical layer technologies: Frequency Hopping Spread Spectrum (FHSS) physical layer, Direct Sequence Spread Spectrum (DSSS) physical layer and infrared physical layer. The IEEE 802.11b physical layer, as in other protocols, consists of two sub-layers: Physical Layer Convergence

Procedure (PLCP) and Physical Medium Dependent (PMD) sub-layers. The PLCP sub-layer is used to prepare the MAC Protocol Data Unit (MPDU) for transmission. It is also used to deliver the incoming frames from the wireless medium to the MAC layer. PMD sub-layer interfaces directly with the air medium and it is responsible for the modulation and demodulation of frames.

Table 4.2

IEEE 802.11 Physical Layer Standards

	802.11	**802.11a**	**802.11b**	**802.11g**
Bandwidth	83.5 MHz	300 MHz	83.5 MHz	83.5 MHz
Frequency	2.4 - 2.4835 GHz DSSS, FHSS	5.15 - 5.35 GHz OFDM 5.725 - 5.825 GHz OFDM	2.4 - 2.4835 GHz DSSS	2.4 - 2.4835 GHz DSSS, OFDM
Data rate	1, 2 Mbps	6, 9, 12, 18, 24, 36, 48, 54 Mbps	1, 2, 5.5, 11 Mbps	1, 2, 5.5, 6, 9, 11, 12, 18, 24, 36, 48, 54 Mbps

4.3.1 Antenna Basics

Antenna is a metallic device that is designed for radiating or receiving radio waves. To choose an antenna for a radio communication system, several important parameters should be considered. The most important are antenna radiation pattern and gain. Antenna radiation pattern can be defined as a plot of the strength of the electromagnetic field in all directions around the antenna while antenna gain is the ratio of the radiation intensity in a specific direction to the radiation intensity of the ideal isotropic antenna. The two important types of antennas are the isotropic Omni-directional antenna and the directional antenna. Isotropic antenna radiates and receives power equally in all directions while directional antenna focuses energy in the desired direction. Directional antennas as we will see in the next sections are usually used in some applications to cover long distances. Figure 4.2 shows the patterns for the omni-directional antenna and directional antenna; the antenna pattern on the left represents the isotropic omni-directional antenna while the antenna pattern on right represents the directional antenna.

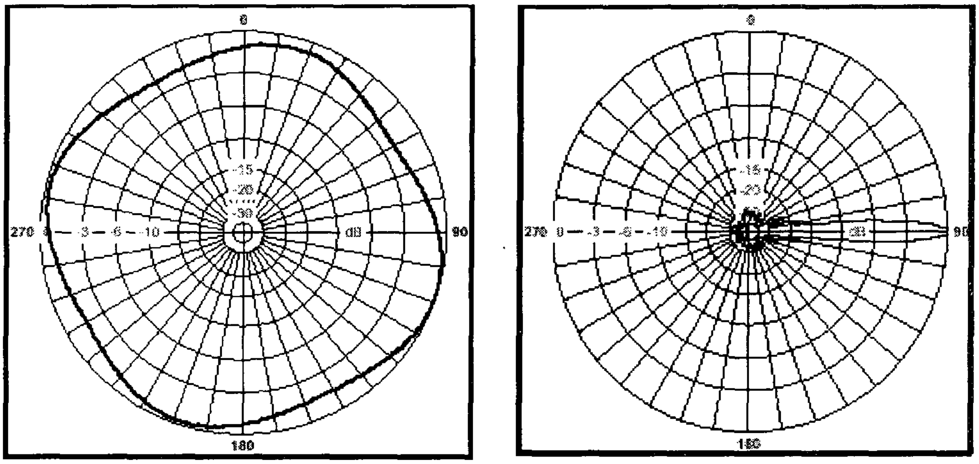


Figure 4.2: Typical Radiation Pattern for Omni-Directional and Directional Antennas

4.3.2 Modeling Smart Antenna

Smart antennas are a promising technology nowadays to address the demand of UAV wireless communication systems in terms of capacity and area coverage. Simply, smart antenna is an array of (N) antenna elements that act together to form the required radiation pattern. This type of antenna is capable of changing its radiation pattern dynamically in order to adjust to the variations in channel's noise and interference. Due to the high mobility of the UAV, the direction between aircrafts will be continually changed. Exploiting smart antenna in UAV Ad-Hoc network requires an intelligent system to decide when and where to point the antenna pattern. In our system we assumed that each UAV is equipped with four antennas, two of them are directional antennas (steerable antenna) and two of them are Omni-directional antennas. Smart antennas in general are classified into two categories: switched beam and adaptive array.

1. Switched-beam antenna: As shown in figure 4.3, a switched-beam antenna system consists of several fixed, predefined beams. Switched-beam antennas are less complex than the adaptive antenna and are easier to implement because they need only a basic switching functionality between separate directive antennas. The number of beams in switched-beam antenna is limited to a certain number and only one antenna can be used at any given time. This type of system switches the beams toward the strongest signal but does not actively null out the interference.

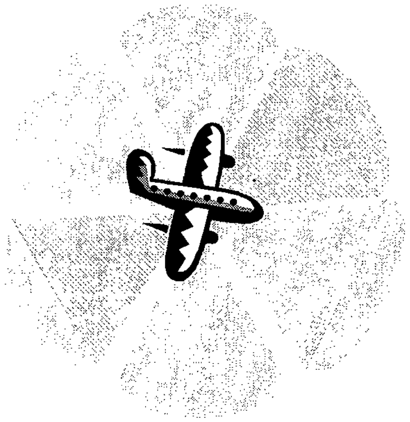


Figure 4.3: Switched Antenna with Six Elements

2. Adaptive array antenna: As shown in figure 4.4, an array of more than two antennas can be arranged spatially in a certain way to generate the required radiation pattern (The array may be circular or linear). This system is able to form multiple main lobes in the desired directions and steering nulls in the direction of interference. Simply, the phases of

the exciting current in the array are adjusted so that the maximum or null pattern is created. Adaptive array is more beneficial than switched beam but it is highly complex in reality. Adaptive array also allows the node to communicate with two or more nodes using the same frequency.

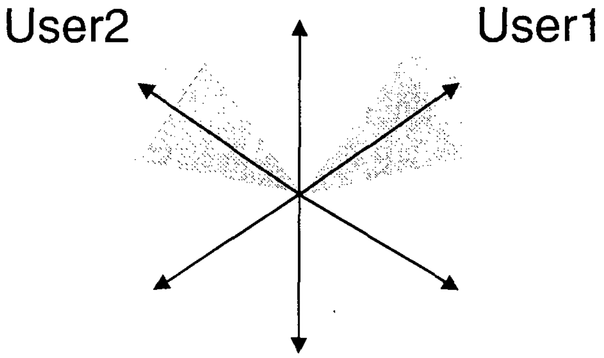


Figure 4.4: Antenna Pattern of Adaptive Array

To illustrate how the radiation pattern is calculated, assume that we have (i) elements of an array receiving signals from (l) sources, the received signal can be written as shown in equation (4.4) where the A_{il} is the signal strength and the P_{il} is the phase lag. The total signal received from the (l) sources is shown in equation (4.5). To find the output y in the direction of (l), we have to multiply equation (4.5) with the weighting coefficient W as shown in equation (4.6). From equation (4.6), the gain of the antenna in the direction of (l) is seen in equation (4.7).

$$K_{il} = A_{il} \times P_{il} \times e^{jwt} \tag{4.4}$$

$$Ki = \sum A_{il} \times P_{il} \times e^{jwt} \tag{4.5}$$

$$y = \sum k_i \times W_i$$

$$y_l = A_l \times e^{jwt} \sum P_{il} \times W_i \tag{4.6}$$

$$G_l = \sum P_{il} \times W_i \tag{4.7}$$

If i= l, we can rewrite equation (4.7) in a matrix form as shown below

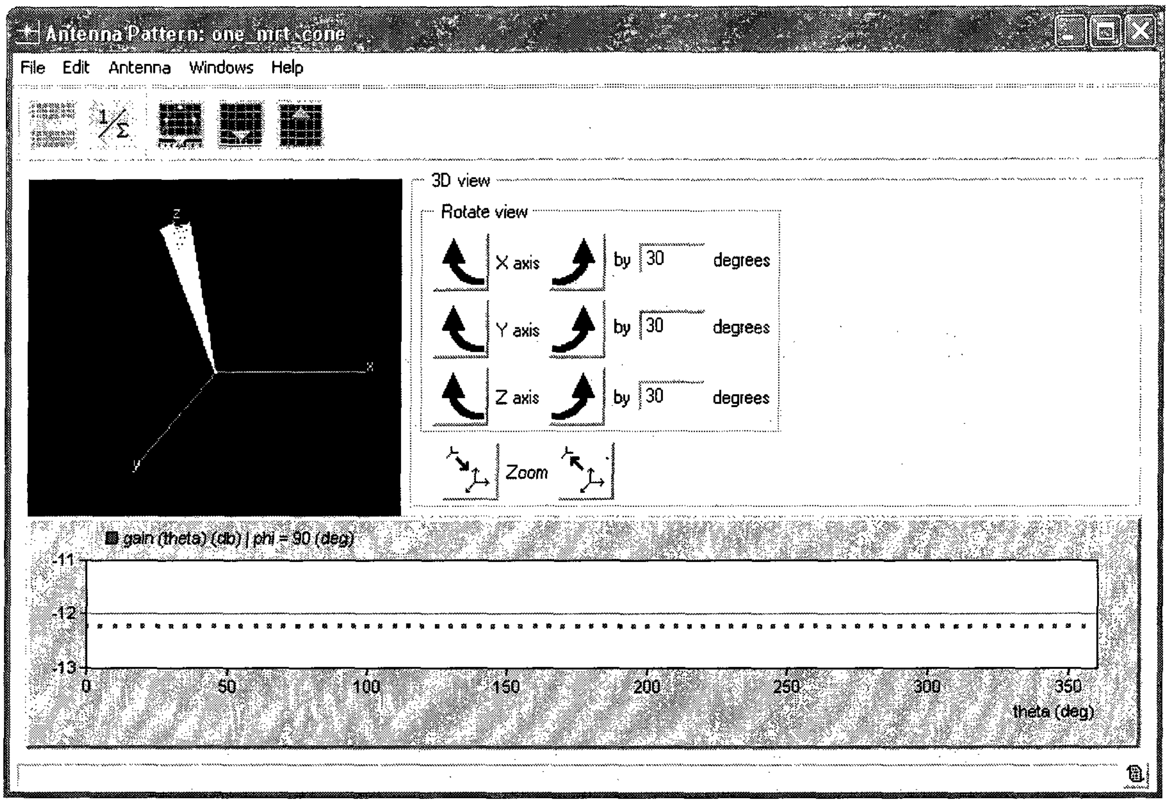
$$\begin{bmatrix} G_1 \\ \bullet \\ G_l \end{bmatrix} = \begin{bmatrix} P_{11} & \bullet & P_{1i} \\ \bullet & \bullet & \bullet \\ P_{i1} & \bullet & P_{ii} \end{bmatrix} \begin{bmatrix} W_1 \\ \bullet \\ W_i \end{bmatrix}$$

To find the radiation pattern in particular direction, W matrix should be calculated as shown below.

$$\begin{bmatrix} W_1 \\ \bullet \\ W_i \end{bmatrix} = \begin{bmatrix} P_{11} & \bullet & P_{1i} \\ \bullet & \bullet & \bullet \\ P_{i1} & \bullet & P_{ii} \end{bmatrix}^{-1} \begin{bmatrix} G_1 \\ \bullet \\ G_l \end{bmatrix}$$

4.3.3 UAV Antenna System

We have constructed our directional antenna pattern in Optimized Network Engineering Tool (OPNET). Figure 4.5 shows the OPNET interface window used to create the pattern of the directional antenna. The maximum gain in the pointed direction is set to 200dB and -12dB in other directions. The beam width is set to 5 degrees .The novelty in our antenna system relies on designing a new MAC protocol that is capable of switching between two directional antennas. Figure 4.6 shows the first antenna that is mounted at the top of the UAV and the second antenna that is mounted at the bottom of the UAV. In our modeling of the antenna system, there are two modes of operations: directional and Omni-directional. In directional mode, antenna consists of a steerable single beam which is dedicated for data transmission, while in Omni-directional mode; antenna is dedicated for control packets. Selection between directional antenna will rely on the altitude of the aircrafts and on the value of the retry counter within the MAC layer.



X axis by 30 degrees

Y axis by 30 degrees

Z axis by 30 degrees

Figure 4.5: Modeling Directional Antenna in OPNET

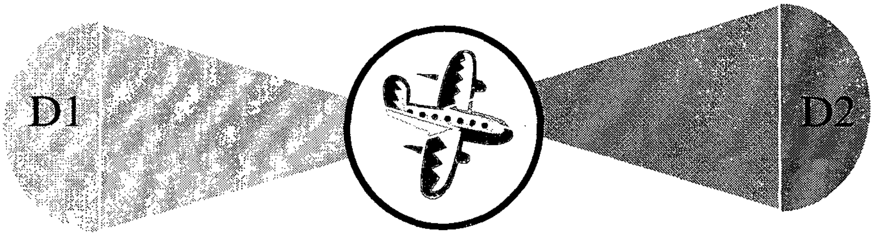


Figure 4.6: Coverage Range of MAC Protocol Using an Omni-Directional and Directional Antenna

Generally speaking, there are many parameters that affect the value of the received power. Assume that the gain of the Omni-directional antenna is (G_o) and the gain of the directional antenna is (G_d). Friis equation (4.8) represents the relation between gains of both transmitter and receiver antenna, and transmitter and receiver power.

$$\frac{P_r}{P_t} = G_t G_r \left(\frac{\lambda}{4\pi R} \right)^2 \tag{4.8}$$

Where P_r represents the received power and P_t represents the transmitted power. G_t and G_r are the antenna gain of the transmitting and receiving nodes, λ is the wavelength, and R is the distance between the transmitter and the receiver. From the equation, the distance between any two nodes is proportional to the gains of transmitter and receiver antenna. For directional antennas, the gain is formulated as a function of the direction of the destination node $\vec{D} = (\varphi, \theta)$ and is given by equation (4.9).

$$G(\vec{D}) = K \left(\frac{Y(\vec{D})}{Y_P} \right) \tag{4.9}$$

Where $Y(\vec{D})$ is the power density in the desired direction $\vec{D}$. Y_P is the average power density over all directions and K is the efficiency of the antenna that accounts for losses. In general, the gain of the directional antenna measures the relative power in one direction compared to an Omni-directional antenna.

The received signal $Y(t)$ can be modeled in terms of the transmitted signal and the background noise. Assume that UAVi and UAVj are in communication session. The signal received by UAVs is given by equation (4.10).

$$Y(t) = WH_{ij} X(t) + N(t) \tag{4.10}$$

Where $X(t)$ is the transmitted signal, W is the weighted vector, which represents the antenna elements in use , for example , two antenna represented by [1 ,1] , H_{ij} is a matrix that models the physical channel between the UAVs, and N(t) denotes additive white Gaussian noise.

4.4 Adaptive MAC Protocol for UAV Node (AMAC_UAV)

The performance of the unmanned aerial vehicle Ad-Hoc network depends on several factors such as mobility and aircraft attitude. We assumed that all UAVs are placed over the ground and flown at different altitudes. The distance between any two UAVs will not go beyond the range of the directional antenna. Two externals hardware are needed in our scheme for node location: GPS and IMU. When a packet comes from the upper layer, the node requires the position of the destination in order to steer the main lobe in the right direction. Control packet of type RTS will be sent using Omni-directional antenna; it should include the position of the aircraft and duration of transmission. On the other hand, the destination node will respond with a CTS packet that has the same information regarding itself. Each node that hears the CTS or RTS should cache this information and update its table for future use. The data packet will be sent using directional antenna. To simplify things, we presented our scheme in Figure 4.7 based on the following facts:

Case A: Every UAV has four antennas. Two of them are directional. One is located above the UAV and marked primary, and the second one is located beneath the UAV and marked secondary. The two other antennas are Omni-directional. If the UAV has no packet to send, it will listen to other UAVs using one of the Omni-directional antennas. On the other hand, if the UAV has a packet to send, it has the choice to send this packet either using directional or Omni-directional antenna.

Case B: The locations of the UAVs are significant factors in our scheme. The new MAC should frequently monitor the positions of other UAVs and compute the effect of Euler angles on the directional antenna.

Case C: The new MAC should frequently monitor the distance, bit error rate and retry counter so that it switches to Omni-directional antenna if the values exceed the limits.

Case D: In the case that there is no activity during a second, UAV should send a heartbeat message using Omni-directional antenna. This message contains the location of the UAV. When it is received by another UAV, the UAV should update its table and respond with a similar heartbeat message.

Case E: In our scheme each UAV is capable of electronically steering the beam towards a specific direction. Our modeling of the antenna is described in section 4.3.3 and is based on a single beam that can target the boresight to any direction.

Case F: In the case that the aircraft changes its attitude, the pattern of the antenna will rotate with respect to its axis, resulting in fluctuations in antenna gain, these fluctuations affect the range of the UAV. Thus, the MAC protocol should compensate for any changes by applying the same value to the target location.

Case G: Switching time between primary and secondary antenna is assumed to be zero.

Case H: The mobility model in such a network is not completely random. In military scenarios, each UAV should move to a predefined location. Thus, our model is based on a rounded rectangle [32] mobility model. Section 4.5.3 will give more detail for the mobility models.

According to the IEEE 802.11 standard, a packet is discarded after the retransmit counter exceeds (7). Meanwhile, as the number of retransmission attempts increases, the number of possibilities for delay increases. Based on the Distribution Coordination Function (DCF), a node should sense the channel to determine whether it is idle or not. Sensing is done through physical and virtual mechanisms. If the medium is sensed idle for a DCF inter-frame-space (DIFS) interval, the node has the right to use the medium and start sending data. On the other hand, if the medium is busy or it becomes busy during the DIFS time interval, the transmission will be deferred for a certain time until no other node occupies the medium. In such a situation backoff timer is enabled. Our scheme follows the IEEE 802.11 standard with some modification to the retry counter.

As stated in section 4.2.1, there are two methods for carrier sensing in IEEE 802.11 standard, physical carrier sensing and virtual sensing. Virtual sensing is done through the use of network allocation vector (NAV). Two messages should precede the data transmissions which are RTS and CTS, these messages contain the duration for which the UAV should reserve the channel to complete the data transmission. On the other hand, any UAV that overhears these messages should defer data transmission for this duration to avoid interfering with other UAVs' transmission. In our scheme, RTS and CTS should contain the location and orientation of the UAV. We use the directional network allocation vector (DNAV) mechanism [27] with some modification to adapt our scheme while using UAVs. Our DNAV is synchronized with the target information table that is created through the handling of the control messages. In addition, the original NAV is also used in our scheme.

The behavior of our scheme works as follows:

1) To resolve the hidden terminal problem, a CTS/RTS packet is exchanged between the UAVs. Consider the case when UAV number one is attempting to send a packet to UAV number two: if the packet is of type control, UAV number one will perform physical carrier sensing as in IEEE 802.11 standard. If the channel is idle, another sensing will be done for NAV to see if the channel is still reserved by another UAV. Once the medium as

well as the NAV are all idle, the UAV will enter the backoff period for a certain time then RTS packet will be sent through the Omni-directional antenna along with the parameters of UAV number one (location, orientation).

2) UAV number one as well as number two are equipped with a GPS and IMU to offer the position at high rates. Once the UAV number two receives RTS from UAV number one, it will sense the channel for short inter-frame-space (SIFS) interval. If the channel is free, it will send the CTS along with the previous parameters in response using omni-directional antenna and update the target information table as shown in table 4.3. UAVs other than number two that also received either RTS or CTS should update their target information table as well as DNAV and NAV.

3) Once UAV number one receives the CTS message, it will update its target information table. Before initiating the transmission of data packet, the MAC will check the distance between the UAVs. If the distance is less than the range of the Omni-directional antenna (Dmax), the data will be sent using Omni-directional antenna; otherwise the MAC will check UAVs' altitude. If the altitude of UAV number one is equal or less than that of UAV number two, data will be sent through the primary antenna (directional antenna) along with UAV parameters then the MAC steers the beam to the direction of UAV number two, otherwise secondary antenna will be steered to the same direction.

4) As soon as UAV number two receives the data successfully and updates its target information table, ACK will be sent using Omni-directional antenna along with UAV parameters.

5) For each data packet, antenna is steered based on the destination location as well as the source Euler angles. To be more specific, consider UAV number one's attempt to send

the second data packet. The location of the UAV number two is obtained from the ACK packet. If the MAC of the first UAV sensed some changes in the angles after receiving the target location, the MAC should compensate for this by applying the same value to the target location.

6) As mentioned above, a packet is discarded after the retransmit counter exceeds (7). Since our goal is to minimize the End-to-End delay, our scheme will switch the transmission from directional to Omni-directional if the retransmit counter reaches five.

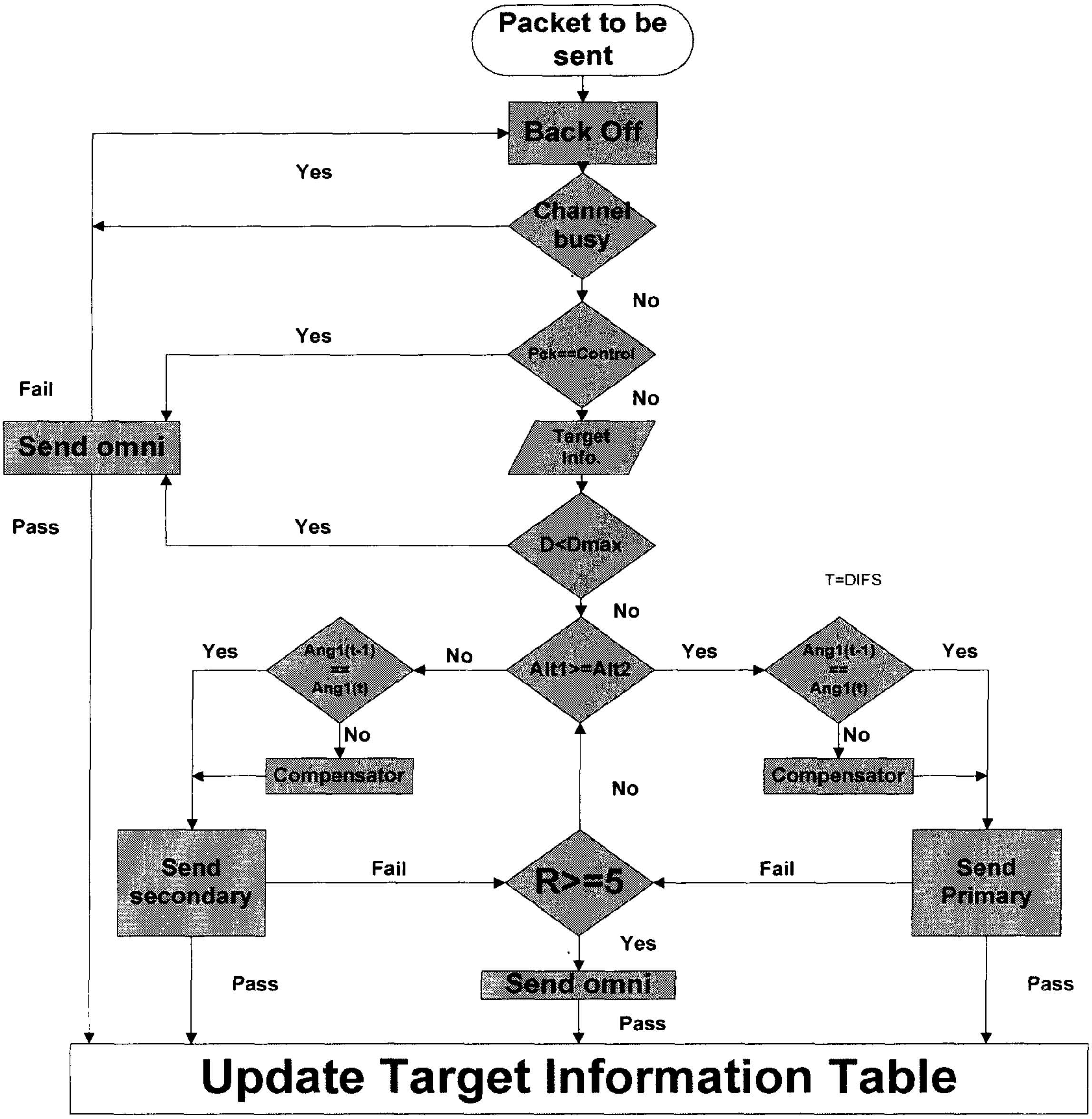


Figure 4.7: MAC Scheme Flow Chart for UAV

Table 4.3

Target Information Table

Target ID	Latitude (Deg Min Sec)	Longitude (Deg Min Sec)	Altitude (Feet)	Direction (Deg)
1	43 16 32 N	85 38 46 W	500	90
2	43 16 32 N	85 38 36 W	450	90

4.5 UAV Implementation in OPNET

4.5.1 OPNET Modeler 14.5

The Optimized Network Engineering Tool (OPNET) modeler is considered as one of the powerful software simulation tools, it is dedicated for network research and development. The OPNET modeler software is a discrete-event network simulator that includes a set of detailed models for Ad-Hoc network. It uses graphic user interfaces and allows the user to create new models by either modifying existing models or building new one. It uses a Finite State Machine (FSM) model in which a collection of states are linked together based on C code. Each state is divided into two parts: enter executives and exit executives. Both parts specify a series of actions that a process implements when it occupies a state. The enter executive is executed as soon as the state is entered by the process while the exit executive is used in the unforced state to implement a response to an interrupt.

4.5.2 Channel Model

In our simulations, we modeled the wireless link between transmitter and receiver with fourteen pipeline stages. These stages are provided by the OPNET modeler and divided between transmitter and receiver as shown in figure 4.8. Six stages (0-5) are associated with radio transmitter and eight stages (6 -13) are associated with radio receiver. Below is a description for all stages.

1. Receiver Group (Stage 0): This stage is called only once for each pair of transmitter and receiver channels in the network; by this stage every transmitter maintains a set of channels that are going to receive its transmission. The purpose of this stage is to model the broadcast nature of the radio by creating links between one transmitter and a set of receiver channels with which it is allowed to communicate.
2. Transmission Delay (Stage 1): This stage is the first stage of the pipeline. It is called immediately as soon as the transmission of a packet is started. It is used to calculate the amount of time that is required for the packet to be transmitted. The output from this stage is computed as the time difference between the beginning of transmission of the first bit and the end of transmission of the last bit and is assigned to the variable (OPC_TDA_PT_TX_DELAY). Another method for calculating this value is dividing the packet's length by the data rate. This result is then used by the Simulation Kernel in order to schedule the end of transmission event for the channel that is used for transmission. As soon as this event happens, the transmitter channel becomes idle and starts sending another packet if it has any. In addition, the output from this stage is added to the output of the propagation delay stage in order to compute the time at which the packet completes reception at the other side.

3. Closure (Stage 2): This stage is called immediately after the end of the transmission delay stage 1, closure here means the ability of the transmission to reach the receiver channel .The purpose of this stage is to determine whether or not the transmitted signal can physically reach the receiver channel.

4. Channel Match (Stage 3): In this stage, transmission is classified with respect to the receiver channel into three types: (a) valid: packet is classified as valid if the transmitter and receiver channels are in agreement on the values of certain key attributes. (b) Noise, packet is classified as noise if the transmitter and receiver channel configurations are incompatible. (c) Ignored: packet has no effects on the state of the receiver channel.

5. Transmitter Antenna Gain (Stage 4): In general, antennas are classified into directional and isotropic. Isotropic refers to the antenna that provides no gain to the transmitted signal while directional refers to the one that provides gain to the signal. The word gain itself is defined as the ratio of the power that is produced by the antenna at a given distance and the isotropic power produced at the same distance. This value is unit-less and given in decibels. The purpose of this stage is to compute the gain value of the antenna attached to the transmitter. This value is used in the calculation of the received power. Simply, the gain is calculated based on the direction between the transmitter and the receiver and the antenna attributes: target latitude, target longitude and target altitude.

6. Propagation Delay (Stage 5): This stage is invoked after the simulator returns from the transmitter antenna gain stage. The output from this stage represents the time required for the packet to travel from the source to the destination and is assigned to the variable (OPC_TDA_PT_PROP_DELAY). The value of this variable depends on several parameters such as: physical medium, distance and frequency. This value is used by the

simulation kernel to schedule the beginning of the reception event for the destination node. In addition, as stated above, this value is used in conjunction with the result from stage 1 to compute the time at which the packet completes reception.

7. Receiver Antenna Gain (Stage 6): This is the first stage that is associated with the receiver and it is invoked at the time that the leading edge of the packet arrives at the destination. The purpose of this stage is to compute the gain of the antenna attached to the receiver. The process for calculating the gain is identical to that presented in stage 4 where it is used in the calculation of the received power.

8. Receiver Power (Stage 7): This stage is invoked after the simulator returns from the receiver antenna gain stage; it is used to compute the power of the arriving packet's signal. The value of the received power depends on transmitter power, distance between the nodes (r), wave length, and transmitter and receiver antenna gains as shown in equation (4.11).

$$P_r = P_{tx} x G_{tx} x (\frac{\lambda^2}{16\pi^2 r^2}) x G_{rx} \tag{4.11}$$

9. Background Noise (Stage 8): This stage is used to represent the effect of all noise sources on the arriving packets. The result is the sum of the power of noise sources such as thermal noise, emissions from neighboring electronics, and un-modeled radio transmissions. This value is later used to find the signal-to-noise ratio.

10. Interference Noise (Stage 9): This stage is responsible for the interaction between concurrent transmissions that arrive at the same receiver channel. This value is used later to decide whether to accept or reject the packet at the last stage.

11. Signal-to-Noise Ratio (Stage 10): The purpose of this stage is to calculate the SNR associated with the arriving packet. Part of the calculation in this process is based on

previous values from stages 7, 8 and 9. This stage is significant because it determine the ability of the receiver to correctly receive the packet's content. The value of the SNR is stored to be used latter by other stages.

12. Bit-Error-Rate (Stage 11): This stage is intended to derive the probability of bit errors during the past interval of a constant SNR. The value provided by this stage is calculated based on the received power value calculated in stage 7 and on the value of Signal-to Noise ratio calculated in stage 10. This value is stored in OPC_TDA_RA_BER to be used later.

13. Error Allocation (Stage 12): This stage is invoked immediately after the end of the Bit-Error-Rate stage. Its purpose is to estimate the number of errors in a packet and it is used to update the Bit-Error Rate (stage11).

14. Error Correction (Stage 13): This stage is invoked when the packet is completely received. The purpose of this stage is to determine if the arriving packet is accepted or not so that it can be forwarded to the receiver's modules. This stage is based on two factors: the result from stage 12 and the ability of the receiver to correct the errors in the affected packet. The decision taken in this stage will be passed to the kernel so that it destroys the packet, or allows it to proceed into the destination node.

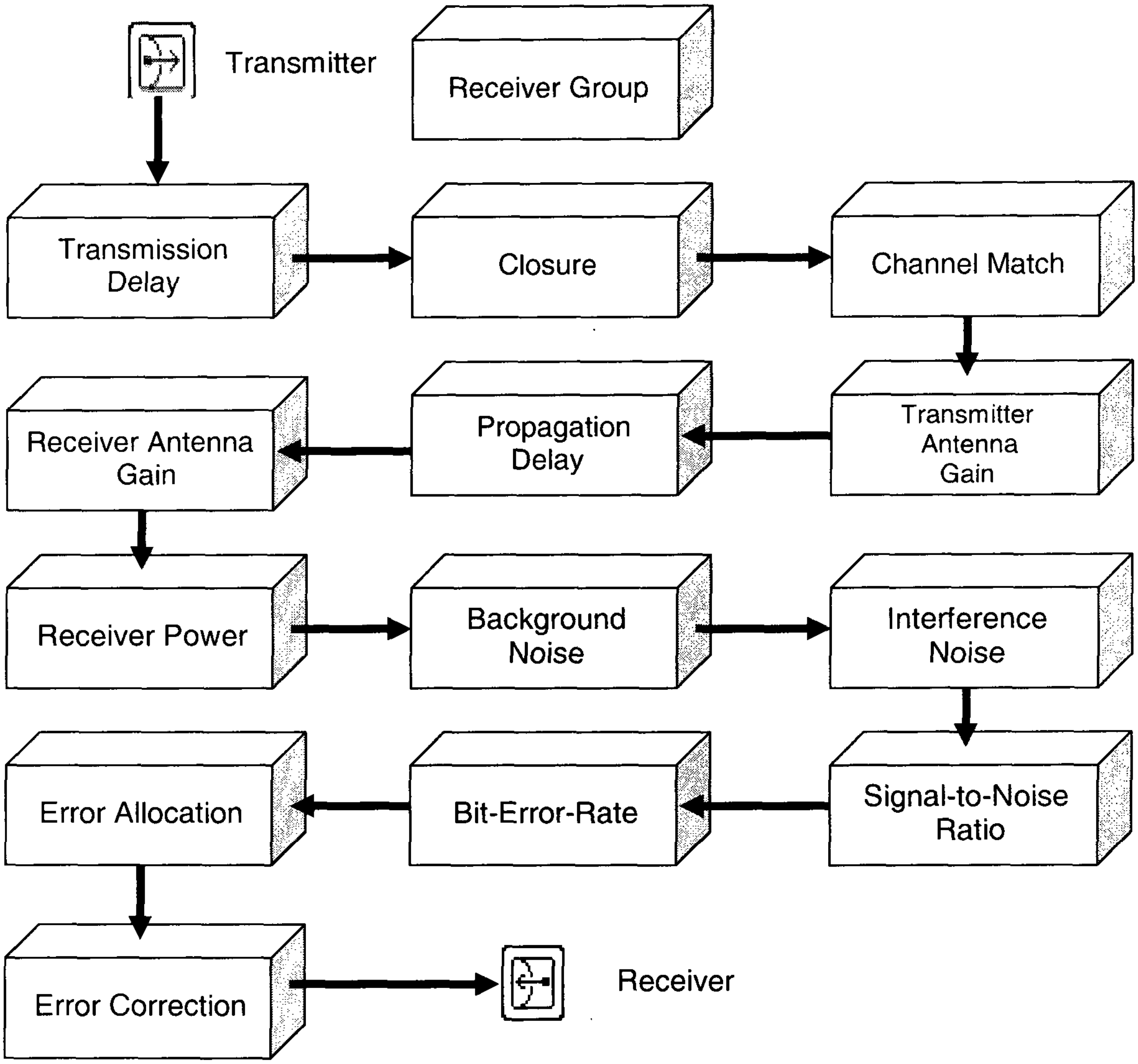


Figure 4.8: OPNET Radio Transceiver Pipeline Stages

4.5.3 UAV Mobility Model

The movement of the UAV has a significant influence on the performance of the network. Therefore, much research was devoted to build different mobility models that are suitable for evaluating the performance of the Ad-Hoc networks. A large number of mobility models were introduced; they have different properties and each has its own advantages and disadvantages. In general, the mobility model of the node in a MANET can be classified into two types:

1. Stochastic mobility models.
2. Realistic mobility models.

In stochastic mobility models, the mobile nodes move randomly and freely without any constraints. Speed, direction and destination addresses are chosen randomly and independently. One type of stochastic mobility model is shown in figure 4.9. This model is called random way point. In random way point, the node randomly chooses a destination and a random speed distributed uniformly in the interval [0, Vmax]. As soon as the node reaches the first destination with the selected velocity, it pauses there for a certain random time. The random time is uniformly distributed in [Tmin, Tmax], then the node moves towards the new random destination with a random velocity. The node will keep doing this procedure until the end of the simulation time. Recent research modifies this procedure by assuming that the pause time is equal to zero and the initial velocity is equal to Vmin.

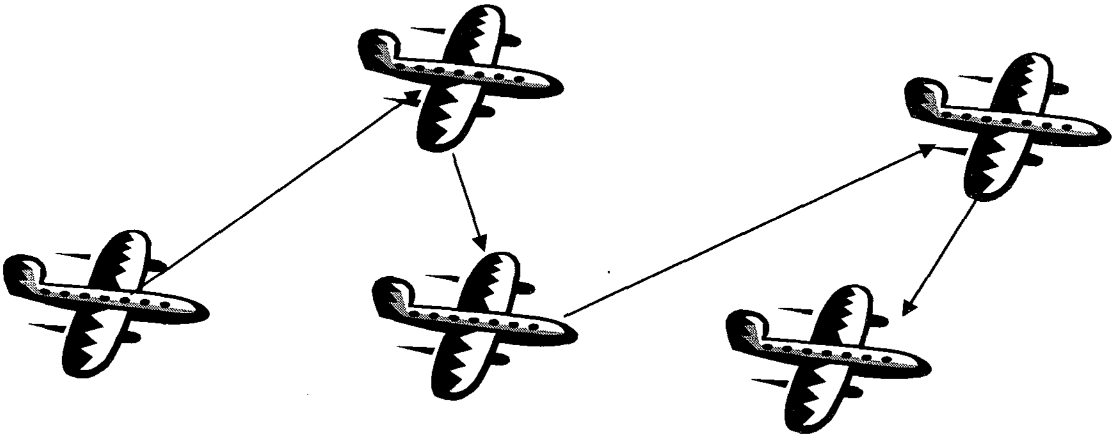


Figure 4.9: Mobility Model of the UAV in Random Way Point Method

Another type of stochastic mobility model is the random walk mobility model; this model is close to the random way point so it can be considered as a random way point with zero pause time. The nodes in random walk model change their speed and direction randomly. Each node chooses a random direction that is uniformly distributed within the range [0, 2π], and also choose a random speed that is also uniformly distributed [Vmin, Vmax]. The node then moves for a certain period of time or over a fixed distance with the chosen speed; at the end of this interval the node repeats the procedure with a new random direction and speed.

The last type is the random direction model which is also considered as a special type of the random way point. In this type, the node chooses a random direction and travels with a random speed until it faced an edge then it chooses another direction and repeats the procedure.

As the random way point, the random walk model and the random direction model are just unrealistic model, the velocity of node is a memory-less random process in that the current speed is independent of the previous one. Thus, a sudden stop, acceleration and sharp turn may frequently occur during the mobility of the node. On the other hand, the real life scenarios assumed that the speed of the node is accelerated incrementally and the direction is changed in a smooth manner. Also the previous models are sometimes called entity mobility model in that the node moves freely and independently of other nodes which totally contradicts the movement of the UAV in the military scenarios. Any node in military scenarios is moved in a predefined trajectory so that the movement is not completely random.

Smooth random mobility model and Gauss-Markov mobility model are classified as realistic mobility models. In smooth random mobility model, the mobile node changes its speed and direction in a smooth way where the parameters are changed gradually. Each node is characterized by a motion vector (V, Φ), V is the speed of the node and Φ is the direction. The following equations show how the motion vector and the position of the node are updated (every Δt) in such a model.

$$X(t+\Delta t) = X(t) + V(t) \times COS(\phi(t)). \tag{4.12}$$

$$Y(t+\Delta t) = Y(t) + V(t) \times SIN(\phi(t)). \tag{4.13}$$

$$\phi(t+\Delta t) = \phi(t) + \Delta(\phi)). \tag{4.14}$$

The mobility model for UAV should be close to the real life. In this chapter, we model the mobility of the UAV with six parameters (pitch, roll, yaw, latitude, longitude and altitude). Each UAV is moving in a pentagon route as shown in Figure 4.10 where X represents the start location of the UAV. The route of the UAV will continue to point B with a constant speed and zero pitch, zero yaw, zero roll. For each segment we changed one parameter, table 4.4 shows the parameters in more details.

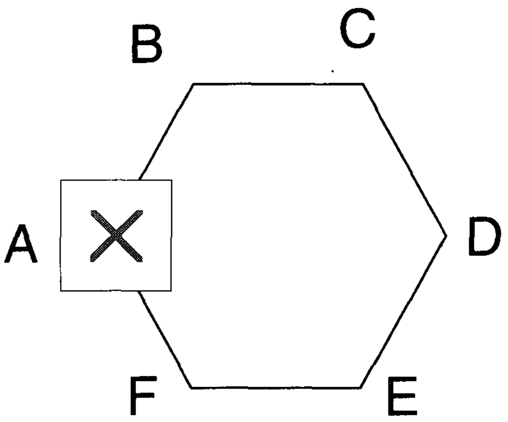


Figure 4.10: UAV Mobility Model in OPNET

Table 4.4

UAV Mobility Parameters

segment	Latitude	longitude	altitude	pitch	roll	yaw
AB	B	B	500	0.0	0.0	0.0
BC	C	C	500	1.0	0.0	0.0
CD	D	D	500	0.0	1.0	0.0
DE	E	E	500	0.0	0.0	1.0
EF	F	F	500	1.0	0.0	0.0
FA	A	A	500	0.0	1.0	0.0

4.5.4 Modeling UAV with Two Directional and Two Omni-Directional Antenna

As shown in Figure 4.11, UAV is modeled according to the OSI stack. Some layers have been omitted and some modifications were added to the original modules. The UAV model consists of three main sections: physical layer, data link layer and upper layers. The first part represents the physical layer; this part is slightly different from the OPNET standard model. As shown in the figure, the physical layer is composed of transmitter module, receiver module and antenna module. In UAV modeling, we have used three transmitters, one receiver and four antennas. One Omni-directional antenna is connected to the receiver module and three antennas are connected to the transmitter modules, one of them is an Omni-directional antenna while others are directional antenna. All of the above modules are responsible for the wireless communication between UAVs.

The second part is the data link layer. This part is divided into two modules: the first one is the original MAC module (wireless_lan_mac) and the second is our module (UAV_SUB_MAC). The wireless_lan_mac module implements the MAC protocol defined by the IEEE 802.11 standards. This module is designed mainly to be used with

Omni-directional antenna. Some modifications have been done to this module in order to link the directional antennas with the radio transmitter modules and enabling this module to work as a two mode module. The second module implements our scheme described in section 4.4 and it acts as an interface between the wireless_lan_mac and the lower layer modules. Both modules work jointly to serve our new scheme.

The last part is the upper layers. The upper layers are mainly composed of the following modules: ARP module, IP module, IP_ENCAP module, TRAF_SRC module, UDP module, DHCP module, MANET_RTE_MGR module and CPU module. These modules mainly generate data packets and implement the OLSR routing protocol. For example, TRAF_SRC module performs the function of generating raw packets. These packets are simply unformatted bits which are encapsulated as IP datagram by the IP_ENCAP module. The IP module implements the IP protocol and the MANET_RTE_MGR module implements the OLSR protocol and manages the statistics for simulation runs.

As discussed earlier, the UAV_SUB_MAC module will work jointly with the wirless_lan_mac module. Figure 4.12 shows the process model for the UAV_SUB_MAC. The process is constructed by seven states where the numbers in parentheses give an approximate number to the line code used in each state. Below is the function of each state.

Init state: This state initializes state variables and target information table.

Idle state: This is the default state. The node enters an idle state and waits for an incoming event. The event can be either self interrupt or an incoming packet from the wirless_lan_mac module. An incoming packet from the wirless_lan_mac will be checked based on its type; control packets will be sent to the Omni state while data packets will be sent to target table state. In addition, this state will read the initial parameters that affect the selection of antenna as well as the MAC attribute values.

Omni state: In this state, the incoming packet will forward to Omni-directional antenna.

Reset state: This state adds some delay to permit other modules to register themselves.

Target Table state: This state determines whether the packet belongs to the primary state or secondary state based on the UAVs' altitude.

Primary state: In this state, the target location is obtained in order to point the directional antenna to that location. The UAV attitude is recorded for each packet so that any change will trigger the compensator.

Secondary state: This state performs the same functionality as the Primary state.

As soon as the packet is received by wireless_lan_mac module from the upper layer, the wireless_lan_mac encapsulates this packet into a frame and sends it to the UAV_SUB_MAC module. In OPNET simulator, each node has an ID. All nodes involved in the network register their IDs in a global array. UAV_SUB_MAC module (Primary state and Secondary state) fetches the destination address (ID) from the received packet and retrieves its location from the global array. Since all nodes are mobile, our module fetches the target location for each packet, which includes longitude in degrees, latitude in degrees and altitude in meters. This information is then used by the primary and secondary states to point the main lobe of the directional antenna to the target location.

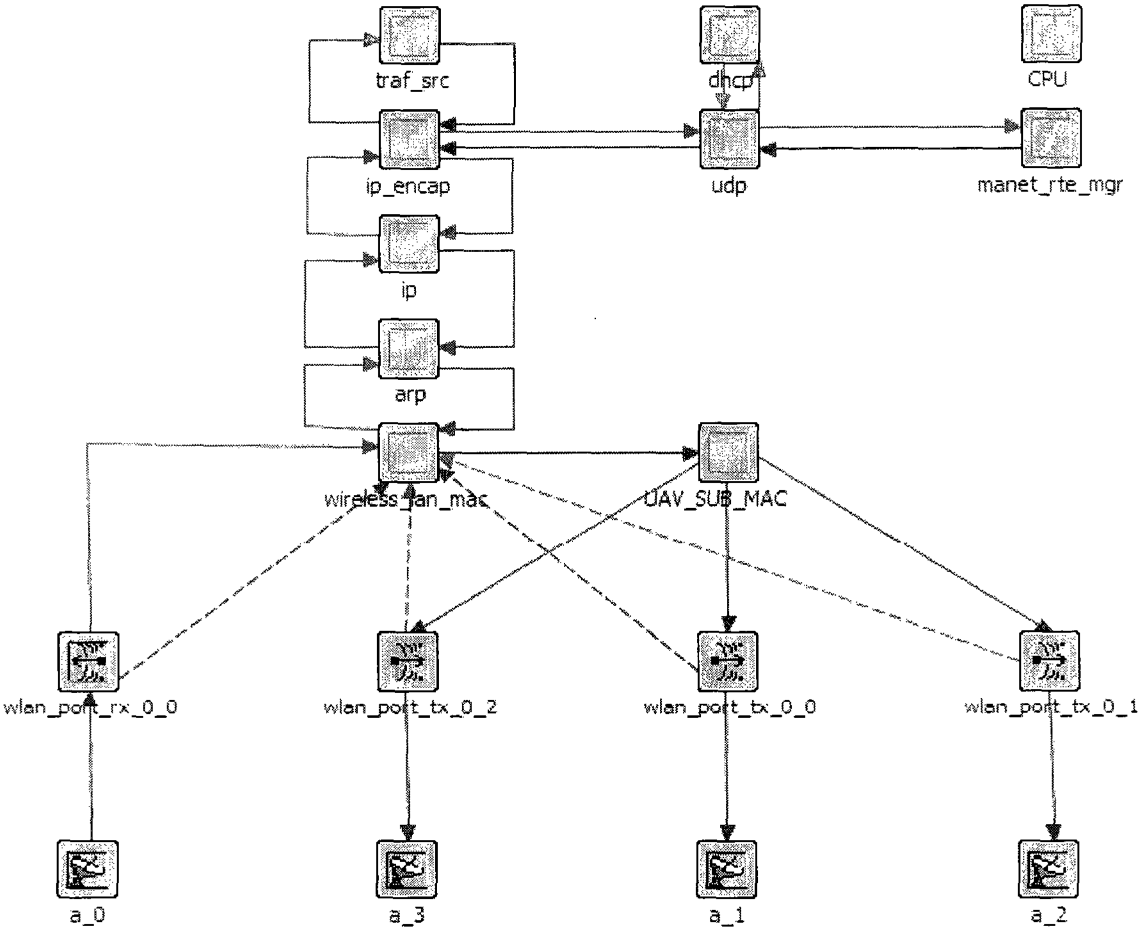


Figure 4.11: Modeling UAV in OPNET with Four Antennas

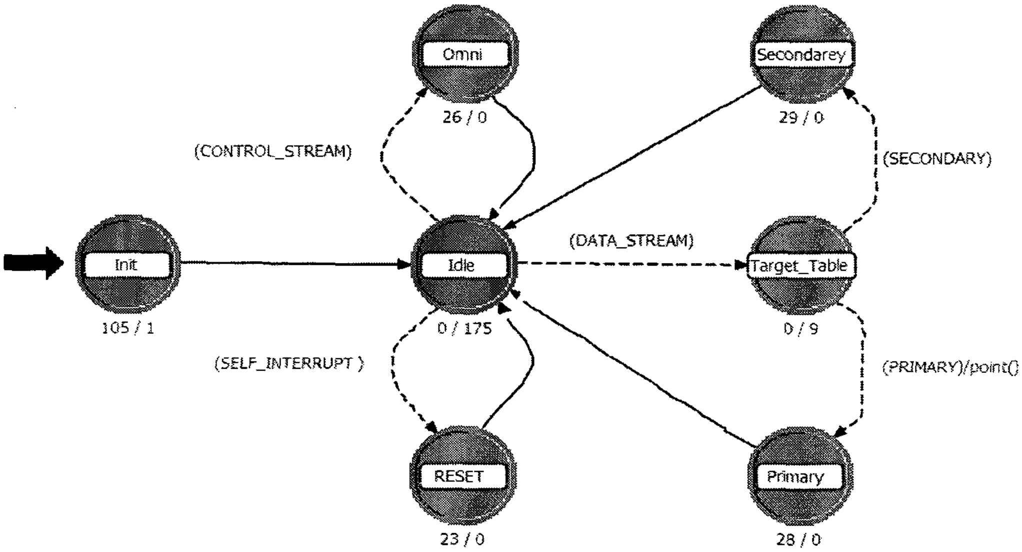


Figure 4.12: OPNET Process Model of UAV_SUB_MAC for Three Antennas

4.6 Performance Evaluation

UAV Ad-Hoc network performance will be measured in terms of the achievable throughput and end-to-end delay. Other features will also be investigated to see the robustness of our scheme such as Bit-Error-Rate (BER) and Signal-To-Noise ratio (SNR). In the following subsection, we will model the channel between the UAVs statistically, then we will investigate the End-to-End delay and finally our simulation result will show the performance of our scheme.

4.6.1 Statistical Channel Models for Wireless Channel between Two UAVs

To analyze the communication link between two UAVs using directional antenna, consider the situation in Figure 4.13 where the first UAVi is located at (Xi,Yi,Zi) and the second UAVj is located at (Xj, Yj, Zj). The aspect angle Φ defines the radiation of UAV_i's directional antenna with respect to UAVj, this angle is divided into two parts, horizontal aspect angle Φ_H and vertical aspect angle Φ_V. Φ_H is determined by the angle between the roll axis and the projection of the line of sight (LOS) perpendicular to the yaw plane while Φ_V is determined by the angle between the projection of the LOS perpendicular to the yaw plane and the line itself. The above angles depend on the location as well as on the attitude of the UAVs. We assumed that each UAV is equipped with a transmitter, receiver, directional antenna and Omni-directional antenna. The link between the two UAVs is represented by L1 (i, j) and modeled with path loss and fast fading. Path loss is mainly caused by dissipation of the power radiated from the UAVs, while fading is due to multipath propagation; both cases are actually referred to the high mobility of the UAVs in which there is a very rapid variation (Fast fading) in received signal power strength. We also assumed that there is a clear line of sight between UAVs. The average strength of the received power can be predicted using Friis free space equation

$$\frac{P_r}{P_t} = G_t G_r \left(\frac{\lambda}{4\pi R} \right)^2 \tag{4.15}$$

$$P_r = G_t G_r P_t \left(\frac{\lambda}{4\pi R} \right)^2 \tag{4.16}$$

Where P_r represents the received power and P_t represents the transmitted power. G_t and G_r are the antenna gain of the transmitting and receiving nodes, λ is the wavelength, $4\pi R^2$ is the surface area of the sphere and R is the distance between the two UAVs. The ratio of the received power to the transmitted power Pr / Pt represents the free space path loss. If we define P_0 as the normalized received power at 1m by

$$P_0 = P_t \, G_t(\Phi_H, \Phi_V) \, G_r(\Phi_H, \Phi_V) \left(\frac{\lambda}{4\pi} \right)^2 \tag{4.17}$$

Where $G_r(\Phi_H, \Phi_V)$ represents the antennas gain of the receiving node and it is equal to 1, $G_t(\Phi_H, \Phi_V)$ represents the antenna gain of the transmitting node. The received power can be written again as a function of distance

$$P_0 = P_t \, G_t(\Phi_H, \Phi_V) \left(\frac{\lambda}{4\pi} \right)^2 \tag{4.18}$$

$$P_r(R) = P_0 / R^2 \tag{4.19}$$

By taking logarithms of equation (4.15) we get

$$10 \, log_{10} \, P_r = 10 \, log_{10} \, P_t + 10 \, log_{10} \, G_t + 10 \, log_{10} \, G_r - 20 \, log_{10} \left(\frac{4\pi R}{\lambda} \right) \tag{4.20}$$

$$P_r(dBw) = P_t(dBw) + G_t(dBi) + G_r(dBi) - Q_0(dB) \tag{4.21}$$

Q_0 represents the free-space path loss and can be written as:

$$Q_0 = 20\, log_{10}\left(\frac{4\pi R}{\lambda}\right)(dB) \tag{4.22}$$

$$Q_0(dB) = 32.4 + 20\, log_{10} f_{MHz} + 20\, log_{10}\, d_{km} \tag{4.23}$$

The signal transmitted between UAVs will experience random variation due to the mobility and fuselage of the aircrafts. Such variation results in attenuation of the received signal power strength. Thus, statistical models should be used to characterize this attenuation. In our case study, we will consider a combined model for the fast fading and path loss. The total path loss is given in logarithmic units by

$$Q_T = Q_0 + X + 20\, log_{10}\, D \tag{4.24}$$

Where X is a zero mean lognormal random variable with standard deviation σ (in dB)

$$P(X) = \frac{1}{\sigma\sqrt{2\pi}} \exp\{-X^2/2\sigma^2\} \tag{4.25}$$

The cumulative probability density function is given by

$$cdf(Q_T \leq \ Q_{threshold}) = \int_{-\infty}^{Q_{th}-Q_0} \frac{1}{\sigma\sqrt{2\pi}} \exp\{-X^2/2\sigma^2\}\, dX \tag{4.26}$$

$$= 1 - \frac{1}{2}\, erfc\left(\frac{Q_{th}-Q_0}{\sqrt{2}}\right) \tag{4.27}$$

Equation (4.27) is used to find the outage probability (SNR>N, where N is desired threshold value). As shown in equation (4.24), D is a random variable that represents the fast fading and it follows the Rayleigh distribution. The Probability Density function *P(D)* with ρ^2 variance is given by

$$P(D) = \frac{D}{\rho^2}\exp\left(\frac{-D^2}{2\rho^2}\right) \text{ , } D \geq 0 \tag{4.28}$$

Since there is a clear unobstructed LOS path between the UAVs, we rewrite equation (4.28) so that it follows the Rician distribution. The Probability Density function *P (D)* is given by

$$P(D) = \frac{D}{\rho^2}\exp\left(\frac{-D^2+A^2}{2\rho^2}\right) I_0 \left(\frac{D\times A}{\rho^2}\right) \text{ , } D \geq 0 \tag{4.29}$$

Where *A* represents the amplitude of the dominant (LOS) component and I_0 is given in equation (4.31) and represents the zeroth order modified Bessel function. The ratio A^2 /2 ρ^2 is called the Rician K factor. This value measures the link quality between the nodes and represents the ratio of the power in the dominant (LOS) component to the power in the other (NLOS) multipath components. Thus, as K increased and approached ∞, the link was cleared and there was no fading. The average received power in the Rician fading is calculated as follows

$$P_r = \int_0^{\infty} D^2\, P(D)dx = D^2 + \ 2\rho^2 \tag{4.30}$$

$$I(D)_0 = \frac{1}{2\pi}\int_0^{2\pi} e^{-D\cos\theta}\, d\theta \tag{4.31}$$

Now substitute $S^2 = K\ P_r / (K + 1)$ and $2\sigma^2 = P_r / (K + 1)$ in equation (4.29) so we can write the Rician distribution in terms of *K* and *Pr* as

$$P(D) = \frac{2D(K+1)}{P_r}\exp\left(-K - \frac{(K+1)D^2}{P_r}\right) I_0 \left(2D\sqrt{\frac{K(K+1)}{P_r}}\right) \text{ , } D \geq 0 \tag{4.32}$$

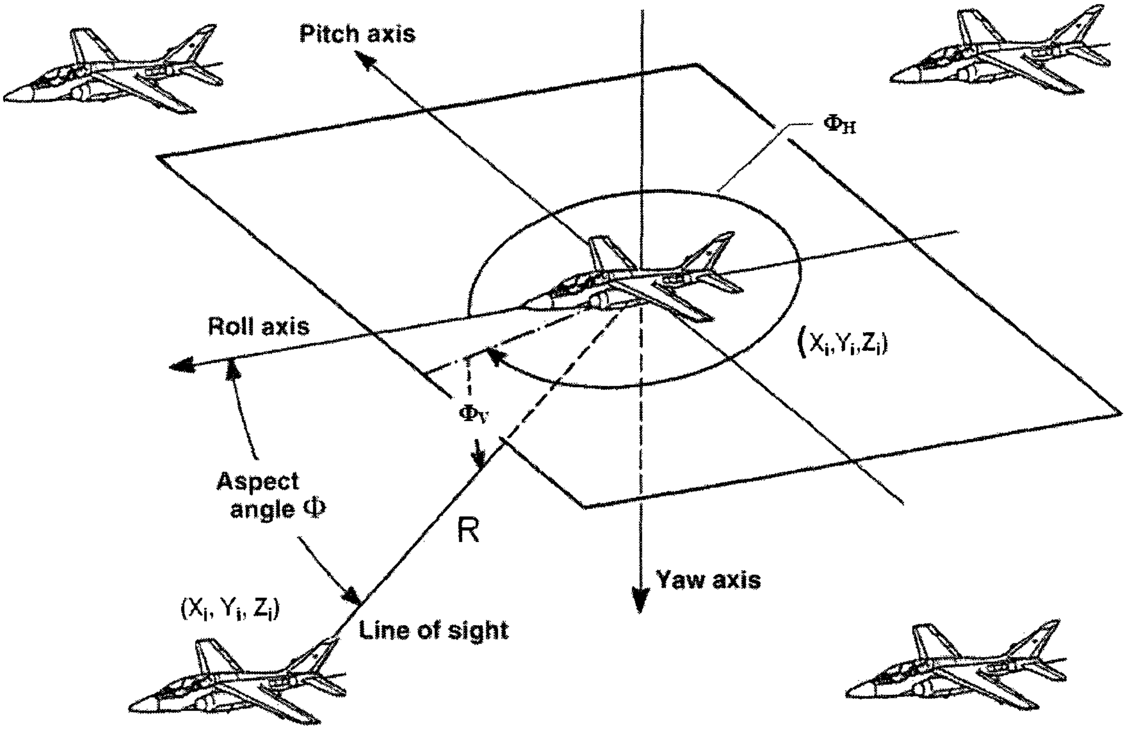


Figure 4.13: Aspect Angle Φ, the Angle between the Roll and the LOS

4.6.2 UAV Performance in Terms of End-to-End Delay

The performance of the UAV node in the network depends mainly on the MAC layer. To study this behavior, we will analyze the performance of the MAC and PHY layers in terms of total time needed to transmit a packet. The total time needed to transmit 2312 bytes is given by equation (4.33).

T (total) = DIFS + Backoff time+ (Data (bytes) +28)*8/ Data Rate (bits/ sec) +SIFS+ overhead time + ACK time (4.33)

DIFS and SIFS are used to ensure the packet reception and to avoid the collision between packets. The time specified for each differs based on the type of the physical layer; table 4.1 shows the difference between them. In the following example, we will consider the parameters of the DSSS.

SIFS = 10 μs, Tslot = 20 μs,

DIFS = SIFS + 2× Tslot = 10 + 2×20 = 50 μs,

Backoff time = Tslot × Random (CW) = 20 × 31 = 620 μs

The overhead consists of a preamble and header. The header of the MAC layer is shown in table 4.5 and it consists of 24 bytes. The whole data unit is shown in table 4.6 where frame control unit sequence (FCS) is attached to frame body and has 4 bytes. Thus, 28 bytes compromise the overhead in the MAC layer. The data length is limited to (4095) bytes in 802.11g and (2312) bytes in 802.11b. ACK packet is short in size and is shown in table 4.7.

(Data (bytes) +28)*8/ Data Rate (bits/ sec) = ((2312+28)*8)/11= 1701.81 μs

ACK time = 14 × 8 / (Data rate= 11Mbps) =10.18 μs

Table 4.5

Medium Access Control Header

Frame control (2 bytes)	Duration (2 bytes)	Address1 (6 bytes)	Address2 (6 bytes)	Address3 (6 bytes)	Sequence control (2 bytes)

Table 4.6

Medium Access Control Data Unit

MAC header (24 bytes)	Frame body (2312 bytes)	FCS (4 bytes)

Table 4.7

ACK Frame

Frame control (2 bytes)	Duration (2 bytes)	Receiver address (6 bytes)	FCS (4 bytes)

To calculate the overhead time, table 4.8 shows the physical layer data frame in which 144 bit preamble and 48 bit header are added to the frame.

Overhead time = (144 + 48) / 11 Mbps = 192 μs

T (total) = 50 + 620 +1701.81 +10+ 192 + 10.18 =2583.99 μs

Table 4.8

Physical Layer Data Frame

Preamble (144 bits)	Header (48 bits)	MAC data unit

4.6.3 Simulation Results

For the comparison of the AMAC_UAV protocol using directional antennas with the IEEE802.11 MAC protocol using Omni-directional antenna, we conducted several scenarios using the parameters shown in table 4.9 below.

Table 4.9

Simulation Parameters

Parameters	Value
# of Nodes	4
Mobility	rounded rectangle
Simulation Time	60 minutes
Data rate	11Mbps
Area (m x m)	2000m X 2000m
RTS threshold	256 bytes
Packet reception power threshold	-95 dBm
Transmit power	1 mw
packet size	1024 bits
Packet inter-arrival time (s)	Exponential (1)
Destination IP address	Random
Radio propagation model	DSSS

We have used the OPNET modeler 14.5. Four UAVs are placed as shown in figure 4.19 in a 2000 X 2000 m area, and form a mobile Ad-Hoc network. Both AMAC_UAV and MAC protocols operate at data rate of 11Mbps. The power transmit level of 1mw was used for all scenarios. The simulation period is 60 minutes and the UAVs are moving in the simulation area according to the rounded rectangle mobility model with a constant speed of 40 m/sec. The packet size is set to 1024 bits and the distribution is exponential. All UAVs in the network are configured to run an OLSR protocol.

Figure 4.14 shows the performance comparison results for End-to-End delay between the AMAC_UAV protocol using directional antenna and the IEEE802.11 MAC protocol using Omni-directional antenna. The End-to-End delay represents the time interval that is calculated from the instant a packet is generated by the source node, to the instant that the packet is received by the destination node. This interval increases much more for the packet that passes through more hops between source and destination. The figure shows that AMAC_UAV protocol provides smaller End-to-End delays than IEEE802.11 MAC protocol. The main reason is that the number of hops during the use of the directional antenna is reduced and thus the End-to-End delay is also reduced.

The next figure 4.15 shows the difference in throughput between the two protocols. The throughput of the wireless system can be defined as the number of packets received correctly. From the figure, we can see that the maximum throughput achieved by the IEEE802.11 MAC protocol using Omni-directional antenna is less than 500 bits/s over the whole period of the simulation time. This value decreases as the UAVs start to move away from each other. On the other hand, as the UAVs move away from each other while using directional antenna, throughput increases its rate until reaching the saturation point. This result indicates that the throughput can be enhanced by the use of directional antenna. Figure 4.16 supports the above result in which the maximum traffic received by the node using Omni-directional antenna is not more than 0.4 packet /s for the same amount of traffic sent during the simulation time.

Figure 4.17 presents our results regarding the Signal-to-Noise Ratio (SNR). As defined in most literature, SNR is the ratio of the signal power to the noise power for given messages exchanged between the source and the destination. This parameter is one of the most important factors in wireless communication. It gives an indication about the quality of the received signal in which the higher the signal to noise ratio, the better the quality of the received signal. As seen in the figure, more than 20% enhancement is achieved using directional antenna over that of using IEEE802.11 standard. Keep in mind that both protocols are modeled with the same pipelines that compute the background noise and the interference noise affecting the incoming signal.

The previous results are consistent with what is shown in figure 4.18. This figure shows a comparison for the Bit-Error-Rate (BER) between the two protocols. BER is the percentage of bits that have errors divided by the total number of bits received by the node. As shown in the figure, our protocol gives less BER than the standard one. It gives a zero BER during the first 1750 seconds, while the standard protocol gives 10^{-4} over the same period.

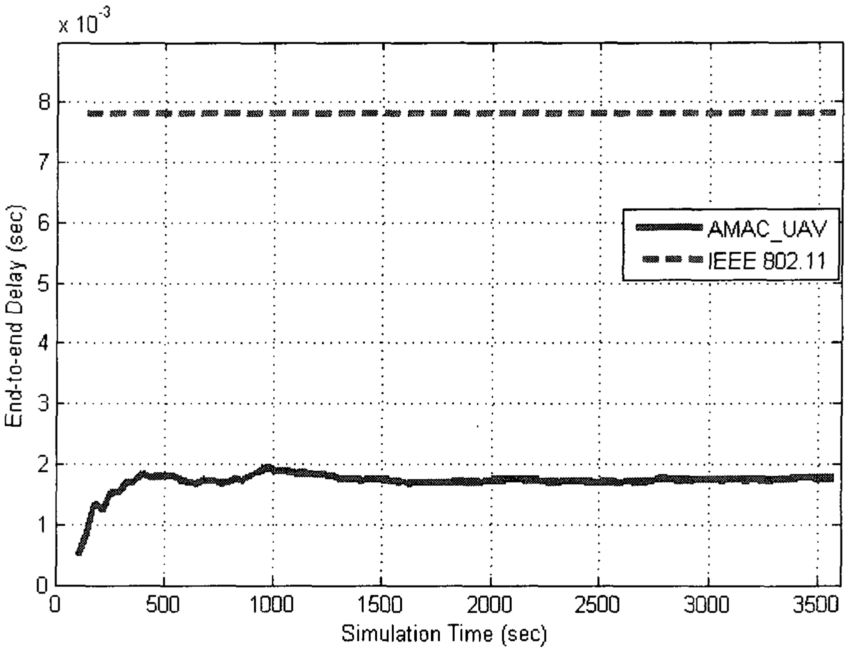


Figure 4.14: End-to-End Delay vs. Simulation Time

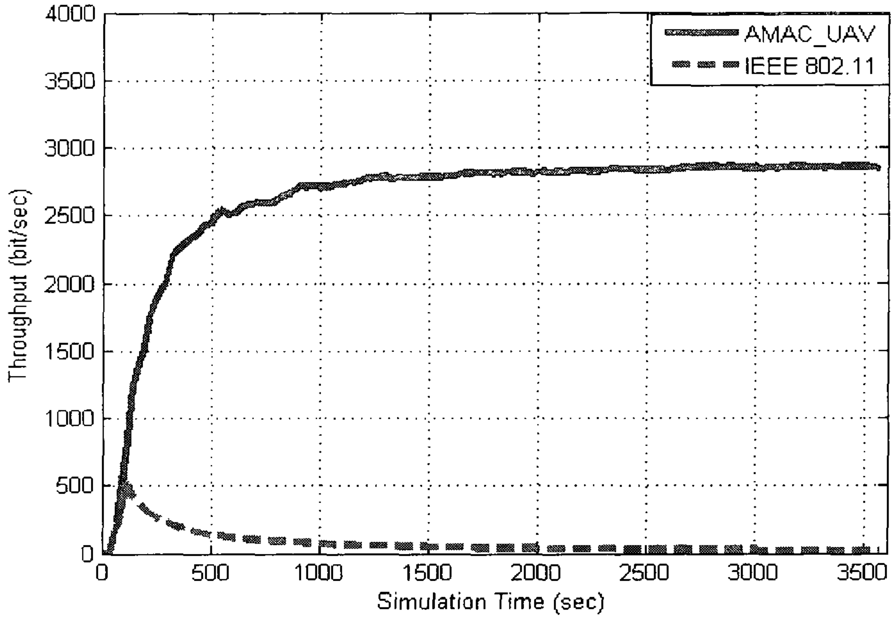


Figure 4.15: Throughput vs. Simulation Time

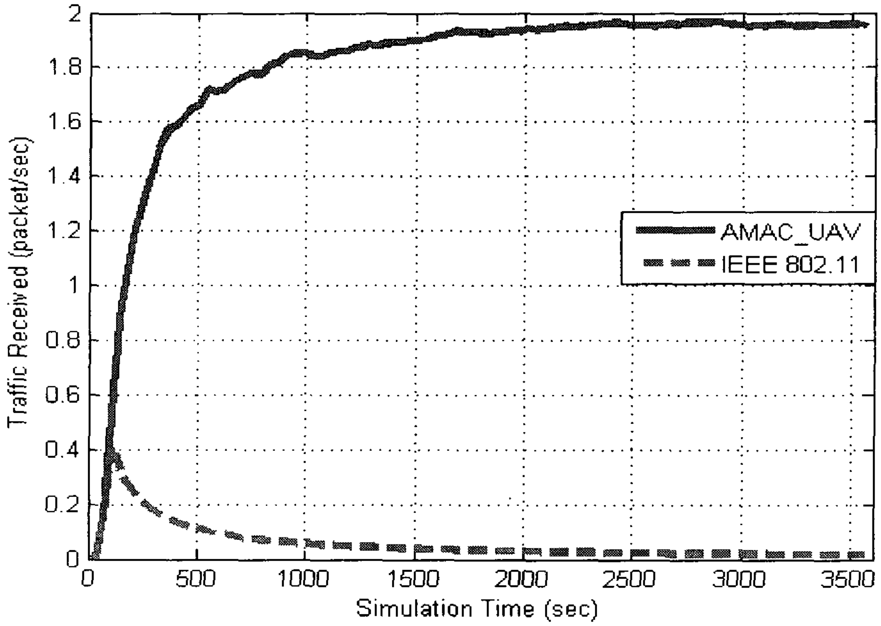


Figure 4.16: Traffic Received vs. Simulation Time

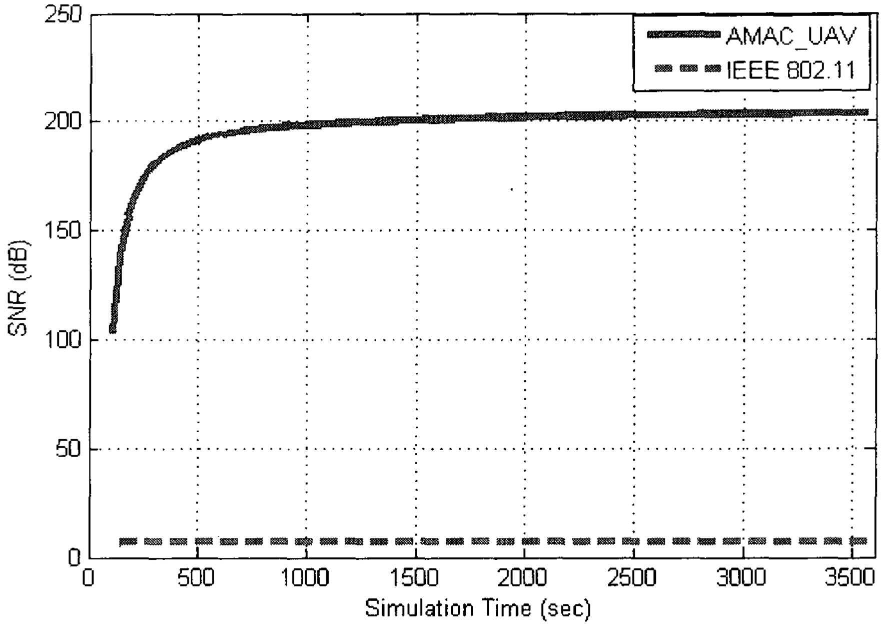


Figure 4.17: SNR vs. Simulation Time

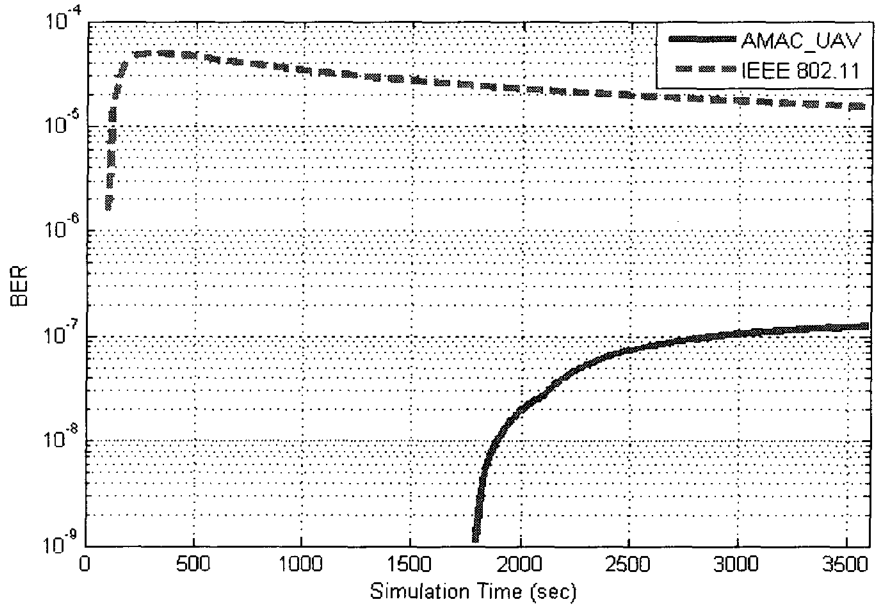


Figure 4.18: BER vs. Simulation Time

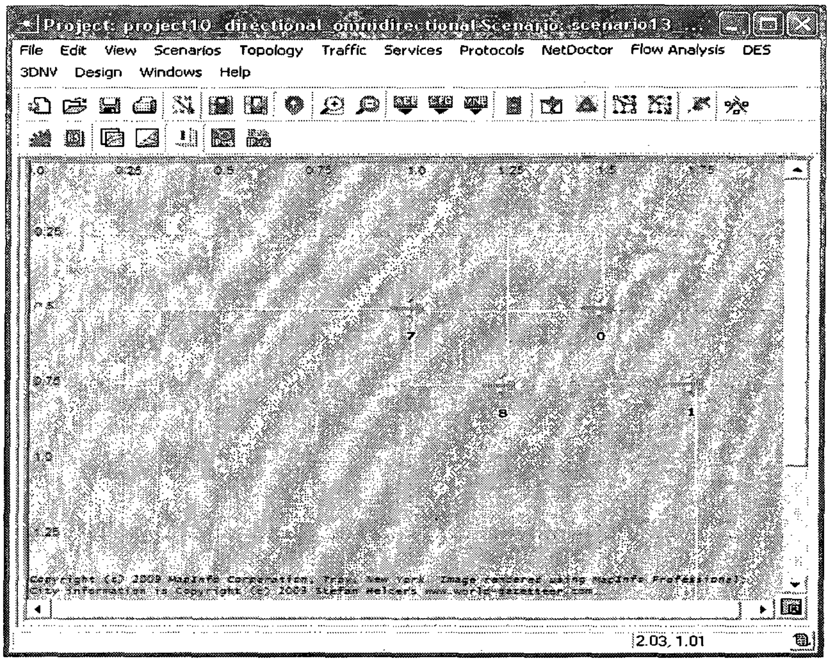


Figure 4.19: Network Topology for Four UAVs

4.7 Summary

In this chapter, a novel Adaptive Medium Access Control protocol is proposed for UAV mobile Ad-Hoc networks (AMAC_UAV). The first part of this chapter reviews both the MAC layer and the physical layer and provides detailed information about IEEE 802.11 standard. In the second part, we focused on UAV implementation in OPNET. We developed a model for each UAV with two directional and two Omni-directional antennas. This model was able to send and receive traffic using both types of antenna. We have constructed our directional antenna pattern using antenna pattern editor provided by OPNET. A short description of OPNET Modeler 14.5 was also given. Channel model, UAV mobility model and our new MAC scheme (AMAC_UAV) were also introduced in full detail. We analytically studied the performance of our scheme and analyzed the data collected from the simulation scenarios. We observed that using directional antenna in UAV Ad-Hoc network provided better performance than Omni-directional antenna in terms of End-to-End delay.

CHAPTER V

DIRECTIONAL OPTIMIZED LINK STATE ROUTING PROTOCOL (DOLSR)

In this chapter, we will describe the Optimized Link State Routing (OLSR) protocol as will as our new scheme that is based on the original OLSR protocol. Our new algorithm is called Directional Optimized Link State Routing (DOLSR) protocol. This protocol is only designed for the use of directional antenna. With this new protocol the number of the overhead packets will be reduced and the End-To-End delay of the network will also be minimized. We will analyze the performance of the OLSR and DOLSR routing protocols and compare them with the Ad-Hoc on Demand Distance Vector (AODV) routing protocol and Dynamic Source Routing (DSR) protocol in OPNET. In addition, we will show how a DOLSR protocol has a positive impact on the network performance in terms of end-to-end delay.

5.1 Introduction

One of the major problems in Ad-Hoc network is the routing protocols. Since nodes in MANET are all mobile, routing protocol should be able to find alternate routes quickly and efficiently. Many Routing protocols have been developed in this area to solve different issues that affect the performance of the network. A novel directional optimized link state routing protocol is proposed in this chapter to provide less end-to-end delay for UAVs mobile Ad-Hoc networks.

MANET protocols are divided into two main types; proactive routing protocols and reactive routing protocols, next section will show the two types. In general, routing protocols use either link state or distance vector routing algorithms. The two algorithms are used to find the shortest path from source to destination. Link state is characterized by maintaining topology information at each node. This information is flooded throughout the Ad-Hoc network and then every node builds its own table regarding all the links in the network, while distance vector is characterized by maintaining a vector which contains the hop distance and the path to all destinations. This vector is then sent by each node to all neighbors and thus the receiving nodes know how to forward the packet to other nodes.

5.2 Routing Protocols for Ad-Hoc Network

As shown in figure 5.1, routing protocols in Ad-Hoc network are classified into two classes: proactive and reactive protocols. Proactive protocols follow the conventional method in finding and maintaining the route between the source and the distention, while the reactive protocols differ from the proactive protocols in that no routing information is maintained at nodes if there is no activity. In the following subsection we will introduce both types and give examples for each.

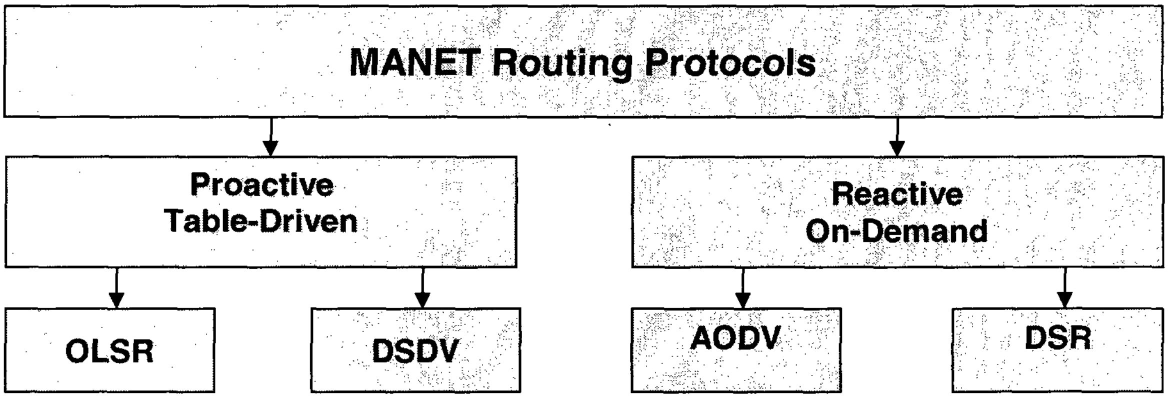


Figure 5.1: Ad-Hoc Routing Protocols

5.2.1 Proactive Routing Protocols (Table-Driven)

Proactive routing protocols maintain up to date routing information for all nodes in the network even before it is needed [95]. This information is exchanged periodically between nodes and updated as the network topology changes. Because of this situation, proactive protocol may add a good feature to those applications that require low latency. Examples of this type include Optimized Link State Routing protocol (OLSR) [94] and Destination Sequenced Distance Vector (DSDV) routing protocol [101]. In the next subsection we will go in detail with the OLSR protocol.

In DSDV, every node should maintain one entry in its routing table for each destination in the network, the number of hops to reach the destination and the sequence number assigned by the destination node. The entry represents the shortest path to the destination. The sequence number is used to avoid routing loops; this number is incremented every time the node discovers a change in its neighborhood. The routing tables are periodically transmitted to the node's neighbors. In addition, the node may also transmit its routing table if a significant change has occurred in it. The new packet, in addition to the routing table information, contains a sequence number. This number is used to distinguish the up-to-date routing table from the old ones. The largest number is taken because it indicates the up to date route between nodes. If two routes have the same sequence number then the route with the shortest path will be used.

5.2.2 Reactive Routing Protocols (On-Demand)

Reactive Routing Protocols do not maintain routing information at the nodes if there is no activity between them. When a node wants to send a packet to some destination, it first checks its routing table to find if it has a route to the destination or not. If no route exists, the node will perform route discovery procedure to find a path to the destination. Nodes in reactive protocol are trying to minimize the overhead by only sending routing information as soon as the communication is initiated between them [96]. Examples of this type include Ad-Hoc on Demand Distance Vector (AODV) routing protocol [102] and Dynamic Source Routing (DSR) protocol [103].

AODV combines the on-demand broadcast route discovery approach used in DSR [97] and the concept of destination sequence number used in DSDV. This protocol allows mobile nodes to obtain routes quickly and it does not require them to maintain routes to destinations that are not in active communication. Moreover it allows mobile nodes to respond to link breakages and to the changes in network topology in a short time.

In AODV, when a node wants to send a packet to a destination and it does not have the route to that destination, it sends a query signal (RREQ-MESSAGE) to the neighbors asking them the route to that destination. The neighbors in turn forward the RREQ-MESSAGE to their neighbors until it reaches the destination. Once the RREQ-MESSAGE reaches the destination, it responds by sending a route reply (RREP) packet back to the original node. Intermediate nodes can reply to the RREQ-MESSAGE only if they have an up to date route to the destination. On the other hand, if the destination node is not reachable, a link failure notification message is forwarded back until it reaches the source node.

DSR protocol uses the concept of source routing in which the header of the transmitted data packet contains the entire route form source to destination. When a node wants to send a packet to a destination and it does not have the route to that destination, it broadcasts a route request message to the neighboring nodes. When the neighboring node receives a route request, it checks whether its address is already listed in the message or not. If not, it appends its address to the message and forwards the route request to its neighbors. Once the route request message reaches the destination, the destination node appends its address to the message and returns it back to the source node within a new route reply message using the same route taken by the route request message.

On the other hand, if the node detects that the next hop is not reachable, a link failure notification message is created and forwarded back until it reaches the source node. This message contains the address of the node that generates the error message and the next hop that is unreachable. Once the error message reaches the source node, it removes all routes from its route cache and start a new route discovery.

5.3 Specifications of Optimized Link State Routing Protocol

In the following subsection we will describe the optimized link state routing protocol that is designed for mobile Ad-Hoc networks (MANET) [93]. This protocol operates as a table-driven protocol which regularly exchanges topology information with other nodes. OLSR protocol mainly consists of three elements: Neighbor discovery, Selection of multipoint relays (MPR), Topology Information and Route Calculation.

5.3.1 Protocol Overview

Optimized link state routing protocol is a popular type of proactive routing protocols (Table-driven) that is designed for MANET. It is considered as an enhancement of the pure link state protocols in that it reduces the size and the number of the control packets. In contrast to other protocols, OLSR protocol reduces the message overhead when it is compared with the classical flooding mechanism in which every node retransmits each message as soon as it receives the first copy of the message. The difference between the simple flooding algorithm and the OLSR algorithm is shown in figure 5.2. The key point in OLSR is the use of the multipoint relay (MPR). MPR is a node chosen by another node that is willing to transmit its data, this node is used to forward packets and flood the control message and thus reduce the number of the retransmission in the network. In addition, this node is a one hop node and it is chosen so that it covers other two hop nodes, figure 5.3.

In OLSR, each node is periodically broadcasting hello messages to its neighbors telling them the neighbors list. This list is used by each node to figure out the nodes that are one hop a way and those that are two hops away and to compute the MPR set. The number of MPRs (MPR set) is not restricted to one and is sent to other nodes in the hello message. As soon as other nodes catch this information, each node builds its topology map and a record for nodes that select it as an MPR (Those nodes are called MPRSelector set, is the set of neighbors that have chosen the node as a MPR). MPRs should then declare the link information for the nodes that have chosen them as MPR (MPR selectors) so that those nodes are capable of computing the shortest path to any selected destination. To maintain the network topology information, the link state is periodically exchanged between nodes.

(a) Link State routing protocol

(b) Optimized Link State routing protocol

Figure 5.2: (a) Simple Flooding Approach (b) Optimized Flooding Approach in OLSR

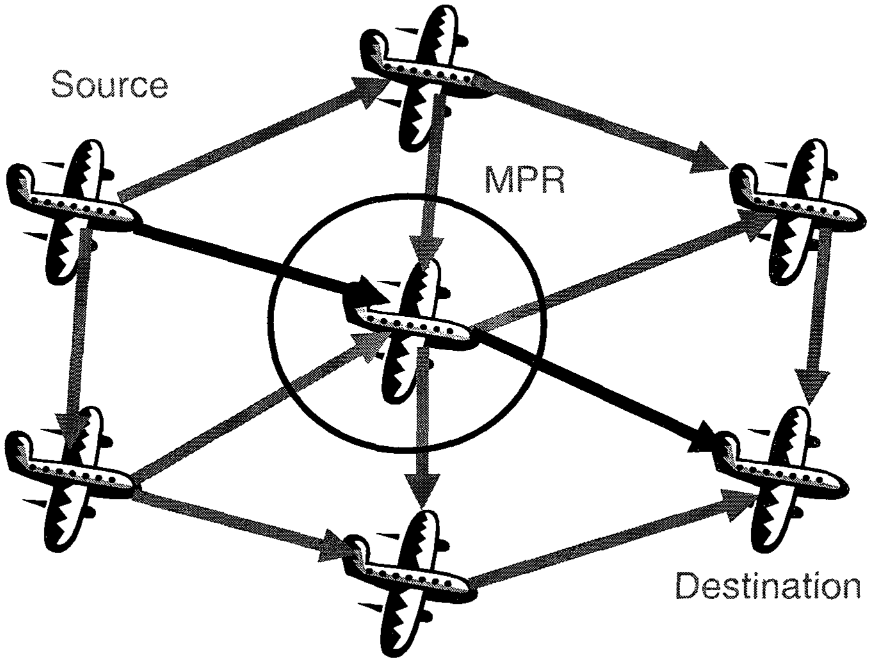


Figure 5.3: Multipoint Relay (MPR)

5.3.2 Control Messages

Three types of control messages are used in OLSR: HELLO, Topology control (TC), and Multiple Interface Declaration (MID) messages.

Hello message is used to carry information about nodes neighbor's and is sent periodically. Generally, hello message serves three independent tasks: link sensing, neighbor detection and MPR selection. This message is sent as part of the general message format with the message type set to HELLO_MESSAGE. Tables 5.1, 5.2 show the format of the Hello message and the format of the general message respectively.

Table 5.1

Format of OLSR HELLO Message

0										1										2										3	
0	1	2	3	4	5	6	7	8	9	0	1	2	3	4	5	6	7	8	9	0	1	2	3	4	5	6	7	8	9	0	1
Reserved																Htime								Willingness							
Link code								Reserved								Link message size															
Neighbor Interface Address																															
Neighbor Interface Address																															
																.															
Link code								Reserved								Link message size															
Neighbor Interface Address																															
Neighbor Interface Address																															

Table 5.2

Format of OLSR Packet

0										1										2										3	
0	1	2	3	4	5	6	7	8	9	0	1	2	3	4	5	6	7	8	9	0	1	2	3	4	5	6	7	8	9	0	1
Packet Length																Packet Sequence Number															
Message Type								Vtime								Message Size															
Originator Address																															
Time To Live								Hop Count								Message Sequence Number															
MESSAGE																															
Packet Length																Packet Sequence Number															
Message Type								Vtime								Message Size															
Originator Address																															
Time To Live								Hop Count								Message Sequence Number															
MESSAGE																															

TC message is broadcasted and retransmitted by the MPRs in order to declare the MPRSelector set. This message is sent as part of the general message format with the message type set to TC_MESSAGE. Table 5.3 shows the format of the TC message.

Table 5.3

Format of OLSR TC Packet

0										1										2										3	
0	1	2	3	4	5	6	7	8	9	0	1	2	3	4	5	6	7	8	9	0	1	2	3	4	5	6	7	8	9	0	1
ANSN																Reserved															
Advertised Neighbor Main Address																															
Advertised Neighbor Main Address																															
.																															

MID message is broadcasted and retransmitted by the MPRs in order to declare a node's multiple interfaces (list of IP addresses used in this node). This message is sent as part of the general message format with the message type set to MID_MESSAGE. It is used to help each node to calculate its routing table and for announcing that a node is running OLSR. Table 5.4 shows the format of the MID message.

Table 5.4

Format of OLSR MID Message

0											1									2										3	
0	1	2	3	4	5	6	7	8	9	0	1	2	3	4	5	6	7	8	9	0	1	2	3	4	5	6	7	8	9	0	1
OLSR Interface Address																															
OLSR Interface Address																															
.																															

5.3.3 Neighbor Discovery

To discover the neighbors in the Ad-Hoc network, Hello messages are broadcasted periodically to all nodes. These messages are only broadcasted one hop away and are not relayed to any further nodes. They contain the information about their one-hop neighbor nodes and the link status. The link in the Ad-Hoc network can be either unidirectional or bidirectional; each node should specify the type of the link during the exchange of the Hello messages. When the node receives a message for the first time in which its address is not found, it registers the link to the source as asymmetric. Figure 5.4 shows the procedure for neighbor discovery. For example, aircraft S first sends an empty Hello message to aircraft D. Since this message cannot have any information about aircraft D, aircraft D registers aircraft S status as an asymmetric neighbor in its routing table and sends a new Hello message for declaring aircraft S as its asymmetric neighbor. When aircraft S receives the Hello message, it finds its own information in this message and registers aircraft D status as a symmetric neighbor in its routing table and sends a new Hello message to aircraft D. Upon receiving this message, aircraft D will change the status of aircraft S to a symmetric neighbor and set the new status in its routing table. Through this procedure, each node is capable of recognizing all its neighbor nodes, including one-hop and two-hops, and knows that their neighbors are alive.

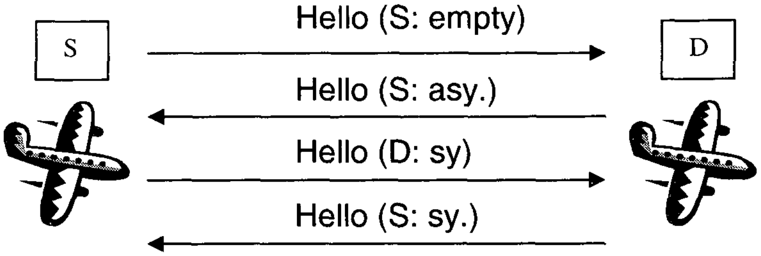


Figure 5.4: Exchanging HELLO Messages for Neighbor Discovery

5.3.4 Selection of Multipoint Relays (MPR)

The Multipoint Relays (MPR) is the key point behind the use of the OLSR protocol. MPR is a one-hop neighbor that has been selected to reach the two-hop nodes. The OLSR protocol uses MPRs to reduce the number of nodes for broadcasting the information throughout the Ad-Hoc network. To select the MPR set, each node should have the link state information about all one-hop and two-hop neighbors. This information is embedded and sent through the Hello message. As soon as the node received Hello message, it constructs the MPR set among its one-hop symmetric neighbors in such a manner that the set covers all the nodes that are two-hops away. This set is then responsible for receiving, processing and retransmitting broadcast messages. The smaller the MPR number, the less of the overhead the protocol introduces to the network. Other nodes that are not recorded as MPRs can receive and process broadcast messages but do not retransmit these messages. In addition to the MPR set, the node should maintain information about the set of neighbors that have selected it as MPR (MPRselector set).

The process of MPR selection is shown in figure 5.5 in which three aircrafts are exchanging Hello message. Aircraft D is in communication range with aircraft S and Y, while there is no communication link between aircrafts Y and S. During the process of neighbor discovery, when aircraft S is receiving the Hello message from aircraft D, aircraft Y knows there is at least an asymmetric link to aircraft D which it announces in its next Hello message. Upon receiving this message, aircraft D knows there is a symmetric link to aircraft Y. When aircraft S sends a new Hello message with aircraft D marked as symmetric neighbor, aircraft D knows upon reception of this message that a symmetric link to aircraft S exists and announces the symmetric links to aircraft S and aircraft Y in its next Hello message. As soon as all have received this message, both aircrafts S and Y know that they have a symmetric link to aircraft D and they can reach each other through aircraft D. Therefore aircrafts S and Y will select aircraft D as MPR and they announce it in their next Hello message. The next step is to record the MPR selector set. Upon receiving the last Hello messages by aircraft D, aircraft D will include aircrafts S and Y in its MPRselector set and start sending TC messages.

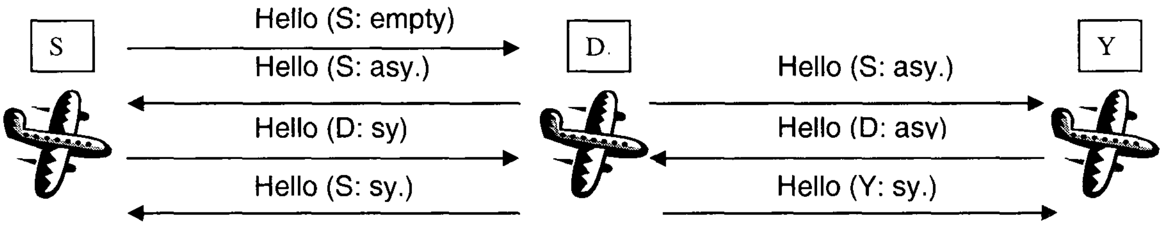


Figure 5.5: Selection of Multipoint Relays (MPR)

5.3.5 Topology Information and Route Calculation

In order to build a table for the network topology, TC message is broadcasted periodically by every node in the network. This message contains the MPRSelector set of a node, and floods into the network using the multipoint relaying mechanism in which the MPRs are only allowed to forward this message. TC message consists of the address of the original node, the address of the MPRselectors set and the sequence number of each message. Any node receiving this message can reach the destination through the last hop from which it received this message. If a change occurs in the MPR selector set, the time to send the next TC messages should be reduced; this will help each node to build its topology table correctly. In addition, updating topology table by TC messages is based on the freshness of the sequence number.

Because OLSR is a proactive protocol, the routing table must have routes for all available nodes in the network. The routing table entries consist of the following: destination address, next address, number of hops to the destination and local interface address. This information is extracted from the TC messages and Hello messages and collected from the topology table and the neighbor table. Upon any change in one of the above entries, the routing table should be recalculated to maintain up to date routing information. To route the packet to other destination in the network, the node tracks the information and pairs it in the form of [last hop, node] where the node represents the addresses found in the TC message. As an example, to find the route from aircraft S to aircraft Y [S, Y], the first step is to find the pair [D, S] then the pair [--, D] and so forth until we find aircraft Y. Because we have only three aircraft, then the pairs are [D,S] and [Y,D], and the route is S-----D-----Y.

5.3.6 Advantages and Limitations of OLSR

Advantages of OLSR:

1. OLSR protocol minimizes the flooding process in the network, reduces the overhead packets and, at the same time, provides a minimum hop route. As shown above, these advantages are achieved by the use of MPRs, which are only allowed to forward the messages.

2. Since the characteristics of the OLSR protocol provides that all nodes should have the routing information by exchanging control messages, routing process is done for each node without any guidance from the others.

3. The time interval for broadcasting the Hello messages can be adjusted to suit the Ad-Hoc network that suffers from rapid change in topology.

4. There is no need for the link to be reliable while exchanging control messages since these messages are sent periodically and do not need to be sent sequentially.

5. OLSR protocol is working well for dense networks and for those applications that need small delay in data packet transmission.

Limitation of OLSR:

Each node using OLSR protocol should periodically send the updated topology information throughout the entire network. This process increases the bandwidth usage and thus limits the use of this protocol when the bandwidth is considered to be a QoS constraint in some applications.

5.4 Specifications of Directional Optimized Link State Routing Protocol

In the following subsection we will describe the Directional Optimized Link State Routing (DOLSR) protocol that is designed for UAV mobile Ad-Hoc networks. This protocol is similar to the OLSR but it differs in the selection of multipoint relays.

5.4.1 Description of DOLSR

As shown in subsection 5.3.4, the most important step in OLSR protocol is the selection of the MPR set. In this subsection we will place emphasis on how to reduce the overhead in the UAV Ad-Hoc network. Generally speaking, as the number of MPRs shrinks, the number of the overhead packets is reduced. In this respect, we proposed a new mechanism that leads to the reduction in MPR numbers. Figure 5.6 shows our block diagram for the proposed directional optimized link state routing protocol. For each packet, the UAV tests the distance to the destination; if the distance is larger than the Dmax, the node will apply the DOLSR mechanism. On the other hand, if the distance is smaller than the Dmax, the UAV will apply the OLSR in cases in which the Omni-directional antenna is used, otherwise, the UAV will go back to the DOLSR.

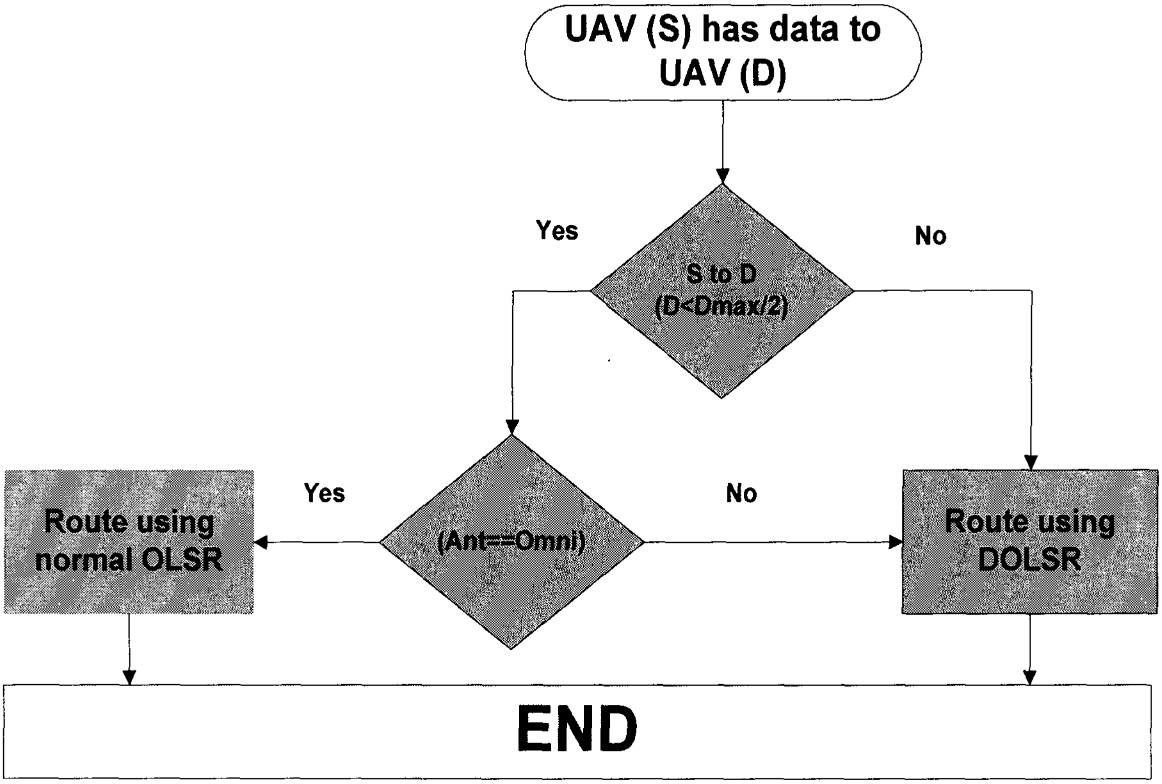


Figure 5.6: DOLSR Routing Protocol Block Diagram

5.4.2 Neighbor Discovery

To discover the neighbors in the Ad-Hoc network using directional optimized link state routing protocol, Hello messages will be broadcasted periodically to all nodes as in OLSR. These messages are only broadcasted one hop away and are not relayed to any further nodes. Through this procedure, each node is capable of recognizing all its neighbor nodes including those one-hop and two-hops away. We assumed that the two-hop nodes are located within the range of the directional antenna. Any node located far away will not be counted as a two-hop node.

5.4.3 Selection of Multipoint Relays in DOLSR

As an example, we will consider the UAV Ad-Hoc topology that is shown in figure 5.7. We present a simple seven node scenario to illustrate our mechanism. In OLSR MPR selection mechanism, a UAV marked as A will select C and D as its MPRs. These UAVs cover all the un-reachable two-hop neighbors. Node F knows that it can reach A via C and node F also knows that it can reach A via D. On the other side, node E can reach A either through node C or node D. In DOLSR MPR selection mechanism, the idea is to benefit from the use of the directional antenna and also from the global profile created as a result of cross-layering technique. Node A will build its routing table based on the OLSR selection as follows: A-C-F, A-C-E, A-C-B, A-D-G, A-D-E, A-D-B. Based on these results, node A has two routes to nodes E and B. Our scheme will calculate the distance between node A and nodes E and B; the longest distance will be considered as MPR. Table 5.5 shows the selection of MPRs for both mechanisms, where node E is selected as A's MPR in DOLSR mechanism while nodes C and D are selected in OLSR.

Table 5.5

MPR Selection in DOLSR and OLSR Mechanisms

Node	2-Hop Neighbors	MPR(s) in OLSR	MPR(s) in DOLSR
A	E , F , G	C, D	E
F	A , B , D	C, G	B

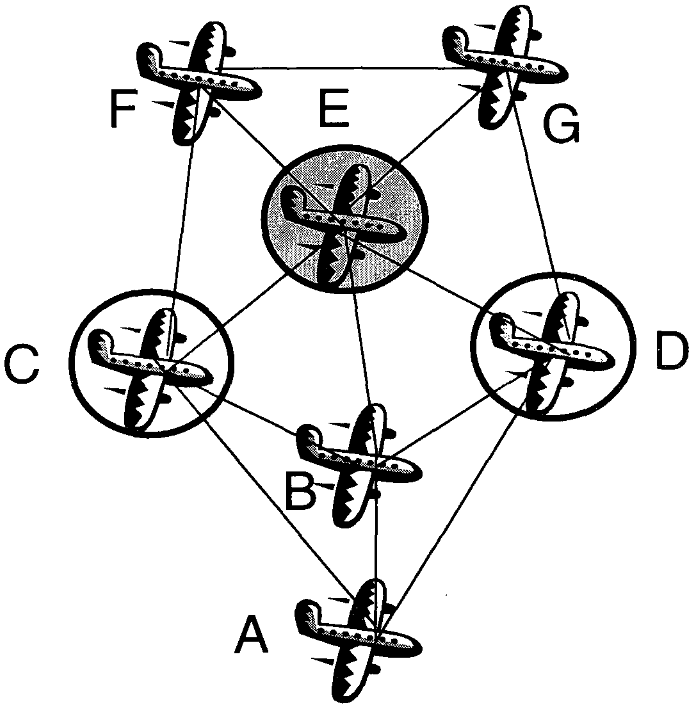


Figure 5.7: Ad-Hoc Topology, Illustration of Multipoint Relays in DOLSR and OLSR

5.4.4 Route Maintenance

Due to the mobility of the UAVs, route links in Ad-Hoc networks will be broken frequently. Each UAV implements a DOLSR sending out a Hello message to maintain local connectivity with other UAVs. Failure to receive a Hello message from other UAVs is considered as an indication that the link to the UAV is broken. A link failure notification message is then forwarded back until it reaches the source node. Once the error message reaches the source node, the source node should respond by switching back to the normal OLSR selection technique.

5.5 Performance Evaluation

5.5.1 Simulation Environment

To demonstrate the performance of the DOLSR protocol presented above, we compared our scheme to the original OLSR protocol, AODV and DSR protocols. For our simulation, which is different from others [99], we have used an OPNET 14.5, a discrete event network simulator that includes a rich set of detailed models for Ad-Hoc network. 25 UAVs are placed as shown in figure 5.8 in a 2000 X 2000 m area and form a mobile Ad-Hoc network. Both AMAC_UAV that is presented in chapter 4 and MAC protocols operate at data rate of 11Mbps. The power transmit level of 1mw was used for all scenarios. The simulation period is 10 minutes and the UAVs are moving in the simulation area according to a random waypoint model [98] with a zero pause time and a constant speed of 40 m/sec. The packet size is set to 1024 bits and the distribution is exponential. All UAVs in the network are configured to run OLSR protocol during the first scenario and DOLSR protocol during the second one. We summarized the parameters used in all scenarios in table 5.6.

Other scenarios were conducted to evaluate the performance of our scheme and compare it with various mobile Ad-Hoc network routing protocols. We compared our scheme to the AODV and DSR protocols. The AODV and DSR simulation parameters used in the comparison are shown in tables 5.7 and 5.8 respectively. Moreover, we added the original OLSR protocol to the comparison with the parameters shown in table 5.9.

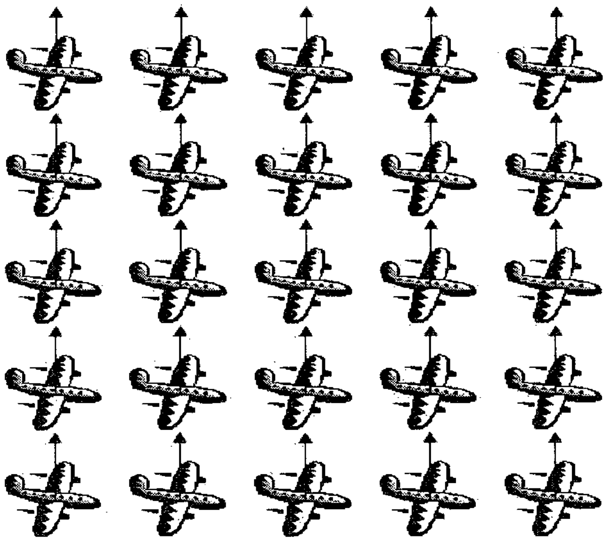


Figure 5.8: Network Topology for 25 UAVs Used for Simulation

Table 5.6

Simulation Parameters for the 25 UAVs Ad-Hoc Networks

Parameters	Value
# of Nodes	25
Mobility	Random
Simulation Time	10 minutes
Data rate	11Mbps
Area (m x m)	2000m X 2000m
Buffer size	256000 bits
Packet reception power threshold	-95 dBm
Transmit power	1 mw
packet size	1024 bits
Radio propagation model	DSSS

Table 5.7

Simulation Parameters Used for the AODV Protocol

Parameters	Value
Hello interval	Uniform(1,1.1) (seconds)
Allowed hello loss	2
Packet queue size (packets)	infinity
Active route timeout	35 (seconds)
Route error rate limit (packets/sec)	10

Table 5.8

Simulation Parameters Used for the DSR Protocol

Parameters	Value
Route expiry timer	300 (seconds)
Max. buffer size (packets)	infinity
Send buffer expiry timer	30 (seconds)
Max. request period	10 (seconds)
Broadcast jitter	Uniform(0,0.01)(seconds)
Initial request period	0.5 (seconds)

Table 5.9

Simulation Parameters Used for the OLSR Protocol

Parameters	Value
Hello interval	2 second
TC interval	5 second
Topology hold time	15 second
Neighbor hold time	6 second
Duplicate message hold time	30 second
Address mode	IPv4

5.5.2 Performance Comparison between OLSR and DOLSR

We have conducted several scenarios and analyzed the results of simulation obtained by the use of OLSR and DOLSR routing protocols for the average number of MPRs selected by the network, total number of TC messages sent and forwarded by the MPRs, total number of Hello messages sent and finally we make a comparison between the two protocols in terms of End-to-End delay.

Figure 5.9 compares the two protocols in terms of the number of MPRs selected by the network. As shown in the figure, our scheme gave better results than the original OLSR. 14 MPRs are selected during the use of the OLSR while 10 MPRs are selected during the use of DOLSR, this result agrees with what we introduce in section 5.4. After 200 seconds, when the nodes have selected their MPR set, the number of MPRs becomes stable and converges to 14 and 10 nodes.

Figure 5.10 shows the number of TC messages forwarded during the simulation time. Since all nodes are mobile, TC messages are used to propagate the changes in the network topology. The number of the TC messages in the original OLSR is higher than 200 during the first 100 seconds, while in DOLSR the number is less than 160. This is due to the reduction of the MPR set. The same result can be seen in Figure 5.11 in which the DOLSR reduced the total number of the generated TC messages.

Figure 5.12 shows the performance comparison results for End-to-End delay between the DOLSR protocol using directional antenna and the OLSR protocol using Omni-directional antenna. Generally speaking, there are three factors affecting End-to-End delay of a packet: time to discover the route, buffering waiting time and the number of hops for each path. Since the number of the MPR set is reduced while using DOLSR, clearly the time should also decrease.

The figure shows that DOLSR has less End-to-End delay than OLSR. The End-to-End delay for both protocols is high at the beginning of the simulation time. This reflects the fact that the size of the control traffic is high before the selection of the MPR set. After each node selected its MPR set, the number of nodes used for flooding the control messages will be decreased and restricted only for the MPR set and thus the time will also be reduced.

Figure 5.13 shows the number of Hello messages used by DOLSR and OLSR protocols. Both protocols deliver the same number of Hello messages over the simulation time and thus the results show that they have the same trend. At the beginning of the simulation time, the number of Hello messages is quite high for both protocols. These messages are generally propagated by all nodes so that each node can discover all its two-hop nodes. After nodes learn all neighbors, they select the MPR set and the number starts to decline.

5.5.3 Performance Comparison between OLSR, DOLSR, AODV and DSR

The implementation of OLSR, DOLSR, AODV and DSR in this simulation is mainly to evaluate End-to-End delay and traffic received (packets/ sec). We chose these two parameters for our simulation in order to study the efficiency of our scheme in reducing the time taken to send the packets from source to destination.

In general, UAV Ad-Hoc networks have characteristics in which the network topology changes very rapidly. If nodes are within the communication range of each other, messages will be exchanged between the senders and the receivers, otherwise messages should be sent through intermediate node. The major challenge in mobile Ad-Hoc networks is how to route the packets with frequent node movement. To see the effects of the routing protocol on the performance of the UAV Ad-Hoc networks, we selected two reactive protocols, AODV and DSR, and one proactive protocol OLSR.

Figure 5.14 and figure 5.15 show the total delay in the network. They are plotted on different scales to make the difference between the four protocols visible. The total delay is represented by the End-to-End delay. The End-to-End delay represents the time interval that is calculated from the instant a packet is generated by the source node, to the instant that the packet is received by the destination node. These figures compare the End-to-End delay between the DOLSR protocol using directional antenna and the OLSR, AODV, and DSR protocols using Omni-directional antenna. The total delay using Omni-directional antenna is higher than that of using directional antenna. This behavior may be explained as follows: The range of the UAVs is extended as a result of using directional antenna, and thus the number of MPRs is reduced due to the use of the DOLSR.

Both figures also show that DOLSR and OLSR provide smaller End-to-End delay than AODV and DSR which is less than 0.005 seconds. Moreover, the End-to-End delay for the AODV and DSR start at an average of 0.25 second and then fall to 0.05 seconds. The difference in time can be related to the fact that AODV and DSR are reactive protocols and construct their route on demand while the OLSR and DOLSR are proactive protocols in which the table is available and has the destination addresses. For all protocols, the graph starts after one hundred seconds because we programmed the OPNET to deliver a packet after other modules register themselves.

Figure 5.16 compares the traffic received using the OLSR, DOLSR, AODV and DSR protocols. It can be seen that DOLSR received more than 20 pkt /s over 10 minutes simulation time, while AODV and DSR received less than 17 packets /s over the same time. The reason is that AODV and DSR protocols tend to flood the network with heavy control traffic which increases the End-to-End delay, while DOLSR minimizes the control messages by multipoint relays which reduces the End-to-End delay.

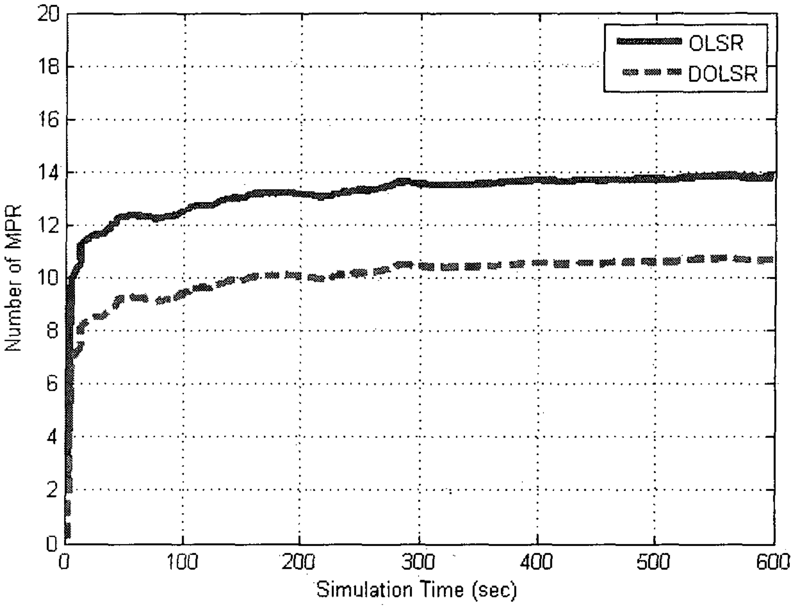


Figure 5.9: Comparison between OLSR and DOLSR Protocols for the Average Number of MPRs Selected by the Network

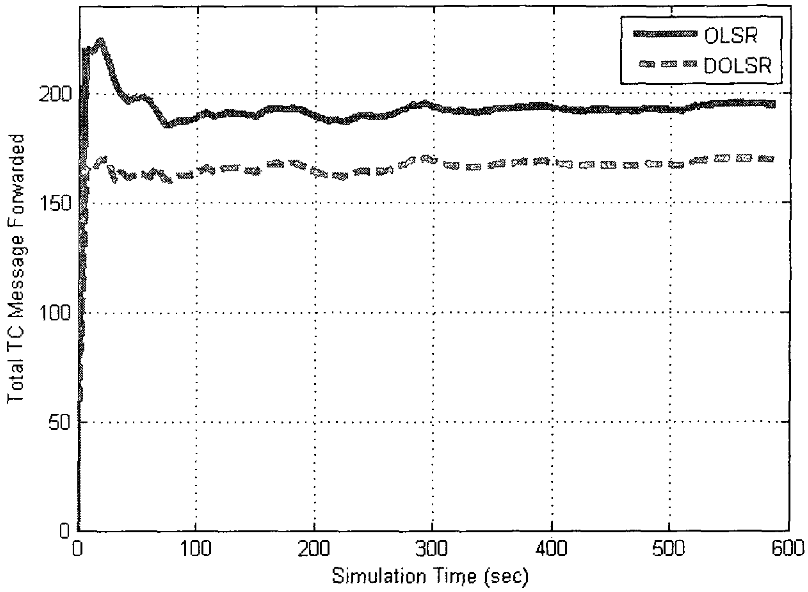


Figure 5.10: Comparison between OLSR and DOLSR Protocols for the Total Number of TC Messages Forwarded by the MPRs

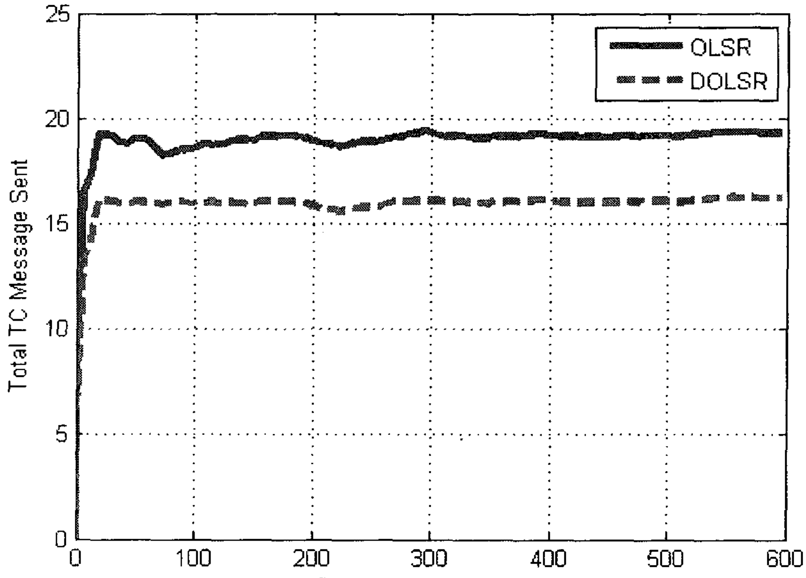


Figure 5.11: Comparison between OLSR and DOLSR Protocols for the Total Number of TC Messages Sent by the MPRs

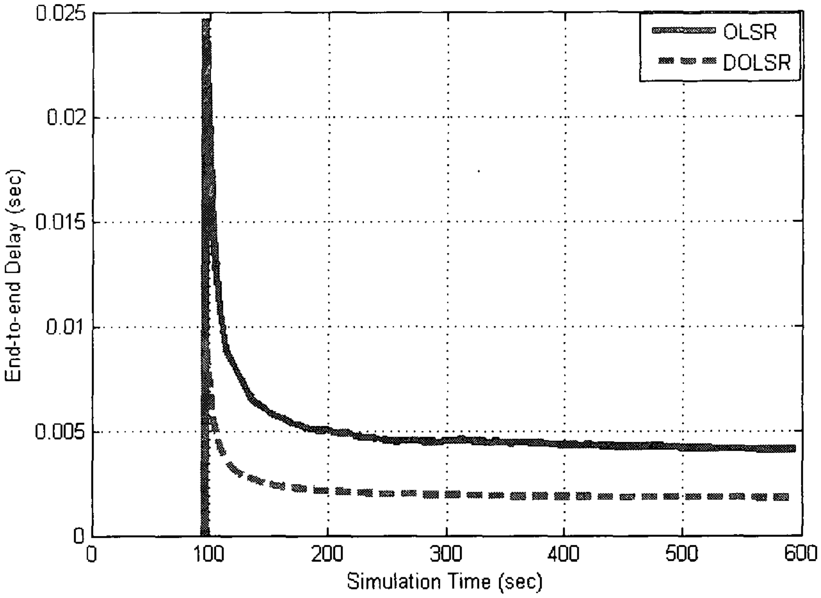


Figure 5.12: Comparison between OLSR and DOLSR Protocols for the End-To-End Delay

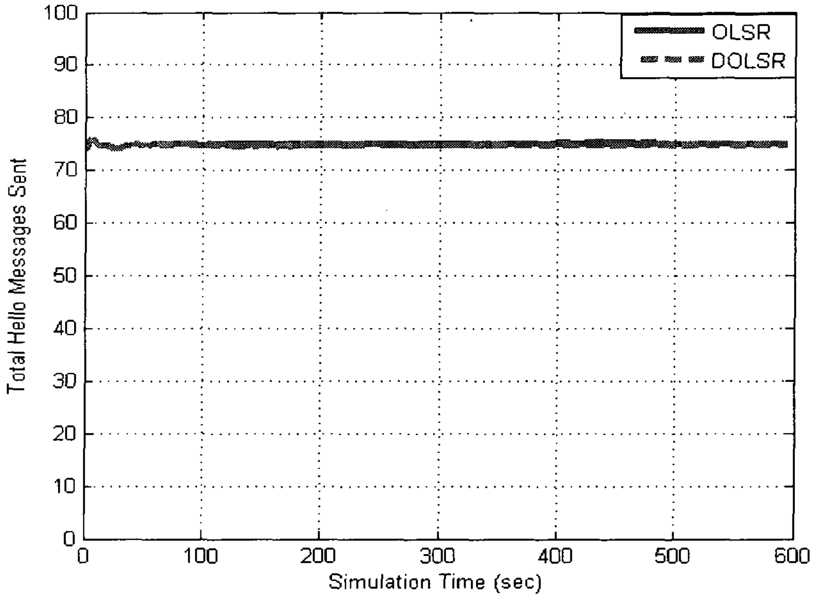


Figure 5.13: Comparison between OLSR and DOLSR Protocols for the Total Hello Message Sent

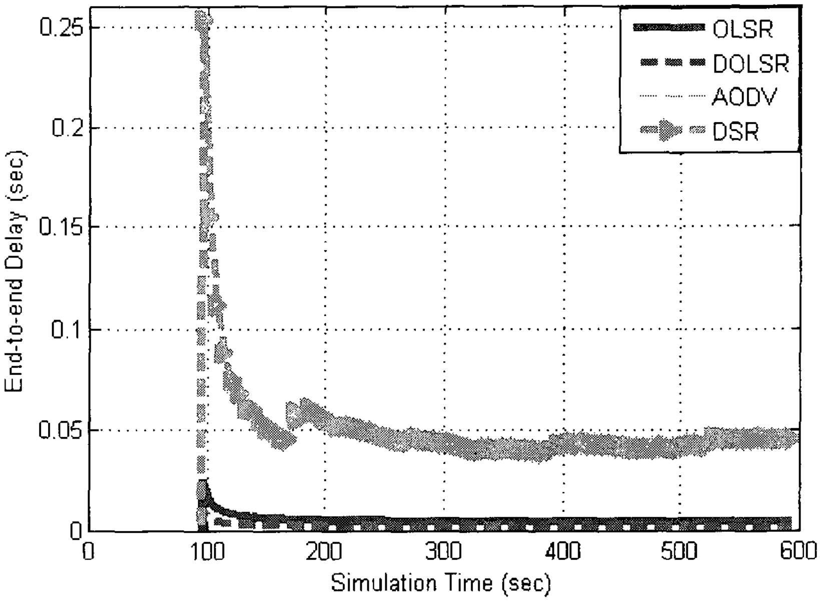


Figure 5.14: Comparison between OLSR, DOLSR, AODV and DSR Protocols for End-To-End Delay

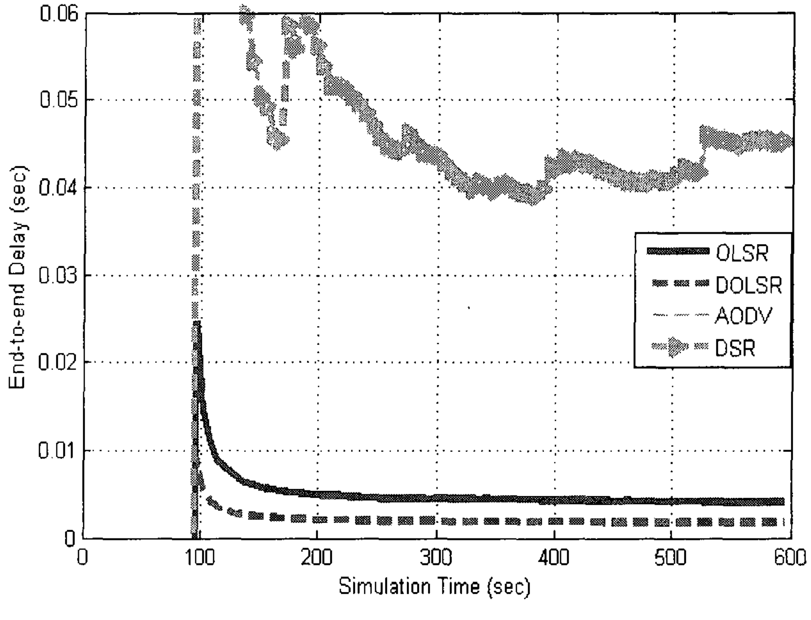


Figure 5.15: Comparison between OLSR, DOLSR, AODV and DSR Protocols for End-To-End Delay (different scale for Y axis)

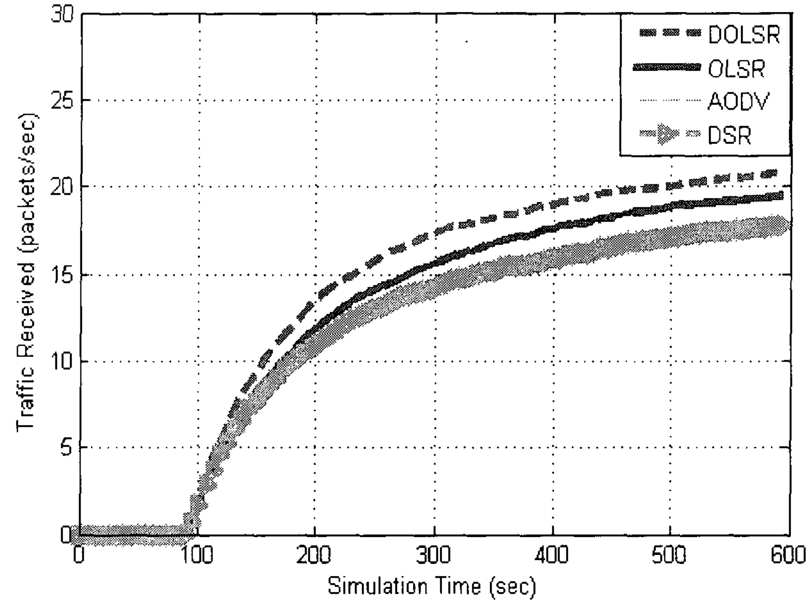


Figure 5.16: Comparison between OLSR, DOLSR, AODV and DSR Protocols for Traffic Received (packets/ sec)

5.6 Summary

In this chapter, a novel Directional Optimized Link State Routing (DOLSR) protocol is proposed for UAV mobile Ad-Hoc networks. Our protocol is capable of reducing the number of the multipoint relays in the network. As a result, the End-to-End delay is reduced and the overall throughput is increased. Performance evaluation and comparison between OLSR and AODV were studied using OPNET Modeler 14.5. The simulation results show that OLSR achieves better performance than AODV in terms of End-to-End delay. Another comparison was conducted between OLSR and DOLSR using the same simulator. The simulation results show that DOLSR achieves better performance than OLSR and AODV in terms of End-to-End delay. It can be concluded that as the number of MPRs shrinks, the number of the overhead packets is reduced and thus the overall performance is enhanced.

CHAPTER VI

CONCLUSION AND FUTURE WORK

6.1 Conclusion

Recently, UAV mobile Ad-Hoc networks have become one of the popular types of wireless networks that are formed by a swarm of UAVs. Each UAV in such network has the capability to communicate with its neighbors and non-neighbors through a wireless medium without using any existing network infrastructure. The UAVs in these networks are designed in such a way that they act as an end system and a router for other aircrafts. Such networks are expected to play an important role in various areas especially in delay critical applications.

Variation of wireless links as a result of using UAVs that are equipped with the directional antenna may create several problems for network protocols that implement the framework of layered architectures. In that respect, to integrate the directional antenna successfully into UAV Ad-Hoc networks and to realize its benefits within the MAC and network layers, Cross-layer technique was implemented in this dissertation so that the first three layers can inter-communicate the useful information and dynamically adjust the transmission parameters according to these variations.

Cross-layer technique was presented in Chapter 3. First, we gave a brief description of the two most important models used in wireless network: the open system interconnection (OSI) model and the TCP/IP model. Then we discussed some characteristics that a UAV network posses and how it differs from other networks, such as the effect of aircraft attitude on the MANET performance and the effect of the aircraft fuselage on the antenna system. These characteristics make the models mentioned above inefficient and not effective in such networks. At the end of this chapter, we presented two architectures that are published for the Ad-Hoc network; those are architectures based on local profiles and architectures based on global and local profiles. Last, we have presented our new architecture that is called Target-Source Based Architecture. This architecture has only incorporated the following layers: physical layer, data link layer and network layer. Both data link and network layers were measured by throughput and delay, while physical layer was measured by Bit-Error-Rate (BER). Layer protocols were adjusted to satisfy our goal and adapt UAV constraints.

In Chapter 4, a novel Adaptive Medium Access Control protocol was proposed for UAV mobile Ad-Hoc networks (AMAC_UAV). The first part of this chapter reviewed both the MAC layer and the physical layer and provided detailed information about IEEE 802.11 standard and the concept of smart antenna. In the second part, we focused on the implementation of the UAV in OPNET Modeler 14.5. We developed a model for each UAV with two directional and two Omni-directional antennas. This model was able to send and receive traffic using both types of antenna. Meanwhile, we have constructed our directional antenna pattern using antenna pattern editor provided by OPNET. A short description of OPNET Modeler 14.5 was also given. Channel model, UAV mobility model and our new MAC scheme (AMAC_UAV) were also introduced in full detail. We analyzed the performance of our scheme and the data collected from the simulation scenarios. We observed that using directional antenna in UAV Ad-Hoc network provided better performance than Omni-directional antenna in terms of End-to-End delay.

In Chapter 5, Directional Optimized Link State Routing (DOLSR) protocol was proposed for UAV mobile Ad-Hoc networks. Our protocol was capable of reducing the number of the multipoint relays in the network. As a result, the end-to-end delay was reduced and the overall throughput was increased. Performance evaluation and comparison between OLSR and AODV protocols were studied using OPNET Modeler 14.5. The simulation results showed that OLSR protocol achieved better performance than AODV protocol in terms of end-to-end delay. Another comparison was conducted between OLSR and DOLSR protocols using the same simulator. The simulation results showed that DOLSR protocol achieved better performance than OLSR and AODV protocols in terms of end-to-end delay. In this chapter, we concluded that as the number of MPRs shrinks, the number of the overhead packets is reduced and thus the overall performance is enhanced.

6.2 Future Work

The ideas presented in this dissertation can be expanded to enable our system to work similar to those systems that are used in commercial aircrafts. For example, Traffic alert and Collision Avoidance System (TCAS is one of the systems that is used to monitor the space around aircrafts; it continually sends a navigation message that describes the position of the aircraft. This message is then processed and an alarm is issued to indicate if there is another aircraft passing too closely to the owner of this message. To do that, application layer should be included in our architecture which is presented in Chapter 3. Also, a new mechanism should be developed to interface the communication system with the navigation system so that the aircraft navigation system can control the movement of the aircraft based on the data coming from our system.

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