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

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***Abstract*— A 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 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 the network protocols is based on an Open Systems Interconnection (OSI) reference model. This methodology divided the stack into seven layers where each layer operates independently. Due to the dynamics of the Unmanned Aerial Vehicle (UAV) Ad-Hoc network, the layered architecture is not flexible enough to achieve certain quality of services (QoS) required by some applications. To overcome the limitations of the layering technique, cross-layering approach is used in this paper so to adjust some key parameters in the first three layers based on the aircraft attitude variations (pitch, roll and yaw), hence we can enhance the performance of such networks. To that respect, directional antenna is going to be used by the UAVs to extend the coverage area and reduce the number of hops. Meanwhile, we designed a new Medium Access Control (MAC) scheme that adapts its parameters based on the channel bit error rate which is indeed affected by the new antenna system and aircraft attitude. we called this scheme Intelligent Medium Access Control Protocol for Unmanned Aerial Vehicle (IMAC_UAV). As for the routing protocol, We developed the Optimized Link State Routing Protocol (OLSR) so that the decision for selecting the route will be based on a local profile that holds the gathered information from the first three layers. Our new scheme is called Directional Optimized Link State Routing Protocol (DOLSR). We proved by OPNET simulator that our proposed techniques gave better end-to-end delay than the IEEE802.11 standard.**

I. INTRODUCTION

CROSS-layering technique 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, cross-layering allows communication between non-neighboring layers as well as reading and controlling parameters of one layer from other layers [1], [2], [3], [4]. 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.

Recently, there has been an increasing interest in employing Unmanned Aerial Vehicles (UAV) in wireless communication networks, especially in Mobile Ad-Hoc Networks. UAVs have been primarily used for military applications [5]. 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 by utilizing the 802.11 wireless protocols and thus forming powerful networking nodes in the air.

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 for such communication system that will compensate for these effects and be largely unaffected by changes in aircraft attitude. In this paper, we will consider a collection of UAVs that communicate through a wireless link as a MANET using directional antenna. Current MAC protocol (IEEE 802.11) that implements the omni-directional antenna may not be suitable while using directional antenna. Thus we will introduce an intelligent medium access control protocol that is capable for adapting any constraints imposed by the UAV. To be more specific, we will introduce 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.

Variation of wireless links as a result of using UAVs 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 layer [6], [7], [8], [9], [10] and network layers, Cross-layer technique is implemented in this paper 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. On more issue is the aircraft location, The location of the UAV is significant in Ad-Hoc networks especially during the use of directional antenna. Therefore, a combination of more than one navigation systems are requred for a practical solution to

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the UAV communication system. As known, GPS provides position information at (1) second interval, this interval will not benefit our scheme since our scheme needs high 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 [11], [12], [13].

The remainder of this paper is organized as follows. In the next section we started with a survey of current research for UAV Ad-Hoc network and cross-layer design framework. In section III, we describe our scheme that is called Intelligent Medium Access Control Protocol for Unmanned Aerial Vehicle (IMAC_UAV). In Section IV, we present our Directional Optimized Link State Routing (DOLSR) protocol and in section V, we give an overview of our cross-layer design framework and explain how it combines the directional antenna with the IMAC_UAV and DOLSR . In Section VI, we present our OPNET simulation results and we provide a comparison between the use of directional antenna and the omni-directional antenna (IEEE 802.11), also we provide a comparison between the use of OLSR and DOLSR . Finally, we summarize the main results in section VII.

II. RELATED WORK

Integrating wireless equipment into a small UAV has been studied recently, especially in the context of MANET. In [14], the authors showed that by integrating small low-cost Commercial Off-The-Shelf 802.11b equipment into a UAV, a powerful networking node in the air can be created. To understand the performance of such a network, the authors in [15] 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 [16], the authors presented a set of field experiments to the wireless link between UAVs and a 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. We think that the impact of the UAV node on the ad hoc network still needs more investigation.

In [17] 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 ground station [18] to accomplish a set of objectives. Communication between UAVs should be established without significant setup so the need for future plans to enhance communication architecture needs strong support by new transport layer protocols.

A lot of software are used to simulate the UAV Ad-Hoc networks. In [19] 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.

Applications with UAV have specific requirements to reduce the overhead under heavy transmission load. In [20] the author presents a new contention-based Medium Access Control protocol for wireless Ad-Hoc networks of unmanned air vehicles. They called their protocol a Receiver-initiated Access Control with Sender Scheduling (RACSS). The RACSS MAC protocol uses the concept of contention-based where the receivers have the power to decide which node transmits.

As a result of the rapid progress in technology, cross-layer design became very important for any wireless network. Most of the available research has proven that PHY and MAC layers are very important especially in wireless networks and should be designed jointly. As for the UAV Ad-Hoc network, previous research suggests that UAV node requires an integrated design to the OSI reference model [21], [22].

Other researchers have shown that cross-layer design of different protocols is essential to meet application requirements. In [23], the authors presented cross layer design to address some problems observed in wireless networks such as mobility, packet losses and delay, while in [24], the authors focused on the limitations of energy resources in Ad-Hoc network and how it affects application requirements

In [25], the authors proposed a new mechanism to enhance the routing protocols by location prediction; cross-layering information is gathered by their technique and then stored in a separate profile so that other layers can access this profile during the decision making.

III. IMAC_UAV SCHEME

We proposed a new medium access control scheme to be used in a UAV mobile Ad-Hoc network. We called this scheme Intelligent Medium Access Control Protocol for Unmanned Aerial Vehicle (IMAC_UAV). In our scheme, We assumed that all UAVs are placed over the ground and flew at different altitudes. The distance between any two UAVs will not go beyond the range of the directional antenna. 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. Upon receiving

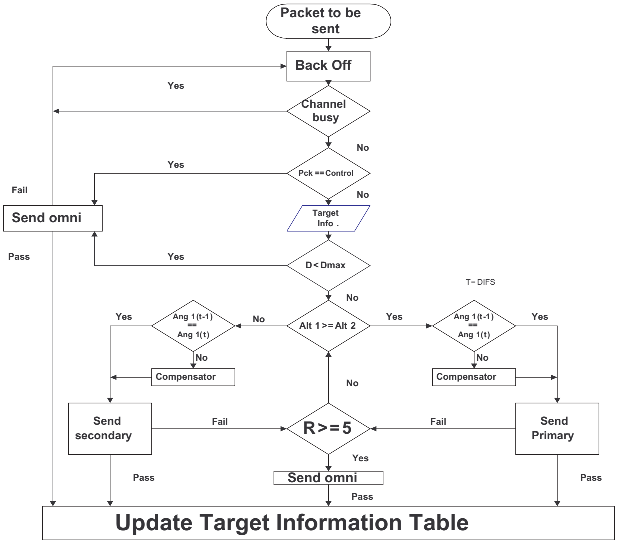

Fig. 1. IMAC_UAV scheme flow chart for UAV.

this message, the destination node will respond with a CTS packet that has its information through the omni-directional antenna . Each node that hears the CTS or RTS should cache these information and update its table for future use. The data packet will be sent using directional antenna. Fig. 1 shows the IMAC_UAV scheme.

Based on the IMAC_UAV, every UAV has four antennas. Two of them are directional and others are omni-directional. One of the directional antenna is located above the UAV and marked primary, The second antenna is located beneath the UAV and marked secondary. If the UAV has a packet to send, it will use the directional antenna, otherwise it will listen to other UAVs using omni-directional antenna. IMAC_UAV should frequently monitor the positions of other UAVs and compute the effect of Euler angles on the directional antenna. In addition, IMAC_UAV should monitor the distances, bit error rate and retry counter so that it switches to omni-directional antenna if the values exceed the limits. In case that there is no activity during a period of one second. A heartbeat message is sent out using omni-directional antenna. This message is used to update the locations of the UAVs. Our modeling to the directional antenna is based on a single beam in which a UAV is capable of electronically steering the beam towards a specific direction. 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

IV. DIRECTIONAL OPTIMIZED LINK STATE ROUTING PROTOCOL (DOLSR)

Optimized Link State Routing Protocol (OLSR) is a popular type of proactive protocol (Table driven) that is designed mainly for MANET. It is considered as an enhancement to the pure link state protocols in that it reduced the size and the number of the control packets. In contrast to other protocols, OLSR 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 message and thus reduce the number of the retransmissions in the network. In addition, this node is a one hop node and it is chosen so that it covers other two hop nodes. In OLSR, each node is periodically broadcasting hello message to its neighbors telling them the neighbors list. This list is used by each node to figure out the nodes that are two hops away and then to compute the MPR set. The number of MPRs is not restricted to one and is sent to other nodes in hello message. As soon as other nodes catch this information, each node builds its topology map and its record for nodes that select it as an MPR. MPR should declare the link information for the nodes that have chosen them as MPR so that those nodes are capable of computing the shortest path to the selected destination. To maintain the network topology information, the link state is periodically exchanged between nodes.

The most important step in OLSR protocol is the selection of the MPR. In this paper we 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. To this respect, we proposed a new mechanism that leads to the reduction in MPR numbers. Fig. 2 showed our block diagram for the proposed Directional Optimized Link State Routing Protocol (DOLSR). 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 that the omni-directional antenna is used, otherwise, the the UAV will go back to the DOLSR. As an example, we will consider the UAV Ad-Hoc topology that is shown in Fig. 3. We present a simple seven node scenario to illustrate the mechanism. In OLSR MPR selection mechanism, a UAV marked as A will select C and D as its MPRs, those UAVs cover all the un-reachable two hops 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 I 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 I

MPR SELECTION IN DOLSR AND OLSR MECHANISMS

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

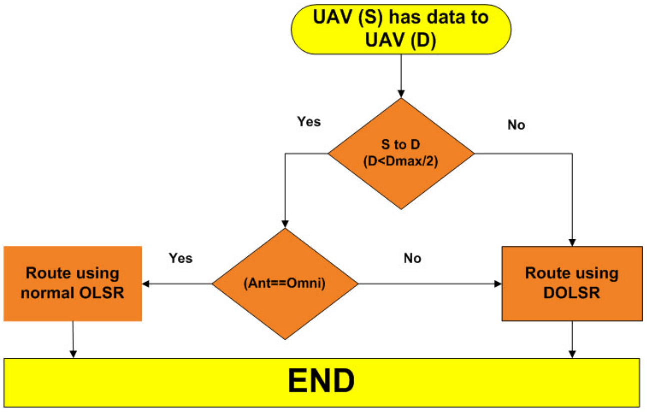

Fig. 2. DOLSR routing protocol block diagram .

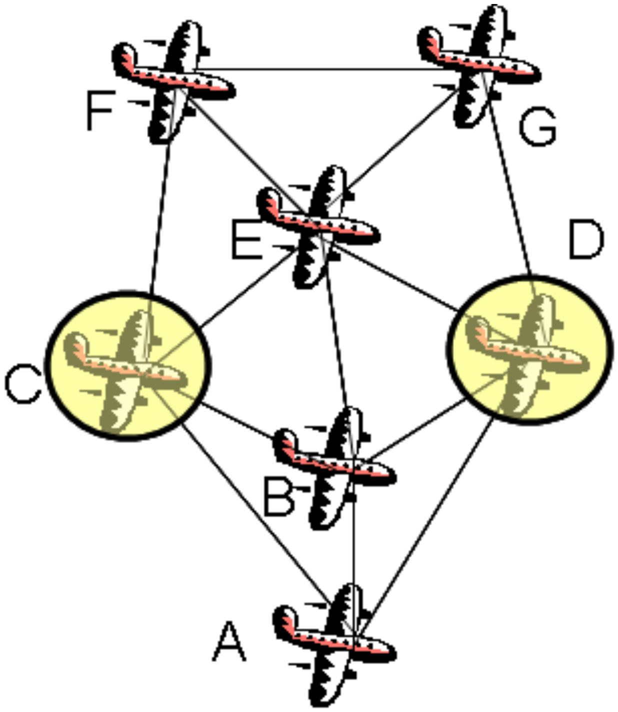

Fig. 3. Ad-Hoc topology, illustration of multipoint relays in DOLSR and OLSR.

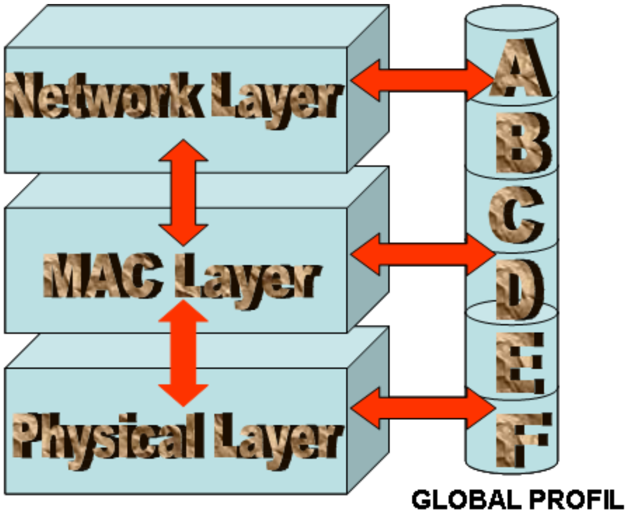

Fig. 4. Target-Source based architecture.

V. CROSS-LAYERING ARCHITECTURE

A cross-layer approach to UAV's Ad-Hoc network aims to enhance the performance of the system by jointly designing multiple protocol layers. This approach allows OSI layers to adapt their parameters to network conditions imposed through the use of UAVs. As shown in Fig. 4, our proposed cross-layer design is based on sharing the following information: bit error rate, 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, bit error rate will be recorded as a result of CTS reception. During the use of omni-directional antenna, the MAC layer will switch to direction antenna in case the BER gets worse. In addition, it will keep transmission on this mode (omni-directional) as the UAVs are getting close to each other.

VI. OPNET SIMULATION RESULTS AND DISCUSSIONS

To demonstrate the performance of the IMAC_UAV and the DOLSR protocols presented above, we compared both schemes to the IEEE802.11 and to the OLSR standard. For our simulation, we have used an OPNET 14.5, a discrete event network simulator that includes a rich set of detailed models for Ad-Hoc network . A 25 UAVs are placed as shown in Fig. 5 in a 2000 X 2000 m area. Both IMAC_UAV and MAC 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 UAV are moving in the simulation area according to a random waypoint model. the packet size is set to 1024 bits and the distribution is exponential. All UAVs in the network are configured to run an OLSR during the first scenario and DOLSR during the second one.

The total delay of the network is shown in Fig. 6 which is represented by end-to-end delay. The end-to-end delay represents the time interval that is calculated from the instance

Fig. 5. Network topology for 25 UAVs used for simulation.

a packet is generated by the source node, to the instance that the packet is received by the destination. This figure compares the end-to-end delay between the IMAC_UAV protocol using directional antenna and the MAC protocol specified by IEEE802.11 standard 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 becomes less due to the use of the DOLSR. Fig. 7 shows the difference between the number of MPRs that is selected by the original OLSR and the DOLSR. 14 MPRs are selected during the use of the OLSR while 10 MPRs are selected during the use of DOLSR. Fig. 8 shows the number of TC messages forwarded during the simulation time. Since all nodes are mobile, TC message is 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 second. while in DOLSR the number is less than 160. This is due to the reduction of the MPRs. The same result can be seen in Fig. 9 in which the DOLSR reduced the the total number of the generated TC messages .

VII. CONCLUSION

Communications through UAVs in Ad-Hoc networks are a new type of wireless network. Due to the high flexibility of the UAVs and the availability of low-cost communication equipments, it is now possible to use this type of aircrafts

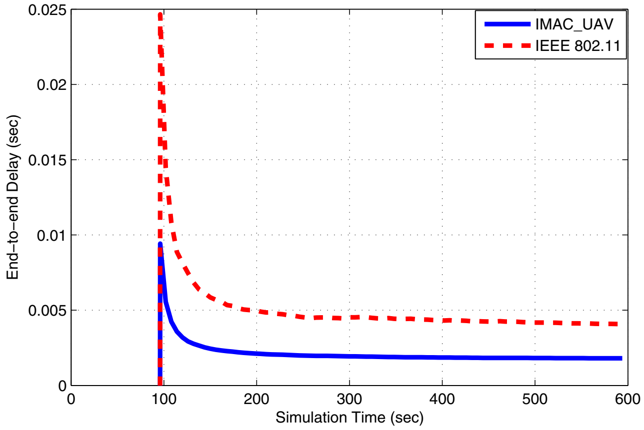

Fig. 6. Comparison between IMAC_UAV and IEEE802.11 MAC protocols for the End-to-end delay.

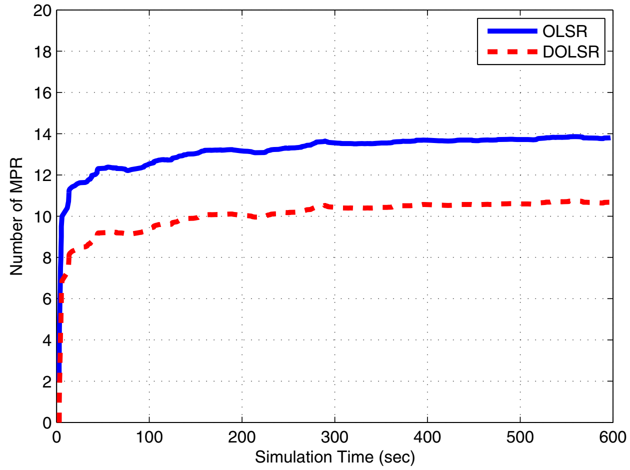

Fig. 7. Comparison between the OLSR and DOLSR protocols for the average number of MPRs selected by the network.

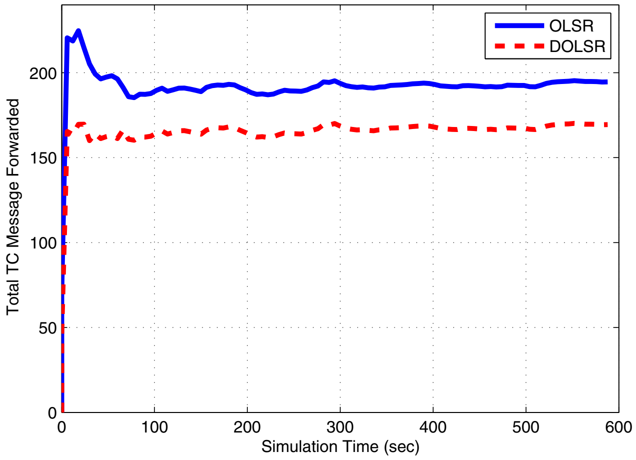

Fig. 8. Comparison between the OLSR and DOLSR protocols for the total number of TC messages forwarded by the MPRs

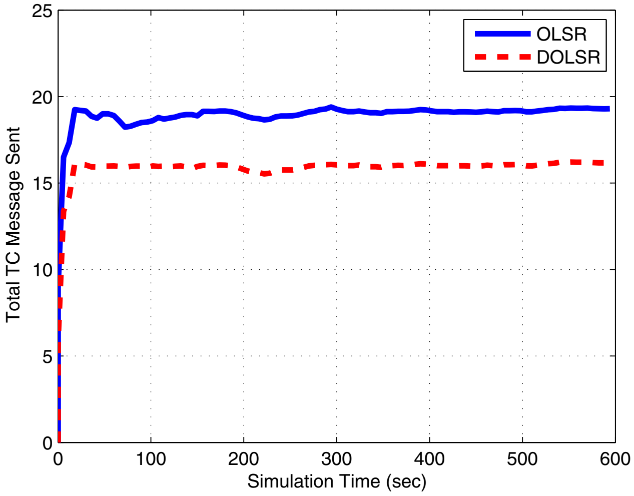

Fig. 9. Comparison between the OLSR and DOLSR protocols for the total number of TC messages sent by the MPRs

as a mobile node in an Ad-Hoc network. Implementation of standard OSI model in such a network may not fit well due to some constraints imposed by the UAV. Therefore, cross-layering technique was introduced in this paper to facilitate the interaction between layers and allow us to tune layer parameters so that the overall performance is improved. In this respect, we proposed the use of directional antenna and we designed two schemes: Intelligent Medium Access Control Protocol (IMAC_UAV) and Directional Optimized Link State Routing (DOLSR) protocol. By OPNET simulator, we compared our two schemes to the IEEE802.11 protocol and to the well known OLSR protocol. The simulation results show that the proposed techniques can enhance the UAV Ad-Hoc network performance in terms of end-to-end delay.

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