On the performance of Flying Ad Hoc Networks (FANETs) Utilizing Near Space High Altitude Platforms (HAPs)

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***Abstract*—High altitude platforms (HAPs) and Flying Ad Hoc Networks (FANETs) are some of the most promising technologies for both military and civilian near space wireless networks. HAP systems usually reside on stratospheric altitudes up to 25 km and have the advantages of flexible deployment, wide area coverage and line-of-sight propagation, compared to ground or satellite based systems. Also Unmanned Air Vehicles (UAVs) have the ability for persistent flight over periods of days to weeks which cannot be achieved by manned aircrafts. Thus, utilization of FANETs in conjunction with HAP stations would present numerous advantages over traditional networking. However one of the most challenging issue for FANETs is the awareness of the locations of the neighboring UAVs. It is vital for FANET scenarios in the sense of reliability, security and collision avoidance. In this study we investigate how HAP&FANET architectures can be usefully employed in such scenarios. We propose a Medium Access Control (MAC) protocol which we name as Location Oriented Directional MAC (LODMAC) protocol. LODMAC successfully handles the neighbor discovery and data transmission in parallel with the help of directional antennas. Also we present the capacity gain of LODMAC protocol which verify that it is a good alternative for HAP&FANET based scenarios.**

***Index Terms*—FANET, HAP, directional antenna, neighbor discovery, LODMAC.**

I. INTRODUCTION

Unmanned Aerial Vehicle (UAV) systems fly autonomously without carrying any human personnel. Usage of UAVs promises new ways for both military and civilian applications ranging from search and rescue operations to disaster monitoring. Also deployment of a group of small UAVs will form a special kind of ad hoc network type which will present many additional advantages [1-2]. This type of networking is named as Flying Ad Hoc Networks (FANETs) which also have unique challenges other than MANETs or VANETs. One of the most prominent challenges is the exact possession of the neighbor's locations and to establish a reliable medium access mechanism among highly mobile nodes. Although there is literature which base on detection of the locations of the periphery nodes with determination of the signal angle of arrival, gossiping the respective neighbor transmission or via heartbeat broadcast messages, they have numerous defects to be deployed for FANETs [1-3]. Alternatively, HAPs can be utilized as location disseminators.

The nodes in FANETs have higher mobility than of MANETs. The velocities of UAVs range from 20 to 40 m/sec. Today many FANET models are utilized with traditional omnidirectional antennas and with standard IEEE Distributed Coordinated Function (DCF) MAC. In addition, because of the high speed of nodes the network topology changes more rapidly. Today, an alternative for the traditional omnidirectional antenna and DCF based systems; directional antennas and directional MAC protocols are projected to be deployed in FANETs [1]. Although utilization of directional antennas on UAVs provides numerous advantages, the neighbor discovery still remains a challenging task. In this paper we propose the usage of HAPs in order to provide a FANET with continuous location information. A typical HAP based FANET scenario is illustrated in Fig.1. As it can be seen from the figure, a HAP could reside up above a FANET. During a FANET flight scenario, not necessarily all of the UAVs may communicate to a ground station. Only one or the cluster head communication could often be adequate. However, every UAV have to be connected to the HAP station continually.

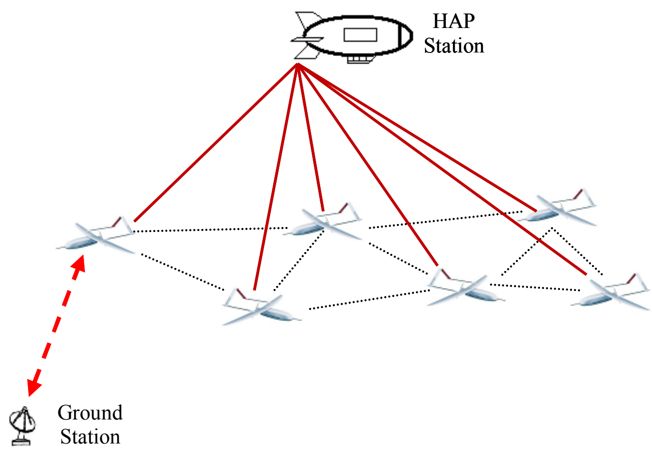

Fig.1. A FANET augmented with a HAP.

HAPs can range from expendable balloons to solar UAVs which can operate at 25 km (>70.000 ft) altitude [4]. Higher altitudes present extended coverage areas. More specifically, at altitudes higher than 50.000 ft, the coverage area would be 150 km [5]. The projected altitudes are above the civil air routes and jet-stream is relatively benign and the station power can be achieved by solar panels. HAP systems present many advantages compared to ground based or satellite based systems such as flexible deployment, wide area coverage, ability to easily maintain payload, low cost and line-of-sight (LOS) propagation [5]. HAP stations also exhibit reduced packet delivery latency, less propagation loss and higher data rates.

Today, most of the studies conducted on FANETs utilize omnidirectional antennas where the capacity and maximum transmission ranges are non-scalable, insufficient or non-reliable enough, especially for military applications [1]. Besides, an alternative for the traditional omnidirectional antenna based systems; directional antennas can be deployed in FANETs. While most of the existing directional antenna based MAC layer protocols are proposed for MANETs and VANETs, the researches for FANET MAC layer design issues is scarce. Although substitution of directional antennas with omnidirectional ones provides numerous advantages, some characteristic problems arise such as the directional hidden terminal problem, the deafness and head of line blocking problems [1]. As far as we're concerned, there isn't yet any proposed MAC layer protocol which addresses all of the aforementioned problems. In the following subsections we argue that the proposed Location Oriented Directional MAC protocol (LODMAC) give solutions to all of the three problems along with providing neighbor discovery in the FANET. Specifically we present a capacity analysis and propose to use small and low cost HAPs for augmenting neighbor discovery. We propose to use three directional antennas on-board of the UAVs. The first antenna is used for neighbor discovery and it operates in conjunction with the HAP station. The second antenna is used for communication control issues (Request to Send / Clear to Send - RTS/CTS exchange) and the third one is for the data transmission. All of the three antennas are managed and synchronized with the proposed directional MAC protocol.

The remainder of the paper is organized as follows: In Sections II, related work is reviewed. In Section III, some preliminaries and the model are presented and in Section IV, analytical evaluation results and an overview are presented respectively. The paper is concluded in Section V.

II. RELATED WORK

Although studies of HAP utilization for neighbor discovery issues for ad hoc networking is scarce, there are some studies which present the advantages. For example in [5], a localization experiment using a high altitude long endurance (HALE) UAV platform is presented. The HALE UAV carries an angle-of-arrival array antenna. In the experiment, the reference stations are employed on the ground which sent signals and whose positions were known in advance. The array antenna elements which are placed under the wing of the UAV receive the signals from the mobile terminals and reference stations and estimate the position of the mobile terminals.

In another study, a heterogeneous network system comprising mission layer, HAP layer and satellite layer is presented [6]. In the system, the mission space is partitioned according to the assumption of one-hop relay which guarantees that all the users are effectively covered by airships in HAP layer. The simulations revealed that the proposed method can get the goal of the minimum energy consumption and achieve a near optimal deployment of HAPs.

In [7], it is stated that aeronautical ad hoc networks can be realized with aircrafts, which could provide direct air-to-air communication between aircrafts without ground infrastructures. They also present a topology aware routing protocol for aeronautical ad hoc networks. The proposed routing scheme uses the position and velocity of aircraft provided by an airborne localization system to eliminate the traditional routing beaconing and presents a velocity-based metric for next hop selection, which could adaptively cope with the fast moving of aircraft and dynamic changes of network topology.

In [8], it is stated that flying (HAPS/UAV) or stationary (Sky Station) at relatively low altitudes may provide backup or support capacity to hot spots. They consider that an innovative architecture using HAPs/UAVs connected to the satellite thereby reducing the impairment of shadowing and introducing a short range link with the user terminal; efficient TCP solutions allow use of standard equipment and applications without sacrificing performance. The combined use of both can greatly improve overall performance. Also in [9], Song et.al. proposes a clustering method of ground nodes. Ground nodes must be clustered in multiple sets and one dedicated HAP/UAV is assigned to each set and act as a mobile base station (MBS). For the intra-set nodes, UAVs must communicate each other in order to establish network links among intra-set nodes. They also state that the HAP based wireless network usually regarded as a viable solution for the networks with minimal ground infrastructures.

There is a trade-off on deployment of directional antennas on UAVs where the speed, the aerodynamic nature and drift caused by wind puts many challenges on establishing an effective link between UAVs. There are a few studies in literature on overcoming such challenges. For example in [10], Alshbatat et.al proposed an adaptive MAC protocol for UAV communication networks where in their model, the RTS/CTS exchange is conducted omnidirectional and data transfer is conducted directionally with one of four beams. They assumed four antennas on a UAV where two of them are located beneath the wing and others above. In this model, it is assumed that UAV has the capability to pan and tilt to the desired transmission direction which actually is not realistic assumption

II. Proposed Model

We assume that in the FANET there are M mobile nodes. We project that for future FANET applications, the network will be sparser than of MANETs and M would be between 3 and 20. The nodes fly on the same altitude and never get so close to each other in order to avoid collision. A typical FANET is illustrated in Fig.2 with six UAV nodes having 4 directional antenna beams.

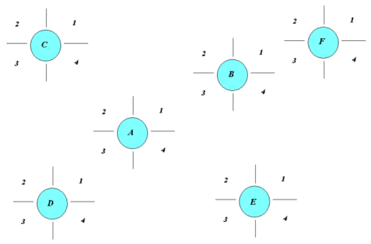

Fig.2. A FANET with six UAV nodes which has 4 beams.

In this study, we propose a novel directional MAC protocol equipped with three antennas and three corresponding receivers (T_1, T_2 *and* T_3) each having N beams. The first transceiver, T_1 is responsible for the neighbor discovery which is utilized in conjunction with the HAP station. It is always pointed to the HAP station. The second transceiver, T_2, is the MAC layer control transceiver (RTS/CTS exchange and connection establishment) and the third one, T_3, is responsible just for data transmission.

For physical layer parameters, IEEE 802.11b PHY layer is employed on 2.4 GHz frequency. We assume that the mutual interference between T_1, T_2 and T_3 is suppressed with physical and digital signal processing (DSP) techniques. As illustrated in Fig.3, the HAP station broadcasts the locations of all the nodes in the topology at the very beginning of every GPS update (1 sec). This broadcast interval lasts t_l msec. During t_l every UAV in the FANET becomes aware of the locations of the UAVs in the network. During the remaining t_c msec, UAVs directionally transmit their location information to the HAP station. Hence, in every 1 second the LODMAC protocol ensures to finish the determination and dissemination of neighbors' locations. When GPS_{int} indicates a GPS update signal interval, which usually equals to 1 second, we get:

$$t_l + t_c = GPS_{int}\ (t_l < t_c) \qquad (1)$$

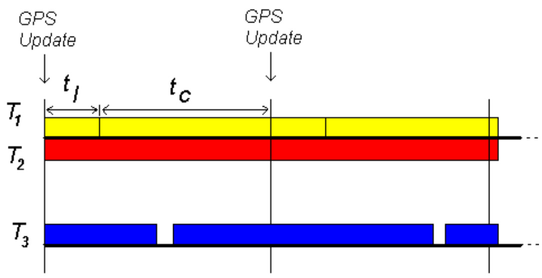

Fig.3. LODMAC sequence with a pair of transceivers.

Initially all of the T_1 transceivers in the network are in directional listening (receiver) mode during t_c. As long as they get a location vector, L_A, they update their neighbor table With L_A some other valuable information is also shared along with the GPS locations of all the nodes in the FANET. One example is the current data antenna orientation and the ID of the current communicating node (if there is one). The structure of a location vector is shown in Fig.4:

1 byte	24 byte	2 bits	6bits	1 byte	1 byte
ID_	**GPS_**	**Data_Flag**	**Beam_**	**D_ID_**	**NUL_**

Fig.4. The location vector

where, *ID_* is the node identification number, *GPS_* is node's current GPS location (latitude, longitude, altitude). *Data_Flag* is set to values presented in Table-1 which indicates the current data transmission or reception status of T_3, *Beam_* is the current antenna orientation of T_3 and *D_ID_* is the ID of the neighbor with which T_3 is currently communicating. Lastly, the *NUL_* byte is reserved for future use. As explained later, the location information sharing adds an additional overhead of 28 bytes to the MAC frames.

TABLE I
VALUES OF THE *DATA_FLAG*

Value	Description
00	There is no data transmission on T_3
01	T_3 is in receiver mode
10	T_3 is in transmitter mode
11	not used

The control phase is conducted with T_2. With the help of T_2, standard RTS and CTS exchange is realized. For LODMAC, we also define an additional busy-to-send (BTS) packet in order to reply an RTS sender that the node is currently busy and it is not convenient to make a data exchange. While any node in the network is provided with the GPS locations of its neighbors, either the RTS, CTS or BTS packets are sent directionally only to the intended beams where neighbors reside. Hence, as in IEEE DCF (Distributed Coordinated Function) MAC protocol, directional hidden terminal problem is minimized.

LODMAC protocol is a deafness-free MAC protocol because the T_2 transceiver is dedicated to listen and reply to RTS packets even the T_3 transceiver is currently on data transmission. Also, LODMAC minimizes the head-of-line-blocking problem because all of the interfaces are employed with independent queues and any packet which is destined for a blocking receiver can be determined on-the-fly and blocking can be solved immediately. To much of our concern, LODMAC is the first protocol which presents solutions both for hidden terminal, deafness and head-of-line blocking problems.

While T_1, T_2 and T_3 work independently from each other, the control overhead will be minimized. Hence, we can expect a utilization increase with LODMAC. For the utilization analysis we utilize the packet delay analysis model presented in [11]. To do so, we first define the average durations that the medium is sensed busy due to a collision $T_{c\text{-}DCF}$, and average duration of a successful transmission, $T_{s\text{-}DCF}$, for DCF protocol as follows:

$$T_{s-DCF} = DIFS + T_{RTS} + SIFS + T_{CTS} + SIFS + T_{h-DCF} + {}^{l}/_{C} + SIFS + T_{ACK} + 4\eta$$

$$T_{c-DCF} = DIFS + T_{RTS} + SIFS + T_{CTS} + 4\delta \qquad (2)$$

where, $DIFS$ is the DCF interframe space duration, $SIFS$ is the short interframe space duration, T_{RTS}, T_{CTS} and T_{ACK} are transmission durations of RTS, CTS and ACK packets respectively, T_{h-DCF} is the interval required to transmit the packet payload header, C is the data rate, l is the packet length, and δ is the propagation delay. We have:

$$T_{h-DCF} = {}^{DCF_{MAC-h}}/_{C} + {}^{DCF_{PHY-h}}/_{C_{control}},$$
$$T_{ACK} = {}^{l_{ACK}}/_{C_{control}},$$
$$T_{RTS} = {}^{l_{RTS}}/_{C_{control}},$$
$$T_{CTS} = {}^{l_{CTS}}/_{C_{control}} \qquad (3)$$

where $C_{control}$ is the data rate of control packets (RTS/CTS) which is taken 2Mbps, l_{ACK}, l_{RTS} and l_{CTS} are the lengths of ACK, RTS and CTS packets respectively, DCF_{MAC-h} and DCF_{PHY-h} are the lengths of MAC and PHY layer packets. In physical layer a preamble and PLCP (PHY layer header) exist in both control and data frames. In order to achieve data rates up to 11 Mbps with 802.11b PHY, the short PLCP version has to be chosen, where with preamble this duration equals to 96µsec. The employed values of utilization parameters are listed in Table-II. Also for LODMAC we have:

$$T_{h-LODMAC} = {}^{LODMAC_{h}}/_{C} + {}^{LODMAC_{PHY-h}}/_{C_{control}}$$
$$T_{c-LODMAC} = DIFS + T_{RTS} + SIFS + T_{BTS} + SIFS$$
$$T_{s-LODMAC} = {}^{l}/_{C} + SIFS + T_{ACK} + 2\eta \qquad (8)$$

where $T_{h-LODMAC}$ is the interval required to transmit the packet payload header with LODMAC protocol, $T_{c-LODMAC}$ and $T_{s-LODMAC}$ are the average durations that the medium is sensed busy due to a collision and average duration of a successful transmission respectively. It is evident as seen in (8) that, LODMAC protocol does not handle any control packets for the data transmission transceiver which improves the utilization dramatically.

The utilization gain rate of DCF and LODMAC protocol is given in Fig.5. As it can be inferred from the figure, utilization is maximized with the maximum packet length of IEEE 802.11b which is 8000 bits. This shows, by deploying two transceivers on nodes, the wireless channel is optimally utilized along with achieving a robust neighbor discovery method.

TABLE II
PARAMETERS USED FOR UTILIZATION ANALYSIS

Symbol	Description	Value
l	Packet payload length	8000 bits
DCF_{MAC-h}	DCF MAC header length	272 bits
$LODMAC_h$	LODMAC header length	496 bits
l_{PHY}	Short PHY header	96 µsec
l_{RTS}	RTS packet length	160 bits + l_{PHY}
l_{CTS}	CTS packet length	112 bits + l_{PHY}
l_{BTS}	Busy-to-send packet	224 bits + l_{PHY}
l_{ACK}	ACK packet length	112 bits + l_{PHY}
DIFS	DCF interframe spacing	50 µsec
SIFS	Short interframe spacing	10 µsec
C	Data transfer rate	11 Mbps
$C_{control}$	Control packet transfer rate	2 Mbps

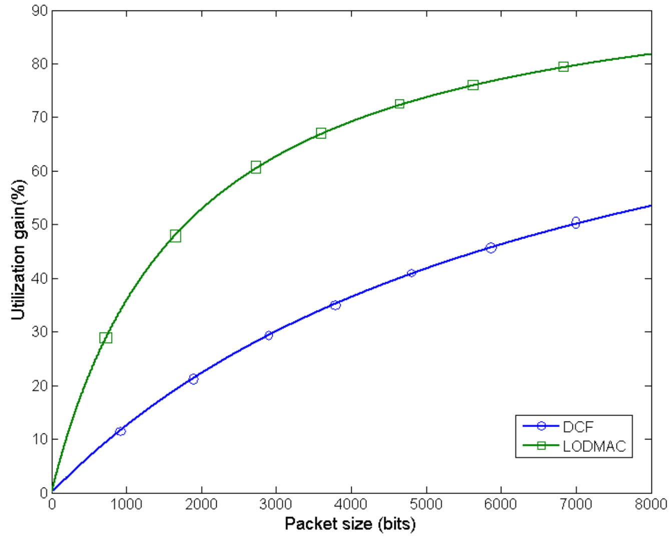

Fig. 5. Utilization rate comparison of DCF and LODMAC with respect packet size.

DISCUSSION

In literature, crushing majority of the studies utilize a single directional antenna because there was no need to deploy a user laptop, pda, vehicle etc. with multiple antennas. In addition when MANETs are in case, the speed of the transmitters and receivers do not deserve much concern. However, FANETs are highly mobile and very convenient to deploy multiple antennas on flying nodes. Also the neighbor discovery and location information may not be important for MANETs as in FANETs, hence most of the studies assume that the neighbor discovery process is provided somehow from upper layers.

In this study we presented a novel MAC protocol, LODMAC, which presents solutions for directional antenna challenges and provide all of the UAVs with exact location information of the neighbors within every GPS update sequence by employing a HAP station and three smart beam antenna arrays.

As a conclusion, we believe that this study presents solutions to some of the controversial issues and contribute to the upcoming universal knowledge on FANET designs.

CONCLUSION

A FANET is an upcoming and novel mobile wireless ad-hoc network type which bear many open research issues and would attract many researches to develop new techniques or reinvent conventional methods. Also HAP systems have the advantages of flexible deployment, wide area coverage and line-of-sight propagation, compared to ground based systems. Hence, HAP systems can be good alternatives to augment FANET applications. Specifically, although a few MAC layer protocols have been proposed for FANETs, there exists many other problems such as spatial reuse, scalability, long range transmission requirements, enhanced security and neighbor discovery issues. One promising means to overcome such problems is utilization of directional antennas instead of omnidirectional ones. However, directional MAC protocols have some unique challenges such as directional hidden terminal, deafness and head of line blocking etc. In this paper, we propose a FANET MAC, LODMAC, which utilize three directional smart beam antennas. LODMAC is a deafness-free protocol and address the directional hidden terminal and head-of-line blocking problems. We also, show that LODMAC presents increased network utilization and provide all the nodes in the topology with exact GPS location of its neighbors.

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