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LODMAC: Location Oriented Directional MAC protocol for FANETs

Samil Temel *, Ilker Bekmezci

Turkish Air Force Academy, Istanbul, Turkey

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ABSTRACT

Flying Ad Hoc Network (FANET) is a novel mobile ad hoc network type where the communicating nodes are Unmanned Aerial Vehicles (UAVs). FANETs promise many new ways for both civilian and military applications. Today, traditional omnidirectional antennas are deployed on UAV nodes which result in reduced spatial reuse and limited network capacity. Alternatively, deployment of directional antennas can significantly increase the capacity, spatial reuse and communication range of FANETs. In addition, being aware of the exact locations of the neighboring nodes in a FANET is vital especially for directional ad hoc multi-UAV scenarios. In this paper, we present a novel MAC protocol, LODMAC (Location Oriented Directional MAC), which incorporates the utilization of directional antennas and location estimation of the neighboring nodes within the MAC layer. By defining a new Busy to Send (BTS) packet along with the Request to Send (RTS) and Clear to Send (CTS) packets, LODMAC effectively addresses the well known directional deafness problem. In terms of throughput, utilization, average network delay and fairness, LODMAC protocol outperforms the well-known DMAC (Directional MAC) protocol which puts LODMAC to be a robust mile-stone for the on-coming FANET MAC protocols.

1. Introduction

Deployment of a group of UAVs, which form a special kind of ad hoc network in the sky, present many advantages for both civilian and military applications. Recently, this novel ad hoc network type is named as FANETs which have unique challenges over Mobile Ad hoc Networks (MANETs) or Vehicular Ad Hoc Networks (VANETs) [1]. One of the most distinct characteristics of FANETs is that, the nodes in FANETs are generally highly mobile with velocities between 10 and 40 m/s in the 3D space. The rapid topology change and movement in 3D space impose many additional burdens on the physical layer (PHY), Medium Access Control (MAC) and network layer design characteristics.

Today, although scarce, most of the FANET applications utilize commercial off-the-shelf (COTS) Wi-Fi (IEEE 802.11) equipments which were mainly developed for MANET usage and the transceivers are often equipped with omnidirectional antennas which radiate the energy to every direction. However, when used for FANETs, many problems arise. Such examples vary from longer packet transmission delays to degraded security and limited transmission ranges [2,3]. In some scenarios, such as a search and rescue mission after a catastrophic event, the application demands may be delay-untolerated where human life is in concern. Hence, much delay effective alternative techniques have to be re-designed or re-invented specifically for FANETs.

Directional antennas have several advantages over omnidirectional ones which enable them to be a promising alternative to be deployed in FANETs [1–3]. One of the prominent advantages is that the transmission range of a

* Corresponding author.
E-mail address: s.temel@hho.edu.tr (S. Temel).

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directional antenna is generally longer and spatial reuse of the network increases with deployment of directional antenna based protocols [2–5]. However, utilization of directional antennas necessitates the usage of directional MAC protocols which mostly suffer from the well-known deafness and head-of-line blocking problems [4]. In this paper, we argue that the proposed LODMAC protocol presents robust solutions for the aforementioned problems.

The possession of the exact locations of the neighboring nodes is vital for FANETs [1]. In the directional antenna case, a node has to be provided with the neighbor location information in advance of a data transmission session because the antenna has to be oriented towards the receiver in advance. Although there are some studies which propose location estimation via broadcasting, flooding or angle-of-arrival estimation, most of these methods depend on the usage of traditional omnidirectional antennas and they are far from being reliable on mission critical FANET posts [4]. Also, the dissemination of the location information among the nodes with an ad hoc manner remains as an unsolved issue. Yet, the majority of the directional antenna based MAC protocols assume that the location estimation is provided from the upper layers which is not a realistic assumption. Thus, unlike other studies, in this paper we propose the LODMAC protocol which provides both an effective way to utilize data transmission over directional antennas and a method to determine and disseminate the exact locations of the neighboring nodes in every GPS update interval sequence.

In this study, we assume that each UAV in the FANET is equipped with two transceivers and each of the transceivers utilize switched beam directional antennas which operate as shown in Fig. 1. According to the figure, basically, the first transceiver, T1 is responsible both for the location estimation and control packet exchange (RTS, CTS and BTS) facilities. The other one, T2, is only responsible for the transmission of data packets.

As shown in Fig. 2, the LODMAC protocol utilizes two of the transceivers concurrently with two parallel phases. Namely, the *probing phase* and the *data transmission phase* respectively. The probing phase is also divided into two sequential slots which are the *location estimation slot* and the *communication control slot*. In LODMAC, one of the transceivers, T1 is assigned for the probing phase and the T2 is assigned for the data transmission phase. The probing phase lasts for 1 s exactly which is equal to the global GPS interval and in this phase, UAV nodes disseminate their location information to the neighboring nodes and

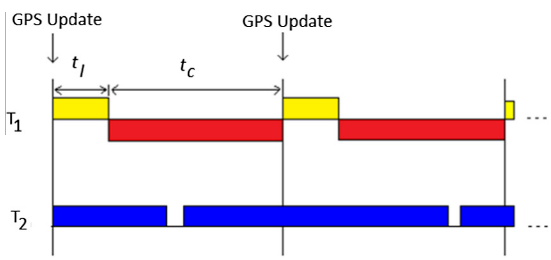

Fig. 1. LODMAC sequence with a pair of transceivers.

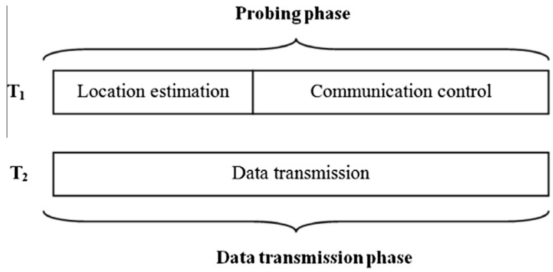

Fig. 2. Phases of the LODMAC protocol.

exchange communication control packets. If we assume that the location information slot is fulfilled in t_ll second, then the remaining period of time, t_c ($t_c = 1 - t_l$), will be assigned for the communication control slot.

One critical question may arise in the determination of the tl period. This period must be determined in advance of the flight and we assumed that UAV nodes take turns in a round robin fashion to get the right to publish their own location. Although this method seems to be unrealistic particularly for dense networks, we project that number of nodes in a FANET will be between 3 and 20 which is far more less than of MANETs [1]. On the other hand, nodes could contend to get the right to access the channel with utilizing the binary exponential backoff algorithm but in our case we assumed that nodes in the FANET take turns according to their node IDs.

Separating the control and data channel result in increased network capacity [6,11–13]. In order to mitigate and suppress the interference among the two antennas, we assume that the two transceivers work on different frequencies and physically they are installed on optimal physical locations on the UAVs. The advantages and novelties of the LODMAC protocol are summarized as follows:

- *Eliminating the range asymmetry:* In LODMAC, all of the control, location and data packets are transferred directionally. Hence, the problem of asymmetry in gain is eliminated.
- *Enhanced communication range:* With the usage of directional antenna communications, the transfer range is increased which result in reduced hop counts and average network delays.
- *Eliminating the deafness problem:* In LODMAC, a new control packet, BTS is used. Thus, a receiver can answer to a sender that it conducts a transmission and will not be available for an amount of time.
- *Eliminating the head of line blocking problem:* In LODMAC, two transceivers are utilized and all of the antennas are employed with independent queues. Also the directional neighbor database (DND) ensures the detection of a busy node and a busy beam which provide valuable information to eliminate the head of line blocking problem.
- *3D flight scenarios:* Unlike other studies nodes in the FANET fly over 3D space. The proposed LODMAC protocol characteristics are coded and adapted for deployment in 3D scenarios.

The paper is organized as follows: In Section 2, related work and directional antenna based studies for FANETs are reviewed. In Section 3, models, preliminaries and the process of LODMAC are presented. In Section 4, simulation results and the overview of results are presented respectively. The paper is concluded in Section 5.

2. Related work

There are only a few studies on directional MAC protocol design which are proposed specifically for FANETs. For example, Alsbatat et al. proposed an adaptive directional MAC protocol for FANETs where the MAC control packets are exchanged omnidirectionally and the data is transferred directionally [6]. They assume that the UAVs are equipped with four antennas two of which are omnidirectional and the other two are directional. Although their work presents some novel aspects for directional MAC design issues, they lack to address the well known directional antenna problems such as the hidden terminal, asymmetric range and the deafness problems.

The antenna types of the transceivers play a major role on the capacity of any wireless network. In [3], Temel et al. present a capacity analysis of FANETs when deploying directional antennas. They state that, side lobe antenna gains, antenna main beam angle value and relative velocity of UAVs have significant effects on the number of maximum concurrent active nodes and achievable maximum data transfer rate. In another study, Gu et al. proposed a centralized channel assigned MAC protocol for FANETs [7]. Their proposed protocol aims to integrate the ground station terminals to the UAV nodes over a channel access mechanism. In [8], Li et al. proposed a MAC protocol which utilizes Carrier Division Multiple Access (CDMA) method. Their work addresses both the code collision and network link update problems. Their proposed MAC protocol uses tokens to exchange information between the UAVs. Although it can be admitted as a novel and interesting work, the control complexity and the cases on the token exchange failures are not handled properly.

Unlike MANETs, the aerodynamics of nodes in FANETs play a major role on choosing an appropriate antenna type. In [9], Cai et al. state that the signal propagation is inherently half duplex which result in higher packet loss ratio and interference. Alternatively, they propose the deployment of full-duplex antennas which result in increased MAC packet transmission performance. In another study, Das et al. present the opportunities and challenges on utilization of reservation based MAC protocols on FANETs. They state that the amount of packet transmission will fluctuate especially when a target is detected, hence on FANET simulations the packet size must be chosen high [10].

In [16], Choudhury et al. propose the Basic-DMAC (DMAC in short) protocol which is considered to be the benchmark for directional MAC protocols. In DMAC, it is assumed that an upper layer is aware of the neighbors of a node and is capable of supplying the transceiver profiles required to communicate with each of these neighbors. The MAC layer receives these transceiver profiles along with the packet to be transmitted.

Consequently, the common attributes and properties of the directional MAC protocols in the literature can be summarized as follows:

- The directional MAC protocols which utilize multi-transceivers and multiple antennas are rare. Alternatively, there are many studies which propose the usage of a single transceiver.
- Most of the studies assume that the location information of the terminals in the FANET is known somehow or location estimation facilities are provided from upper layers.
- The majority of the studies assume that the RTS/CTS packets are sent omnidirectionally and the DATA/ACK packets are sent directionally which result in an asymmetric gain in transmission. The studies for sending all the packets directionally are rare.
- Most of the studies for FANETs assume 2D flat scenarios where every node in the network is at the same altitude.
- Mostly, the smart beam antenna arrays are utilized for directional MAC protocols.

3. The LODMAC protocol

3.1. Antenna model

In this study, we utilize switched beam antenna arrays which can focus more energy on predefined directions. At a given time interval, only one transmission is conducted over one of the k directions of the antennas. Given a main beam angle, θ, in radians, the number of beams of the antenna is calculated with (1):

$$k = 2\pi/\theta \quad (k > 1) \tag{1}$$

We assume that each UAV in the FANET is equipped with identical antennas and in order to cover the whole region, an antenna may carry out contiguous transmissions. The beams are numbered from 1 through k. At a given time, a node can transmit or receive over only one of these antenna beams. In order to perform a broadcast, a transmitter must carry out sequential transmissions through all the beams. We assume that all nodes use the same antenna patterns and can maintain the orientation of their beams at all times. Also the switching time between the antenna beams is assumed to be zero and realized with some digital signal processing techniques.

As stated above, LODMAC uses a pair of transceivers and ensures that the transceivers work in collaboration and cooperation. The main intension to utilize two transceivers and separating control and data channels is to increase the overall network capacity and mitigate the average network delay of the FANET [2,3,11–13]. The first transceiver, T1 is responsible for location dissemination and exchange of control packets. The other transceiver, T2, is responsible just for data exchange. LODMAC protocol utilizes these two of the transceivers concurrently with two parallel phases. The phases of LODMAC are the *probing phase* which is conducted by T1 and the *data transmission phase* which is conducted by T2. The probing phase is also divided into two sequential slots which are the *location estimation slot* and the *communication control slot*. The location estimation duration is defined as t_l and the communication control duration is defined as t_c where $t_l + t_c = 1$ s (GPS interval) and $t_l \ll t_c$.

3.2. Capacity analysis

The capacity of any wireless network is related and constrained with the number of active nodes in the network. In our previous studies, we have shown that, depending on the higher spatial reusability, the number of active nodes of FANETs increase when utilizing directional antennas [2,3].

The basic negative effect when deploying omnidirectional antennas for every type of ad hoc networks with traditional CSMA/CA protocol is that the neighboring nodes have to defer their transmission until an ongoing transmission between a transmitter and a receiver is finished. Otherwise, collisions occur which degrades the overall performance of the network. In other words, all the nodes inside the union of the spherical transmission region of the transmitter and the receiver have to be silent. When deploying narrow beam directional antennas, multiple concurrent communications can occur without disturbing the ongoing transmissions of each other. Yet, there is a bound on the maximum number of independent active node pairs depending on the aggregated interference caused by the neighboring transmissions. If the signal-to-interference ratio (SIR) is high enough, then the receiver can capture the signal but there is a limit on it. The limit can be defined as the sum of all interference from all communication pairs which is bound to garble each others communication.

For the capacity analysis of FANETs with directional antenna support, we follow the interference model and notation derived from [3,17,18]. The free-space propagation model can be defined as:

$$P_r = P_t \frac{c G_T G_R}{d^{\alpha} L}, \quad c = (\lambda/4\pi)^{\alpha} \tag{2}$$

where P_t and P_r are the transmit and receive power values in Watt respectively, λ is the wavelength in meters, α is the path loss exponent, d is the distance between transmitter and receiver in meters, G_t and G_r are the transmitter and receiver antenna gains respectively and L is the loss factor ($L = 1$). In this analysis, the transmit power is assumed to be constant and equals to 1 W and α is chosen to be 2.01 which reflects a near-optimal atmospheric condition. Also G_t and G_r are assumed to be equal to 1 for the sake of calculation ease. The total interference caused by all of the nodes in the FANET, I_{tot}, which is seen by a receiver can be expressed as follows:

$$I_{tot} = \sum_{i=1}^{N} I_i \tag{3}$$

where N is the total number of nodes in the FANET and I_i is the amount of interference for the node i. The signal to interference ratio (SIR) caused by the total interference in the FANET can be expressed as follows:

$$\mathrm{SIR} = \frac{P_t c G_m G_m}{I_{tot} d^{\alpha}} \tag{4}$$

In order to successfully receive a signal, the SIR must be greater than or equal to a given threshold value, $\mathrm{SIR_{th}}$. Hence, the maximum number of active nodes, N_{act}, that can reside without disturbing the ongoing transmission in the field can be expressed in as follows:

$$N_{act} = \mathrm{SIR}/\mathrm{SIR_{th}} \tag{5}$$

In order to evaluate the maximum achievable active node number in a FANET scenario we have analyzed main beam angles of 30°, 60°, 90° and the omnidirectional case. We made 10,000 simulation runs in a 1 km^3 zone for a 30 s of flight and the results are averaged. For the simulations, the transmit power P_t is chosen to be 1 W, the base frequency is set to 2.4 GHz, path loss exponent, α, is equal to 2 and $\mathrm{SIR}_t h$ is 15 dB. The result of the capacity analysis according to a receiver node which is situated in the very middle of the field is shown in Fig. 3. As shown in the figure, the main beam angle value highly affects the maximum number of active UAVs in the FANET and with narrower angles more simultaneous communications can occur. On the other hand, we observe that when utilizing omnidirectional antennas, the achievable active nodes number stays constant and very limited. As an example, throughout the simulations, the number of maximum achievable active nodes for the omni-directional case stays around 10. As a result, we can infer from the analysis that the channel utilization of LODMAC outperforms single transceiver cases such as the traditional IEEE 802.11 DCF (Distributed Coordination Function) MAC protocol (DCF from hereafter).

In order to justify the performance of LODMAC over DCF, we have conducted a deterministic packet delay analysis model. In this model, we assume an ideal non-erroneous channel under ideal network conditions. In DCF, the average duration of a successful transmission, Ts-DCF can be stated as follows:

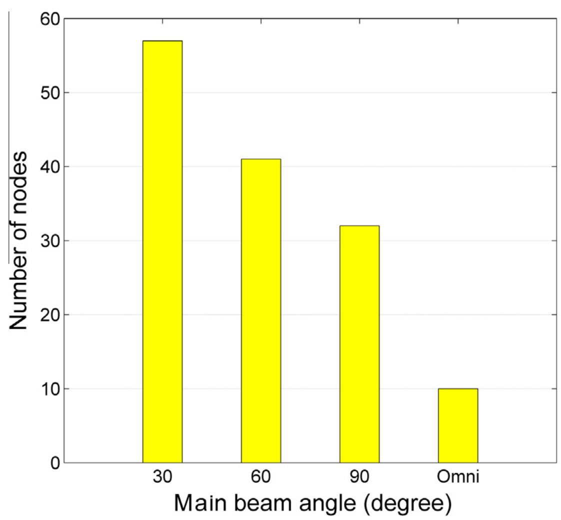

Fig. 3. Number of maximum achievable active nodes for main beam angles of 30°, 60°, 90° and for the omnidirectional case.

$$\mathrm{Ts_{DCF}} = \mathrm{DIFS} + T_{\mathrm{RTS}} + \mathrm{SIFS} + T_{\mathrm{CTS}} + \mathrm{SIFS} + \mathrm{Th_{DCF}} + L/C + \mathrm{SIFS} + T_{\mathrm{ACK}} \quad (6)$$

where DIFS is the DCF interframe space duration, SIFS is the short interframe space duration, T_{RTS}, T_{CTS}, T_{ACK} are transmission durations of RTS, CTS and ACK packets respectively, $\mathrm{Th_{DCF}}$ is the interval required to transmit the packet payload header, C is the data rate and L is the packet length. On the other hand the average duration of a successful transmission for LODMAC can be stated as follows:

$$\mathrm{Ts_{LODMAC}} = \mathrm{Th_{LODMAC}} + L/C + \mathrm{SIFS} + T_{\mathrm{ACK}} \quad (7)$$

$\mathrm{Th_{LODMAC}}$ is the interval required to transmit the header of a LODMAC packet which can be calculated as,

$$\mathrm{Th_{LODMAC}} = \mathrm{LODMAC}_h/C + \mathrm{LODMAC_{PHY}}/C_{\mathrm{control}} \quad (8)$$

where LODMAC_h is the header payload of the MAC layer packet which is 496 bits, $\mathrm{LODMAC_{PHY}}$ is the header payload of the physical layer which is chosen to be 96 bits. C is the data rate and C_{control} is the control channel packet transfer.

For the physical layer we assume that a preamble and PLCP (PHY layer header) exist in both control and data frames for DCF and LODMAC protocols. In order to assign 11 Mbps data rates, the short PLCP version has been chosen which equals to 96 bits. The remaining values of utilization parameters are listed in Table 1.

The channel utilization of DCF and LODMAC protocol is illustrated in Fig. 4. 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. As a result, the proposed LODMAC protocol outperforms the traditional methods when a pair of transceivers is utilized with directional antennas which have narrower main beam angles.

3.3. Location estimation

Unlike other studies, in LODMAC the exact locations of the neighboring nodes are determined in the MAC layer during t_l. In the location estimation slot, each node in the FANET directionally broadcasts its own location information (GPS coordinates) to the neighboring nodes over T1. Initially, all of the T1 transceivers in the FANET are in

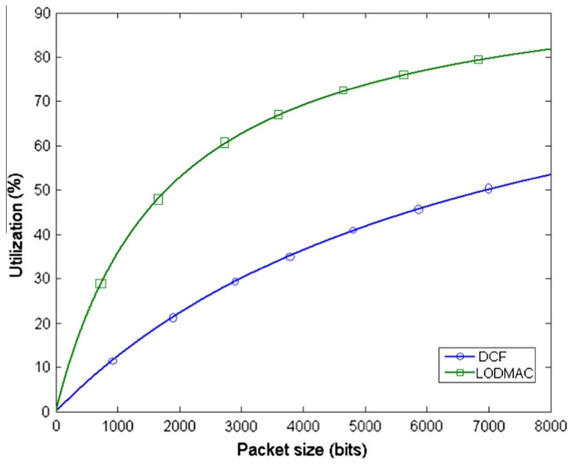

Fig. 4. With two transceivers on nodes, the wireless channel is utilized more effectively.

directional listening (receiver) mode. As soon as a node becomes to be a sender, it directionally broadcasts its location vector, LV, over the entire antenna beams sequentially which is illustrated in Fig. 5. For this study we assume that there is not a contention to be a location sender. In a round-robin fashion, UAV nodes in the network take turns and the UAVs are provided with their exact time slot values to be a sender in advance.

The structure of a LV, packet is illustrated in Fig. 6, where, ID_ is the node identification number; GPS_ is nodes current GPS location (latitude, longitude, altitude). Data_Flag is set to the current data transmission or reception status of T2 (00-idle, 01-receive, 10-transmit, 11-not used), Beam_ is the current antenna orientation of T2 and D_ID_ is the ID of the node which the node is currently communicating. Lastly, the Duration_ reflects the estimated duration of the ongoing data transmission of a node. Consequently, each LV packet puts an additional 18 bytes of overhead for the MAC layer.

In LODMAC, as soon as a UAV node becomes to be a sender in the location estimation period, it directionally broadcasts its location vector over the first transceiver, T1. Instead of flooding the LV packet into the network, we propose a one-hop transmission scheme. This transmission

Table 1
Parameters used for utilization analysis.

Description	Value
Packet payload length	8000 bits
DCF MAC header length	272 bits
LODMAC header length	496 bits
Short PHY header	96 bits
RTS packet length	160 bits
CTS packet length	112 bits
Busy-to-send packet	224 bits
ACK packet length	112 bits
DCF interframe spacing	50 s
Short interframe spacing	10 s
Data transfer rate	11 Mbps
Control packet transfer rate	2 Mbps

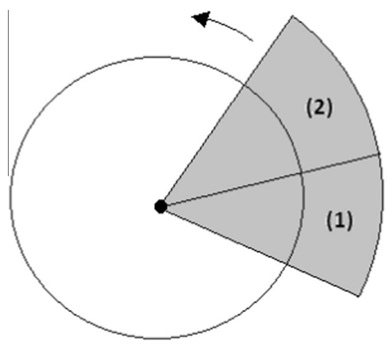

Fig. 5. Directional broadcasting.

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1 byte	14 bytes	2 bits	6 bits	1 byte	1 byte
ID_	GPS_	Data_Flag	Beam_	D_ID_	Duration_

Fig. 6. The frame structure of the location vector (LV).

scheme is conveyed over the directional antenna beams sequentially. For example, if the main antenna beam angle is assumed to be 60°, then there will be 6 beams for the antenna. Starting from *beam1*, the LV packet is published clockwise as illustrated in Fig. 5. The LV packet is sent just only to the nodes which are in the directional antenna transmission range. At that time being, the neighbors are in directional listening mode and defer their transmission (of any control or LV packets) in order to avoid collision. The nodes which successfully get a LV packet update their DND and do not relay the LV packet any further. Hence, the location information dissemination is restricted to one-hop neighbors. The main reason for restraining the location information dissemination procedure within one-hop neighbors is to eliminate the network overhead.

During t_l, as long as a node gets a location vector from any of its neighbors, it immediately updates its DND. The DND corresponds to the fields defined for a LV packet. With LV, some valuable information is also shared among the nodes in the FANET. One of this information is the current data antenna orientation and the ID of the communicating node (if there is one). This information plays a major role in eliminating the head of line blocking problem [2]. Because all of the interfaces are employed with independent queues, any packet which is destined for a blocking receiver can be determined on-the-fly and blocking can be solved immediately. Consequently, at the end of the location estimation time slot, we expect that the nodes in the FANET are provided with the exact location information of their neighbors.

3.4. Communication control

In IEEE 802.11 DCF protocol, RTS-CTS packet exchange sequence is used as a standard in order to ensure a reliable communication. In LODMAC, this exchange is conducted over T1 during the t_c time slot. In order to mitigate the well known deafness problem, we also define the BTS control packet. Deafness occurs when two nodes, say A and B, directionally exchange RTS-CTS packets and a different neighboring node, C, does not hear about this packet exchange [14]. This phenomenon is illustrated in Fig. 7. Later, when data transfer takes place between A and B, the node C may attempt to initiate communication with A or B. However, A or B will not hear about C's attempts thus, C will not get a response for its RTS packets and will back off. The problem may repeat itself that C will eventually think that a link failure is occurred.

In LODMAC, a BTS packet is used to reply to a sender that the node is currently conducting data a transmission with another node and it is not convenient to communicate for a defined amount of time. As long as a sender gets a BTS packet, it waits until the target gets convenient to make a data exchange. The duration time to wait for the sender is also provided in BTS hence, the need for backoff is also eliminated. The T1 transceiver is dedicated to listen and reply to RTS packets with a BTS packet even the T2 transceiver is currently on data transmission. By this scheme the well-known deafness problem is successfully addressed with the LODMAC protocol.

The communication control sequence of LODMAC is illustrated with an example in Fig. 7.

As shown in the figure, node A wants to communicate with B and it first checks the DND. If node B is seen as *idle* (have no communication on its T2 transceiver), node A sends a directional RTS packet to node B. On receiving an RTS packet, B waits until SIFS (short interframe space) amount of time and replies with a directional CTS packet to A. Node A gets the CTS packet and begins data transmission via T2 after a SIFS amount time. By the time, another node, C, wants to communicate with A. C first checks its DND and faultily sees that the node A is idle and sends a directional RTS packet to A. After then, A replies back with a directional BTS packet. In the BTS packet, the amount of time that will take A to finish its current communication is appended hence; C defers its transmission until A gets convenient. When the waiting period ends, C sends an RTS packet to A. This time A replies back with a CTS packet and C begins transmission via its T2 transceiver.

In an extreme case, a busy node, say A, has just sent a BTS message to node B and hence, oriented its T1 antenna towards B. By the time, another node, say C, sends a request to A. In this case A must be able to answer to C too, otherwise, A will still be deaf to Cs packet. In order to avoid deafness for the aforementioned cases, the *Duration_* field of the LV packet is utilized which reflects the estimated duration of the ongoing data transmission of a node. Thus, any neighboring node will defer its transmission on the specified beams provided in LV. In addition, we assume that the T1 transceiver is equipped with a smart antenna which is able to capture the angle of arrival (AoA) of a signal even it has been beamformed towards another direction. These kinds of antennas have been successfully used with mechanical sweeping for decades. Today, mechanical sweeping is replaced with smart beam antennas and are now quite common in wireless communication which are implemented with digital signal processing (DSP) techniques [4,19]. Nonetheless, in LODMAC, a BTS packet forwarding queue is used which holds the IDs of neighbors to be replied with a BTS packet. As for the above scenario, in As BTS packet forwarding queue, node B and C are in line and within a sweeping time interval (which is assumed to be zero in our simulations) BTS packets are sent sequentially to node B and node C.

3.5. Data transmission

Data transmissions in LODMAC take place over the T2 transceiver. In a particular time, if a node has a data to send to a neighboring receiver node, it first points its antenna towards the receiver. The location information of the receiver is taken from the DND. Similarly, the receiver will point its antenna to the sender after the RTS/CTS sequence is finished. The data packets are then transferred directionally from the sender to the receiver. This orientation process takes place in the communication control slot. We assume

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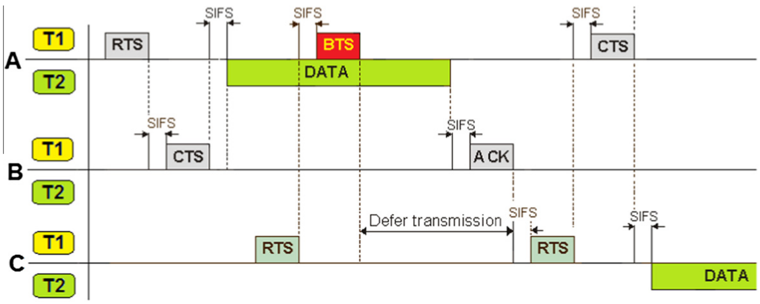

Fig. 7. Communication control sequence with BTS packets.

that the mutual antenna synchronization process is realized in other layers of the network.

4. Simulation results

For simulations, we have implemented the LODMAC protocol in MATLAB and in ns2.33 environments with directional antenna and multi-interface supports. For the simulations, we have used data rates of 100 Kbps to 2000 Kbps. The transmission range of the directional antennas is set to 1 km and the main beam angle is set to $\pi/3$ radians. The overall network data rate is set to 11 Mbps on the base frequency of 2.4 GHz. The nodes move with velocities of 10 m/s towards random directions. The altitude of a UAV depends on the terrain elevation on which the UAV flies over. The flight zone is a 1 km^3 cube. The number of nodes is set to 3–15. In order to guarantee a challenging media access environment, we place all the nodes within each others' communication range. If the number of nodes in the network is n, there are $(n-1)/2$ transmitters and receivers in the network. The remaining node is also a transmitter node which sends packets to a random node in the network which ensures the occurrence of deafness. For example suppose that there are 3 UAV nodes in the network (nodes A, B and C). Node A and B are having an ongoing transmission. By the time, node C sends connection requests to node A but while node A is busy it replies back with BTS packets. In traditional directional MAC protocols, these types of scenarios always result in deafness. For the omnidirectional case this type of scenarios always results in packet collision in the MAC layer.

Throughout the simulations, we ensure that all of the nodes stay in range of each other in order to simulate a challenging channel access environment because we aim to eliminate the probability of packet drops caused by the over-long distance between the transmitters and receivers. In other words, we analyze the effect of the proposed protocol for the common communication channel access issues between the UAV nodes. Thus, the average network delay rates mostly stem from the packet drops and retransmission timeouts when a receiver node remains out of the transmitters antenna beam cone. Also we aim to analyze the performance of the algorithm in concurrent transmission scenarios (by replying back with a BTS packet). In our case, a receiver can get the message if it stays in range and in beam of the transmitter. Hence, in the MAC layer, the transmitter orientates its antenna towards the receiver in advance of transmission.

We have employed constant bit rate (CBR) traffic with packet size of 4096 bytes. The CBR interval is set to 50 ms. To the best of our knowledge, LODMAC is the first protocol that the location estimation is provided within the MAC layer with a dedicated transceiver. Hence, in order to make a fair comparison, we have tailored and re-coded the DMAC protocol with multi interface support [16]. In DMAC, RTS/CTS/DATA/ACK packets are all transmitted directionally. An idle node listens to the channel omnidirectionally but when it receives a signal, its antenna system is capable of determining the direction of arrival of the incoming signal. The physical carrier sensing and the backoff phase are performed while the antenna is in a directional mode. However, in DMAC it is assumed that an upper layer is aware of the location information of the nodes and is capable of supplying this information among neighbors. Yet, in order to make a fair comparison with LODMAC, we have re-coded the DMAC protocol to provide nodes with the location information. The nomenclature of the simulation results are summarized in Table 2.

For the simulations, we have analyzed and compared the total network goodput (which is the successful throughput of the network without retransmissions of the packets), average network delays, and the fairness of the network. The fairness of the network is determined with the Jains fairness index as follows [15]:

$$f = \frac{\left(\sum_{i=1}^{n} t_i\right)^2}{n\sum_{i=1}^{n} (t_i)^2} \tag{9}$$

where f is the fairness index value, n is the number of nodes, t_i is the throughput value of node i. The fairness

Table 2
Nomenclature for simulation parameters.

Description	Value
Data rate	2000 Kbps
Packet type	CBR
Packet payload	4096 bits
Range of antennas	1 km
Main beam angle	60°
Base frequency	2.4 GHz
Velocity of nodes	10 m/s
Number of nodes	3...15

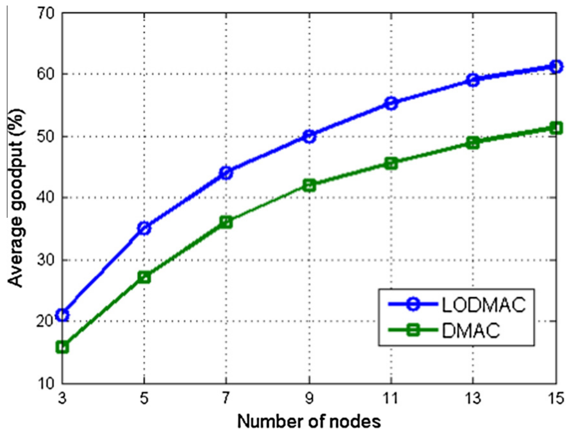

Fig. 8. Average goodput of LODMAC and DSMAC protocols.

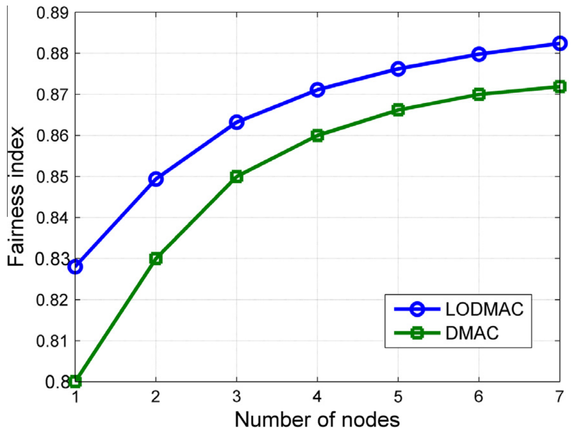

Fig. 10. Fairness indexes of LODMAC and DSMAC protocols.

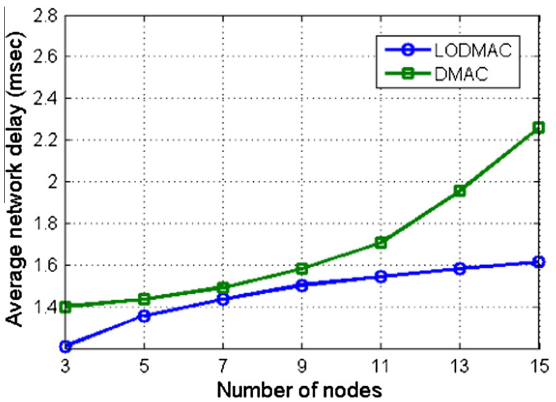

Fig. 9. Average network delay of LODMAC and DSMAC protocols.

index will be between 0 and 1. If a protocol gives the same throughput to every user, i.e., ideal fairness, than the fairness index will be 1. On the other hand, if one user gets the entire throughput, the fairness index will be $1/n$. Hence we expect the fairness index values to be higher for the proposed LODMAC protocol.

The result of average goodput is shown in Fig. 8. As shown in the figure, LODMAC is 15% more effective than the DMAC protocol. Also in heavy traffic load, LODMAC outperforms the DMAC protocol over goodput results.

The result of average network delay is shown in Fig. 9. As it can be followed from the figure, LODMAC is more effective in terms of delays. This is mostly because the backoff duration in LODMAC protocol is minimized when a busy channel is detected. As stated earlier, in LODMAC a busy receiver replies back to a sender with a BTS packet. The sender defers its transmission until the ongoing transmission ends. There is no need to implement a backoff duration because the information of the waiting time is found within the BTS packet. The results of fairness index are shown Fig. 10. The figure implies that the LODMAC protocol is fairer than DMAC which means that the total throughput is shared with balance among the nodes in the network.

5. Conclusion

A FANET is a novel and upcoming mobile wireless ad hoc network type which bears many open research issues. In FANETs, the communicating nodes in the network are UAVs and in order to overcome many of the constraints imposed by the utilization of traditional omnidirectional antennas on UAV nodes, directional antennas can be used as an alternative. In this study, we propose a novel directional MAC protocol, LODMAC, which utilize a pair of transceivers and directional antennas. Along with successfully addressing the well-known location estimation and deafness problems of directional MAC protocols, LODMAC increases the spatial reuse and overall network capacity of FANETs in 3D space. Simulation results show that LODMAC protocol outperforms IEEE 802.11 DCF and DMAC protocols and it is a good alternative for directional MAC protocols specifically for FANET usage.

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Samil Temel is a Ph.D. researcher/student in computer engineering at Turkish Air Force Aeronautics and Space Technologies Institute (ASTIN). He is also a computer programming lecturer at Turksich NCO College. He received his M.S. degree at TUAFA in 2008 and he holds a B.S. degree in Computer Engineering from Yildiz Technical University, Istanbul, Turkey. His research interests include directional MAC protocols and wireless sensor networks.

Ilker Bekmezci received B.Sc., M.Sc., and Ph.D. degrees in computer engineering from Bogazici University, Istanbul, Turkey, in 1994, 1998, 2008, respectively. He is currently an assistant professor with the Department of Computer Engineering, Turkish Air Force Academy, Istanbul, Turkey. His current research interests are in wireless communications and ad hoc networks.