Medium Access Control for Flying Ad Hoc Networks Using Directional Antennas: Challenges, Research Status, and Open Issues

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Abstract. As flying ad hoc networks (FANETs) are increasingly used in military and civilian scenarios, and the utilization of directional antennas can significantly increase the communication distance between UAVs and anti-interception capability of transmission, the research on media access control (MAC) protocols using directional antennas has become a new research hotspot. In this paper, we first summarize the design elements and requirements of directional MAC protocols for FANETs are summarized considering the characteristics of FANETs and the challenges brought by directional antennas. Based on the classification of channel access mechanisms, contention and scheduling based MAC protocols for FANETs with directional antennas are then reviewed. Finally, the characteristics and performance of various typical protocols are compared and analyzed. Problems that need to be further addressed are summarized, expecting to provide some illumination for those researchers engaged in this field.

Keywords: FANET · Directional antenna · MAC protocol

1 Introduction

In recent years, the advantages of relatively low cost, easy deployment and flexible networking have enabled unmanned aerial vehicles (UAVs) to be applied in both civilian and military tasks such as emergency rescue, intelligence gathering, target monitoring and tracking, etc. Ad hoc networks composed of UAVs are called flying ad hoc networks (FANETs). This concept was originally proposed by Temel in [7]. FANETs have also several other names in the literature, such as unmanned aeronautical ad hoc networks (UAANETs) [29], network of UAVs [8], and airborne networks [9]. For the sake of unity, this paper uses the term FANETs. FANETs use the architecture of mobile ad hoc networks (MANETs), which have the characteristics of no infrastructure, distributed control, dynamic networking flexibility, self-healing and strong invulnerability. The special ad hoc networks of UAVs can enhance the interoperability between UAVs and has become a research hotspot.

Currently, the research on FANETs mainly focuses on network management, mobility model [23] and control [10], and network protocols [21]. As part of the

J. Zheng et al. (Eds.): ADHOCNETS 2019, LNICST 306, pp. 122–132, 2019.
https://doi.org/10.1007/978-3-030-37262-0_10

network protocol stack, medium access control (MAC) protocols provide fair and fast access mechanisms for nodes to ensure time efficient, reliable and stable data transmission. The functionality of MAC protocols directly affects the channel utilization and the network throughput, playing a decisive role in the performance of FANETs. However, owing to high dynamics of UAVs, frequent three-dimensional topology changes, and unreliable wireless communication links, existing MAC protocols for MANETs cannot be fully applied to FANETs. Modification or developing new MAC protocols are necessary to meet the communication needs of FANETs.

Different from existing surveys in the literature [7, 20, 22, 24], which provide general networking frameworks for FANETs, this review aims at the research progress and prospects of MAC protocols using directional antennas in FANETs. The reasons why emphasize the implementation of directional antennas are as follows: available bandwidth below 3 GHz is narrow and frequency interference is severe, causing difficulty in enhancing channel capacity. Therefore, the high frequency becomes the choice when designing communication systems in the future. However, the attenuation of high frequency signal is more serious than that of lower frequency together with limited transmission distance of omnidirectional antennas, while directional antennas can effectively alleviate transmission loss of high frequency signals, expand the communication distance and reduce the number of hops. Directional transmission also reduces mutual interference of neighboring nodes, increasing the chance of spatial reuse and network capacity [5, 18]. Additionally, directional communication can enhance the concealment of transmission and enhance anti-interference ability of networks.

This paper is organized as follows. Section 2 describes the characteristics of FANETs, and discusses the challenges and key points for designing MAC protocols with directional antennas. Section 3 reviews MAC protocols for FANETs using directional antennas. Section 4 summarizes and compares the characteristics and performance of several typical MAC protocols. Section 5 concludes this paper with open issues in future research.

2 Challenges and Design Requirements

2.1 Characteristics of FANETs

FANETs not only have the problems of the limited bandwidth and frequent topology changes faced by MANETs, but also face other challenges, such as more dramatic topology changes in 3D space and link failures caused by high node mobility, and poor network environment as a result of communication in open air. FANETs have the main characteristics as follows:

1. **Low node density**
   Currently, the mainly used UHF frequency band has enabled single-hop communication distance up to several hundred kilometers, resulting in high transmission delay. In a real network scenario, the number of nodes in a network is small and thus the network density is relatively low, which may cause poor network connectivity.

2. **Wide distribution in 3D space**
   When UAVs are on missions, they tend to be far away from neighboring UAVs. Therefore, the coverage of FANETs in 3D space can reach tens or even hundreds of cubic kilometers, which poses a great challenge to the neighbor discovery in the initialization of the network.
3. **High node mobility**
   The speed of UAVs is usually between 30–460 km/h [26]. High-speed mobile nodes would cause dramatic topology changes, making mobility models especially important in protocol design.
4. **Unstable communication links**
   Since the transmission space of FANETs is open air with bad channel conditions such as high fading and Doppler effects, resulting in unreliable communication links between UAVs. High bit error rate, transmission delay and communication interruption may also occur especially when the distance between UAVs is large.
5. **Network heterogeneity**
   In addition to the communication between UAVs, communication with fixed nodes such as ground stations may also be needed. Therefore, both UAV-to-UAV and UAV-to-infrastructure connections may exist concurrently, making the FANET as a heterogeneous network.

2.2 Problems Brought by Directional Antennas

Directional antennas may bring several particular problems when they are used in a FANET.

1. **Hidden terminal problem**
   A hidden terminal is a phenomenon in which a node does not know that its target node is communicating, and a collision occurs at its target node after the node sends out the RTS packet. In this case, this node is called a hidden terminal of its target node. An ad hoc network using directional antennas may have 2 kinds of hidden terminal problems: unheard RTS/CTS and asymmetry in gain when both directional and omnidirectional transmission are adopted in the protocol [6].
2. **Deafness problem**
   When a node transmits the RTS packet to its target node which is communicating with other nodes directionally, the targeted node cannot hear the RTS packet and thus the transmitting node cannot receive the CTS reply. In this case, the targeted node is called a deaf node. And the transmitting node will retry the RTS transmission repeatedly until it receives the CTS reply. In the worst case, the transmitting node may drop the packet when the number of retries exceeds a certain value. Through the above illustration, it can be concluded that the transmission of redundant RTS packets makes the transmitting node suffer from low transmission efficiency and high delay.
3. **Header-of-Block (HOL) problem**
   The HOL problem occurs as a result of using the first-in-first-out (FIFO) queuing policy in the MAC layer. The HOL problem is a phenomenon that a node detects that the channel in a certain direction is idle and thus it can send packets to the

targeted node located in this direction, but if the packet at the top of the queue is destined to a busy direction, the subsequent packet will be blocked due to the FIFO policy. As a result, nodes suffering from the HOL problem fail to fully utilize the spatial multiplexing function of directional antennas, and thus the network throughput is reduced.

2.3 MAC Design Elements

Considering the characteristics of FANETs, the design requirements for FANETs using directional antennas are described as follows.

1. **Flexible networking ability**
   In FANETs, the network nodes are organized in a peer to peer manner. Meanwhile, a node may join or leave the network dynamically. A MAC protocol needs to realize rapid establishment of communication links of incoming nodes and optimize channel access mechanism to achieve fair and efficient resource allocation.
2. **Stable and reliable QoS guarantee**
   FANETs are expected to provide a variety of network services. Different applications or different types of user traffic have diverse quality of service (QoS) requirements in terms of transmission delay, data loss, etc. For instance, low transmission delay and non-collision data delivery is of vital importance for command and control information, while voice and video services require high throughput. In addition, the high propagation delay and potential link failure need the MAC layer to achieve stable services.
3. **Cross-layer interaction capability**
   Geographic information is of vital importance in a FANET because a node in the network may move beyond the beam coverage. A MAC protocol needs to obtain the latest neighbor information from the upper layers frequently to ensure reliable transmission.

3 Classification and Research Status

Currently, there is no uniform classification of MAC protocols using directional antennas for FANETs. There are many classification criteria, such as contention and scheduling mechanism; distributed or centralized mechanism; single channel or multichannel, and whether or not a protocol is based on a busy tone mechanism, etc. A MAC protocol may belong to different classifications. Next we present a review of MAC protocols proposed for FANETs using directional antennas according to contention and scheduling mechanism.

3.1 MAC Protocols Based on a Contention Mechanism

In the contention mechanism, when a node has a packet to send, it will first detect whether the channel is idle. If the channel is idle, it will immediately send the packet. Otherwise, it will wait for a period of time, referred to as backoff time. After the waiting process is completed and the channel is detected idle, the packet will be sent out, then the sending node will wait for an acknowledgement packet from its target node. If the sending node successfully receives the acknowledgement packet, the communication is completed. Otherwise, the sending node will retry the transmitting process, that is, it will repeat the aforementioned process. If the number of retries exceeds a certain value, the node will drop the packet. This mechanism does not need to allocate time slots for each node in advance. It can effectively deal with a dynamically changing number of nodes and burst services. The IEEE 802.11 DCF is the most representative contention mechanism widely used in wireless networks. Many benchmark MAC protocols with directional antennas are based on this mechanism [5, 17].

1. Adaptive MAC Protocol for Unmanned Aerial Vehicle

In [2, 4], Alsbatat et al. proposed a MAC protocol named Adaptive Medium Access Control Protocol for Unmanned Aerial Vehicle (AMAC_UAV). The antenna model used in the AMAC_UAV protocol is an antenna array consisting of two omnidirectional antennas and two adaptive antennas. One omnidirectional antenna and directional antenna pair are installed on the UAV, responsible for communication in the airspace above the UAV, and the other pair is responsible for transmission in the airspace under the UAV. The protocol uses an omnidirectional antenna to broadcast periodic heartbeat information to frequently update node's location information. In order to avoid the hidden terminal problems, the protocol transmits an RTS/CTS/DATA/ACK packet in an omnidirectional mode by default, and switches to a directional transmission mode when the distance between two nodes exceeds the omnidirectional transmission range. In the directional antenna mode, if the packet error rate and the number of retransmissions are higher than the predefined threshold, the antenna mode is switched to the omnidirectional transmission mode. The OPNET simulation results show that average end-to-end delay is nearly quartered and the throughput is increased more than fivefold with the protocol when compared to IEEE 802.11.

However, some problems still exist in the protocol. Firstly, after switching to the omnidirectional transmission mode, the communication requirement of the nodes whose distance is between OO (omnidirectional transmission and omnidirectional reception) and DO (directional transmission and omnidirectional reception) cannot be satisfied. Secondly, the collision problem in the heartbeat information broadcasting process is not considered. Thirdly, this protocol cannot handle the hidden terminal problems caused by gain asymmetry. Based on the above MAC protocol, the authors further proposed a cross-layer structure of FANETs called IMA_UAV in [3]. This protocol merges the lower three layers of the OSI model into one layer to provide a OLSR protocol modified under directional transmission conditions, of which the routing related information can be provided directly by the lower layers.

2. Location Oriented Directional MAC Protocol

In [27], Temel et el. proposed a location-oriented MAC protocol (LODMAC). The core of this protocol is to use two transceivers with different working frequencies to separate the control channel from the data transmission channel. The authors point out that there is a problem in existing MAC protocols where location information is somehow obtained from the upper layer. To solve this ambiguity, the proposed MAC protocol uses transceiver T1 to detect the location of neighbor nodes. The duration of each probing phase lasts for one second. GPS update, called location estimation, is performed at the beginning of each probing phase, and the remaining time is used for communication control. Additive to RTS/CTS interactions in the 802.11 DCF mechanism, in order to solve the well-known deafness problem, the transceiver T2 of a busy node, which works at a different frequency from T1, is used to send the busy-to-send (BTS) packet to inform the current transmitting node of the busy time of the busy? node. Moreover, the protocol also cooperates well with near space high altitude platforms [25].

However, this protocol still has several problems. Firstly, the hidden terminal problem is not alleviated. Secondly, in the process of location estimation, which is actually the process of neighbor discovery, it is stated that the nodes in the network take turns to become the only sender to inform the neighbors of its own location without collision. But at the beginning of location estimation period, since the node does not know the IDs of the remaining nodes, this process is difficult to achieve without collision. Thirdly, in the directional broadcasting process, the article does not give the way of scheduling antenna beam in a 3D scenario.

3.2 MAC Protocols Based on a Scheduling Mechanism

In MAC protocols based on the scheduling mechanism for FANETs, Time Division Multiple Access (TDMA) mechanism is most widely used. The basic idea of TDMA is to divide the time into frames, and each frame is divided into multiples time slots. A time slot is assigned to transmission links, so that the packets in the transmission queue are sent in the corresponding time slots. When an appropriate slot allocation algorithm is adopted, packets can be transmitted without any conflicts. Compared with MAC protocols based on the contention mechanism, the TDMA mechanism reduces flexibility of networking to a certain extent, but more reliable transmission of packets is guaranteed.

1. Distributed Spatial TDMA MAC Protocol

In [13], Huba et al. proposed a cross-layer protocol based on directional antennas, called D-STDMA. In network layer, the authors propose a meshed tree clustering algorithm [1] that creates multi-hop clusters of configurable cluster size. For cluster clients (CCs) and cluster heads (CHs), multiple proactive routes are established. Furthermore, the overlap among neighboring clusters, which can be used for reactive routing establishment, is supported. In MAC layer, a distributed TDMA scheduling algorithm is proposed, which allows nodes in the cluster to schedule their own transmission and reception time slots with their neighbors. Besides, the cluster formation process is utilized to determine when nodes join to establish a new link scheduling. However, D-STDMA lacks support for multi-priority services.

2. MAC Protocol for FANETs Using Directional Antennas

In [11], Guo proposed a MAC protocol for FANETs using directional antennas (DAMAC). In DAMAC protocol, one time slot consists of two sub time-slots. One of the sub-timeslots is fixed, which is used for the transmission of high-priority services, while the other is called additional sub-timeslot with variable frame length. The timeslot allocation algorithm is as follows: when the fixed sub-timeslot is insufficient to satisfy the transmission of high-priority services, the unsent high-priority services are transmitted in the additional sub-timeslot, which can dynamically change the frame length according to the queue buffer of high-priority services. If there are more caches, the frame length is doubled. Otherwise, the frame length is compressed to half of the original length. After the transmission of the high priority services is satisfied, the remaining additional sub-timeslots are used to transmit the low-priority services. The advantage of DAMAC protocol is that it is oriented to the QoS requirements of multi-priority services, and can adaptively adjust the slot allocation strategy according to the network traffic load. The disadvantage is that the transmission fairness of DAMAC protocol is poor. When the network traffic load is large, low-priority services will suffer from severe packet loss problem to guarantee the transmission of high-priority services.

Note that since there are only few studies on directional MAC protocols for FANETs and whether omnidirectional antennas or directional antennas are utilized, MAC protocols need to solve common problems such as multi-priority service sup-port and dynamic network topology, so MAC protocols with omnidirectional antennas for FANETs using TDMA mechanism will also be briefly described below.

1. A TDMA MAC Protocol with Piggybacking ACK
   In [14], Jang points out that existing protocols need two guard times in a time slot because an aircraft node will wait an ACK packet after it sends data in a time slot, thus two guard times in one time slot are needed. To overcome this problem, the author proposes a TDMA MAC Protocol using a novel piggyback mechanism, where data and ACK are not sent to the same destination different from traditional piggyback mechanism where node sends both of data and ACK together in one frame. The proposed MAC make the data sent to the next relaying aircraft, while the ACK is sent to the previous relaying aircraft. This proposed protocol provides better network utilization because only one guard time is required in a time slot compared with traditional MAC protocols.
2. Location-based TDMA MAC Protocol
   In [15], Jang proposed a Protocol Termed Location-Based TDMA (LTTM). The proposed LTTM protocol uses location information to solve the ACK guard interval problem. Moreover, it can effectively support various broadcast modes. With LTTM, a receiving node calculates the propagation delay of the transmitting node based on the location information. It can effectively reduce the guard interval of ACK to achieve collision-free transmission, thus achieving better delay performance.
3. Interference-based Distributed TDMA MAC Protocol
   In [16], Li et al. proposed an interference-based Distributed TDMA Algorithm (IDTA) aiming at the frequent changes of the network topology and link state in a FANET. The degree of a link interference and the structure of a time frame are defined. With the link interference, the time slot allocation for neighbor nodes and traffic priorities, a node selects the communication link. The simulation results show that IDTA can achieve better delay performance than STDMA when the network topology changes more dramatically. However, time slot allocation can be further optimized by using a dynamic allocation mechanism and a variable frame length for different traffic priorities.

3.3 MAC Protocols Based on a Hybrid Access Mechanism

The hybrid mechanism is a combination of the contention mechanism and the scheduling mechanism. In the hybrid mechanism, according to the network load, one mechanism is set as the main mechanism while the other mechanism serves as the supplementary mechanism, which is beneficial to the global optimization of the network. A typical idea is to use the contention mechanism when the network load is low to reduce the delay and improve the channel utilization. When the network load becomes high, the protocol switched to the TDMA mode to reduce the collision probability.

In [28], Li et al. proposes a Multi-beam Smart Antennas based MAC Protocol (MBSAs_MAC). The MBSAs_MAC protocol divides the MAC layer into two sub-layers. The upper sub-layer uses TDMA-like scheduling mechanism to alleviate the packet collision in multi-beam data transmissions. In the lower sub-layer, an enhanced PCF/DCF mechanism compatible with conventional IEEE 802.11 protocols is introduced. In addition, a Hierarchical Dirichlet Process (HDP) enhanced hidden Markov model (HMM) is used for mobility prediction in each beam of a node. However, in the enhanced PCF phase, this protocol uses a star node to transmit a QoS query message to its neighbor nodes, which is quite centralized and thus cannot support flexible networking well.

4 Analysis and Comparisons

Tables 1 and 2 give a comparison of the characteristics and performance of different types of MAC protocols for FANETs using directional antennas.

Table 1. Characteristic comparison.

Name	Type	Antenna model	Number of channels	Cross-layer design	Centralized control
AMAC_UAV	Contention-based	2 adaptive arrays and 2 omni-directional antennas	Single	Not considered	Not needed
IMAC_UAV	Contention-based	2 adaptive arrays and 2 omni-directional antennas	Single	Considered	Not needed
D-STDMA	TDMA-based	4-phased array antenna	Single	Considered	Not needed
LODMAC	Contention-based	Switched beam antenna	Multi	Not considered	Not needed
MBSAs_MAC	Hybrid	Multi-beam antenna	Single	Considered	Needed
DAMAC	TDMA-based	Switched beam antenna	Single	Not considered	Not needed

Table 2. Performance comparison.

Name	Delay	Throughput	Multi-priority	Networking flexibility	Disadvantages
AMAC_UAV	One quarter of IEEE 802.11	Fivefold than IEEE 802.11	Not supported	Relatively high	Lack of addressing hidden terminal problems caused by asymmetry in gain
IMAC_UAV	Slightly better than IEEE 802.11	Not mentioned	Not supported	Mediocre	Lack of addressing the deafness problems
D-STDMA	Relatively low	Not mentioned	Not supported	Poor	Lack of supporting multi-priority services
LODMAC	Low	Relatively high	Not supported	Relatively high	The hidden terminal problems are not considered and the contention in location estimation is ignored
MBSAs_MAC	Relatively high	High	Supported	Relatively poor	The protocol runs in a centralized manner
DAMAC	Mediocre	High	Supported	High	The performance degrades obviously under high load

Due to the real-time and randomness of contention approach, this kind of MAC protocols can dynamically and flexibly set up the network, while providing relatively low end-to-end delay. These features are consistent with features of FANETs, but due to random packet delivery, even with multiple mitigation methods, collisions cannot be completely avoided. Thus, this method is difficult to provide a stable and reliable QoS guarantee, and it is difficult to ensure system stability when the load is heavy.

The TDMA-based MAC protocols statically or dynamically allocate time slots to each user in a certain manner, which can ensure fair scheduling, an average delay with an upper bound, and a robust system once the network size is determined. However, the requirements for synchronization are extremely demanded. Furthermore, it is difficult to effectively cope with dynamic changes of the number of nodes and burst traffic. Dynamic TDMA protocols have improved in flexibility, but the mechanism of time division multiplexing is difficult to be applied to occasions with high delay requirements. Additionally, the implementation is of high complexity.

5 Open Issues and Conclusion

Comparing and analyzing different types of MAC protocols for FANETs with directional antennas can provide guidance for further studies. In the next step, the key technologies of directional MAC protocols for FANETs still need to be further addressed in terms of stability, flexibility and scalability:

The assumptions in current theoretical studies on traffic models, communication links, and mobility models are too ideal and simplified. For instance, most work uses a Poisson arrival to model traffic, which is not suitable for burst traffic. The disparity between a theoretical model and the actual situation limits the proposed MAC protocols from theory to practice.

In most cases, UAVs' trajectory is not random but predefined. Adding a node's speed information on the next time interval to the control information can largely alleviate the link failure of beamforming towards wrong direction caused by a node's mobility. In addition, location prediction has been merged into protocols in both MANETs and VANETs [12, 19]. FANETs can also utilize some effective techniques such as artificial intelligence to predict nodes' location and reduce poor connectivity.

The existing MAC protocols do not fully consider dynamic changes of node members and link failures, which limits the flexibility and reliability of the network.

Providing reliable information transmission is the major goal of the design of MAC protocols. In actual scenarios, however, it is also necessary to focus on the delay and successful transmission of multi-priority packets as well as the system throughput.

Acknowledgement. Special thanks for Professor Zheng for his helpful and detailed comments. The work is supported by the National Natural Science Foundation of China (No. 61671471).

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