

A Multi-Channel MAC Protocol with Retrodirective Array Antennas in Flying Ad Hoc Networks

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Abstract—In this paper, we propose a multi-channel medium access control (MMAC) protocol for the exploitation of retro-directive array antennas in Flying Ad Hoc Networks (named FA-MMAC). This FA-MMAC employs multiple channels and retro-directive array antennas to adjacent unmanned aerial vehicles (UAVs) to transmit simultaneously over the same channel without causing interference. The channel utilization characteristic of FA-MMAC increases the spatial reuse of channel and thus improve the system performance. The key idea is that UAVs first exchange control packets in control window to select data channels and to align beams before exchanging data packets in the data window. In this way, the hidden-terminal and deafness problems are reduced. UAVs can reserve channels and align beams through a circular directional transmission of control frames so that the protocol can take advantage of the benefits of retro-directive array antennas of spatial reuse and increased coverage without prior knowledge of the locations. We develop both antenna model and channel model for FA-MMAC protocol. Analysis and simulation results show that our proposed FA-MMAC can offer a significant performance gain for both static and mobile scenarios than the existing MMAC and 802.11-based protocols. Our findings reported in this paper provide some insights into the performance of multi-channel Flying Ad Hoc Networks which might help network researchers to contribute in the development of next generation UAVs.

Index Terms—Unmanned Aerial Vehicle (UAV), multiple channels, interference, retro-directive array antennas, FA-MMAC.

I. INTRODUCTION

DUE to the characteristics of low cost, versatility and agility, the cooperation in an Ad Hoc fashion between several UAVs to form a flying Ad Hoc Network (FANET) is becoming widely used in various military and civilian applications, for example as an air base station [1] [2] to improve the connectivity and to extend the coverage of a specific area. Challenges and solutions in FANETs have also become the focus of current research. Researchers in [3] conducted a comprehensive survey on FANETs focusing on architecture, the mobility models, and the routing techniques. Aiming at the problem of the unbalanced energy consumption in FANETs, OS Oubbati et al. [4] proposed a routing protocol that supports the use of the movement information and the residual energy level of each UAV to guarantee a high level

of communication stability while predicting a sudden link breakage prior to its occurrence. Peng Feng et al. [5] discussed two serious problems in FANETs: One is the problem of rapid topology change, and the other one is the connection issue which is neither durable nor reliable. Aiming at the problem of time-varying network topology and frequent link interruption caused by UAVs movement in FANETs, Jingjing Wang et al. [6] maintains stable network structure by designing effective gateway selection algorithm and management mechanism. The paper also points out that energy saving and privacy security are important challenges for FANETs research, and that directional transmission has advantages over omnidirectional transmission in terms of power limitations. In fact, directional transmission can also solve the privacy security problem in FANETs effectively.

FANETs are developing rapidly in recent years. The number of UAVs has been increasing and the network density is getting higher and higher. The US Department of Defense has released eight versions of UAV/Unmanned System Roadmap in just a few years, making UAV clusters an important development. An important development trend of UAV system in both commercial and military areas is to develop from independent work to collaborative work of UAV cluster. The cooperation of UAVs must solve communication and large-scale networking problems. In one hand, UAV's communication should adapt to the complex electromagnetic environment with conflicts, interference, and eavesdropping. On the other hand, the amount of data is so large that competition for wireless media is intense in FANETs. The use of multiple channels and advancement of channel reusability are important for improving throughput and spectrum resource utilization.

When configuring a FANET, one of the most important challenges is to design a good medium access control (MAC) protocol based on antenna and channel resources to achieve high-efficiency data transmission. UAVs are usually assumed to equip with omnidirectional antennas, therefore, most of the research in designing MAC protocols are based on omnidirectional antennas. However, omnidirectional antennas can easily be intercepted. In addition, as network load increases, the probability of simultaneously data transmission (by various nodes) increases, resulting in more interference, conflicts, and network performance deterioration.

Therefore, in this paper, we focus on retro-directive array antennas for data transmission in FANETs to reduce channel interference and to improve system utilization. Retro-directive array antennas are composed of many radiation elements. When receiving a non-directional signal, they can track the direction of the incoming signal automatically.

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The retro-directive array antenna has the following advantages [7] [8] [9]. (i) It adopts analog circuit to track and align incoming waves automatically without any prior knowledge of radiation source direction; (ii) The retro-directive array antennas produce a directional beam rather than an omni-directional beam. This communication paradigm helps to achieve better system performance as a result of power synthesis, and thus the transmission range can be increased; and (iii) The retro-directive array antenna is received by a cell and has the ability to trace multiple sources simultaneously. It will generate independent beam response to each source, so it can achieve omnidirectional tracking.

Combining the retro-directive array antenna with the multi-channel is suitable for parallel transmission of FANETs. The combined frequency domain and airspace bring great benefits to the mitigation of resource competition. Firstly, directional transmission allows a message to be only received by the node within the specified beam range, and nodes unrelated to the transmission are not subject to electromagnetic interference allowing more nodes to transmit simultaneously. Secondly, directional transmission can transmit farther than omnidirectional transmission at the same transmission power, and data packets can reach the destination from the source with fewer forwarding, which can reduce packet delay and the transmission energy consumption of UAVs. Moreover, FANETs is a three-dimensional network and therefore, it's three-dimensional directional transmission has more angle selections than two-dimensional directional transmission, which can greatly improve the parallel transmission capability of FANETs.

Nevertheless, directional transmissions still face very challenging problems in FANETs including hidden terminal, deafness, and the alignment of beams problems. In this paper, we propose a multichannel MAC protocol for FANETs (FA-MMAC) using retro-directive array antennas for resolving the issues of deploying retro-directive array antennas. This protocol discusses the access mechanism of nodes within the range of a single hop in half-duplex communication, and we deal with access control of each node in the directional network environment based on retro-directive array antenna. It includes an effective mechanism that ensures the alignment of beams between communication pairs and reduces the hidden terminal and deafness problems more effectively. The main contributions of this paper are as follows.

- We allocate resources from the spatial and frequency domain by dividing subchannels and multiplexing multiple beams, and propose FA-MMAC, a multi-channel MAC protocol for the full exploitation of retro-directive array antennas in FANETs.
- We modified the traditional available channel list (ACL), solving the interference problems under directional transmission, hidden terminal and deafness problems. We redesign the system to improve the parallel transmission capability between UAVs.
- We conduct extensive experiments to validate the proposed protocol. Results show that the protocol can improve the network performance.

The rest of this paper is organized as follows. In Section II, we discuss preliminaries and related works. In Section III, we present the antenna model and channel model, and describe the proposed FA-MMAC protocol. The performance evaluation is conducted in Section IV. Finally, we conclude our paper in Section V.

II. PRELIMINARIES AND BACKGROUNDS

In this section, we first introduce the communication interference problem of omnidirectional antennas in FANETs. In order to solve this problem, we propose a technique of combining retro-directive array antennas and multiple channels.

A. Communication interference in FANETs

As shown in Fig. 1, Node A and B are transmitting, with a communication radius R and interference radius r . Nodes F and G are also transmitting to other nodes using the same spectrum resource (i.e., channel). Although the destination Node is not B, the wireless signals are superimposed on Node B to create interference.

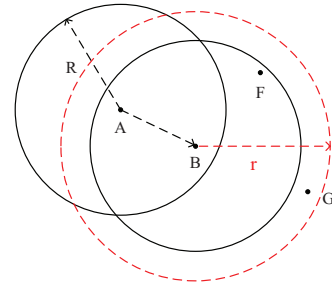


Fig. 1. Illustrating the Communication Interference Problem.

To mitigate interference, adjacent nodes can avoid to use the same channel by adopting multi-channel MAC protocols [10]. As shown in Fig. 2, Node A and B are transmitting on Channel 1, while Node F and G are transmitting on Channel 2 which does not overlap with Channel 1. The use of different channels in transmitting in the interference range can avoid interference to a large extent. Multiple nodes communicate simultaneously and thus improves network throughput performance.

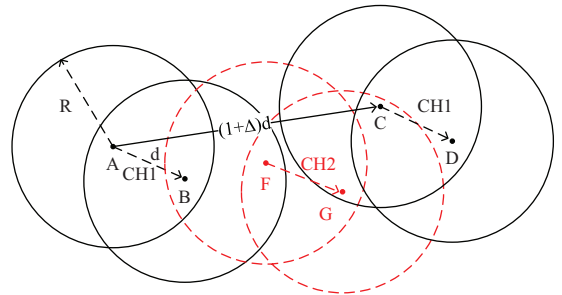


Fig. 2. Illustrating Multi-channel Interference Problems.

For a limited number of channels in the network, the channel can be reused. For instance, Nodes A and B are communicating in Channel 1 (Fig. 2). If Nodes C and D

are also transmitting over Channel 1, they need to keep a certain distance from Nodes A and B to avoid interference. The symbol ‘ Δ ’ is a protection parameter used to reduce interference and to minimize the number of neighboring nodes sharing a common channel.

The network capacity is greatly affected by the spatial reuse level of the network. In this paper, we propose a Multi-channel MAC protocol with retro-directive array antennas for FANETs (FA-MMAC) that avoid interference through the directional transmission of data. However, directional transmission can also cause serious hidden terminals and deafness problems as discussed next.

B. Hidden terminal and Deafness problems

When using retro-directive array antennas, the hidden terminal problem would occur when a node sends data to a receiver which is stuck in an ongoing transmission. In Fig. 3, Nodes A and D perform the directional request-to-send/clear-to-send (RTS/CTS) handshake. However, Node B is outside the directional beam coverage of A, so it does not know the handshake process of Nodes A and D. After finishing the transmission with Node C, Node B has data packets for Node D. Consequently, the control frames of Node B collide with the data packet of Node A at Node D.

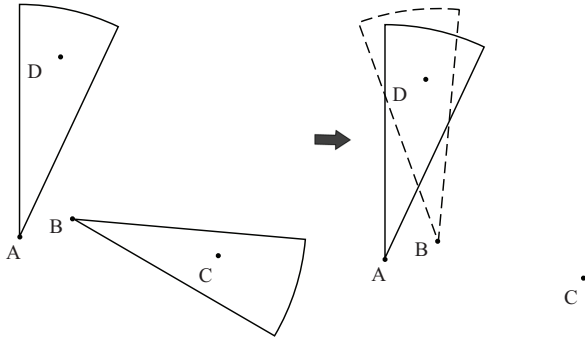


Fig. 3. Illustrating Hidden Terminal Problems.

The MAC protocol with retro-directive array antennas allows the sending node to transmit control frames for channel reservation while its adjacent node is communicating. Deafness occurs when the sending node attempts to establish communication with a non-idle node but is not answered.

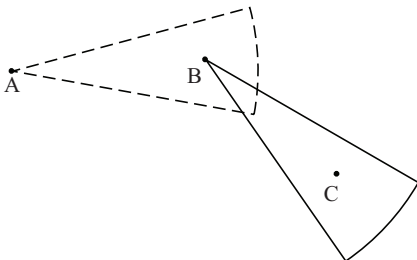


Fig. 4. Illustrating the Deafness Problems.

In Fig. 4, let us suppose Node B is sending data to Node C with a directional beam. Node A finds that the channel is idle, so it sends RTS signaling to Node B to request a connection establishment. However, Node A cannot get a CTS response because Node B is communicating, then Node A will try to retransmit the RTS signal. If the backoff time of Node A is too long, Node A may still be in the backoff state when Node B ends the transmission. If Node B establishes connection with other nodes before Node A completes the backoff, Node A will not receive any response from Node B after the backoff. In extreme cases, Node A will be stuck with this backoff wait state.

C. Related work

The research in the field of FANETs are inspiring and growing in recent years. H. Zhao [11] considered the deployment of UAV networks to maximize network coverage. Some solutions are proposed to maintain the connectivity of UAVs while forming specific topologies [12] or in the process of flock motion [13]. And many other works consider the application of UAV networks [14] [15] [16]. But none of the researchers have considered the use of MAC protocol in the network.

Regarding the MAC protocol that could be used in UAV FANETs, Researchers in [17] and [18] studied the impact of carrier thresholds on network capacity. These works focus on maximizing network space reuse by adjusting carrier monitoring threshold. Researchers in [19] and [20] controlled the transmission power to balance the interference caused by the local hidden terminal. Our own work also address some crucial problems in the application of multi-channel MAC protocols, including access delays [10], channel allocation [21], and blind rendezvous [22]. Unfortunately, very little work has been done by considering MAC protocols that enable with multiple channels as well as retro-directive array antennas in UAV FANETs. In using multiple channels and spatial antennas, the interference in high-density UAV networks can be reduced significantly. However, the hidden terminal problems as well as deafness problems have to be carefully resolved. The proposed FA-MMAC described in the next section addresses the above issues.

In recent years, many researchers have studied the MAC protocol of directional antennas. Alsbatat et al. [23] proposed a directional MAC protocol for FANETs. First, control packets are transmitted to exchange location information by omnidirectional antenna, and then data packets are exchanged with directional antenna. This work can not support multi-channels. Duc Ngoc et al. [24] proposed a multi-channel MAC protocol with directional antennas that adopts IEEE 802.11-based power saving mechanism. It employs omnidirectional transmission of control packets, thus limiting the coverage area. Takai et al. [25] proposed a MAC protocol that transmits directional request to send (RTS) and clear to send (CTS) assuming that the transmitter is aware of receiver’s location. Basically the authors in [25] have proposed omnidirectional transmission of RTS. However, it is not easy to combine directional transmission with multiple channels, and there are many disadvantages of using directional antennas in FANETs.

(i) Directional antennas need to know the location of neighbors for the beam alignment and channel reservation, thus the complexity of transmission is greatly increased; and (ii) Directional antenna can only be transmitted along the normal direction of the antenna array face and cannot adjust the direction flexibly. Therefore, it has great limitations in FANETs with node mobility. In addition, the work need many antenna elements to achieve beams in different directions, which has higher complexity and cost. Compared with directional antennas, the advantage of retro-directive array antennas is that the direction and width of thier beams are adjustable, which is more flexible. Moreover, with its automatic response capability, it does not require complex neighbor discovery algorithms and additional information logging.

III. DESCRIPTION OF THE PROPOSED FA-MMAC

In FA-MMAC, we have designed a multi-channel structure to avoid hidden terminal and deafness problems in directional transmission. In this structure, the time axis into several beacon frames, and each beacon frame is divided into a control window (CW) and a data window (DW). Then, in the CW, the nodes use the novel control frame polling transmission mechanism to perform multi-channel negotiation and antenna beams alignment in the DW. At the same time, for the multi-channel and multi-beam structure of FA-MMAC, we also designed an available channel and beam list (ACBL). Each node avoids directional interference by maintaining its own ACBL.

A. ANTENNA MODEL

The electromagnetic energy of the signal from an omnidirectional antenna is shown in Fig. 5(a). It is spread over a large region of space, whereas only a small portion of it is received by a predetermined receiver.

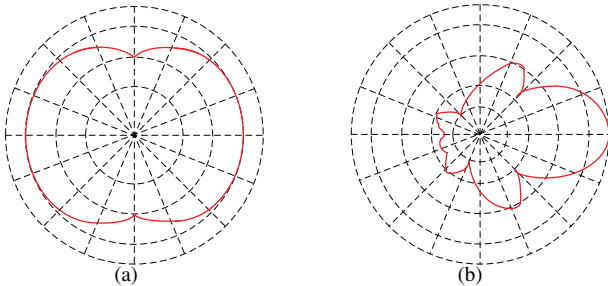


Fig. 5. Signal energy distribution of the antenna.

The retro-directive array antenna has two transmission modes: omnidirectional transmission and directional transmission. The electromagnetic energy of its directional mode is shown in Fig. 5(b). Electromagnetic waves can be enhanced in some directions and weakened in other directions by changing antenna arrays. In addition, the retro-directive array antenna can also control the transmitting power and send signals in all antenna sectors with the same distance as the omnidirectional antenna. Thus, the antenna can operate in either omnidirectional mode or directional mode.

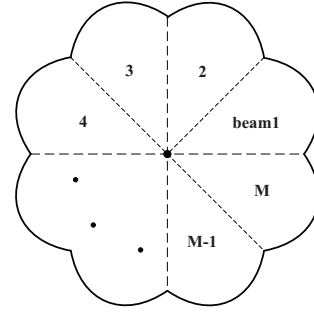


Fig. 6. The proposed Antenna Model.

In this paper, we develop a model of the retro-directive array antenna as shown in Fig. 6. We divide the beam of an antenna into M (M is an even number) fixed directions, and the antenna can select any one of them to transmit. When the antenna receives the signal, it can align the incoming wave direction and record the aligned beam number automatically. In fact, the antenna model is in three-dimensional space, and the retro-directive array antenna's beam shape is similar to a cone in three-dimensional space. In order to simplify the complex research problems, we simplified the FANETs and antenna models into two-dimensional models in our research.

B. The FA-MMAC Approach

We define a multichannel structure that supports retro-directive array antennas. As shown in Fig. 7, the time axis is divided into several beacon frames, and each beacon frame specifies a time window for controlling negotiation and a time window for data transmission. In the control window (CW), all nodes in the network switch to the temporary control channel (CCH) to negotiate the use of channels and beams, and then transmit data on the negotiated channels and beams in the data window. The CCH is agreed by the node in advance, and this method is also used by many network researches on Ad Hoc Networks, such as [26] [27]. It should be noted that the transmission of A-B will not affect E-F in data window (DW) thanks to spatial reusability under retro-directive array antenna, so no collision will occur. There is no special control channel in CW, but a data channel acts as the control channel temporarily, which improves the channel utilization rate. By separating control window from data window, we can avoid the conflict between control frame and data frame effectively, and to solve the problems of directional hidden terminal and deafness caused by retro-directive array antennas. This structure requires all nodes to be synchronized, and many current studies use GPS [28] or other recently proposed methods [29] [30] for nodes synchronization. We use GPS positioning method, the main reasons include: (1) it has very high synchronization time accuracy; (2) its stability is better. The status of each node in synchronization is equal, and the failure of a single node will not affect other nodes. Unless the GPS system fails, there will be no problem with the main clock source; and (3) using GPS synchronization in the FANET network, the algorithm is relatively simpler.

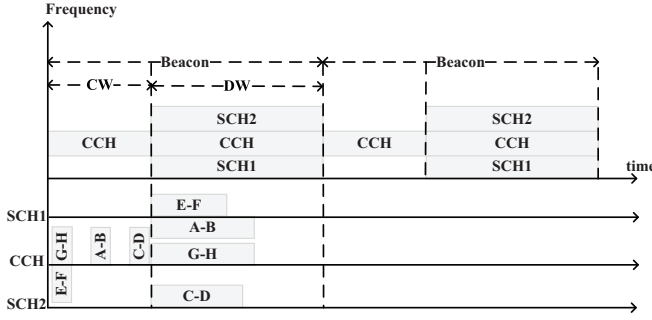


Fig. 7. Multi-Channel Structure.

In the traditional multi-channel MAC protocol based on the division of time slot, the node competes for the channel according to 802.11DCF mechanism in the control window, and adds a channel state vector (CSV) $\{c_1, c_2, \dots, c_N\}$ in the control frame. The symbol N represents the number of sub-channels, $c_k = 1$ means that subchannel k has been successfully reserved; $c_k = 0$ means the subchannel is free. Each node also maintains an available channel list (ACL) $\{a_1, a_2, \dots, a_N\}$. The ACL is updated according to the CSV in the received control frame to ensure that interference is not caused by the reuse of one channel between neighboring nodes. However, this mechanism is limited to the protocol application of omnidirectional antennas and cannot take advantages of spatial multiplexing in retro-directive array antennas. Therefore, in this paper we redesign the system to improve the parallel transmission capability between UAVs.

Each UAV maintains an available channel and beam list (ACBL) to store the status of all channels in each beams direction: Busy (0) or Available (1). And the ACBL is updated according to the control frames. The node can select the channel in a specific beams direction according to the ACBL and avoid interfering with the communications of other UAVs. The ACBLs of all nodes is reset at the beginning of each beacon, and then all nodes rebook the beams and channels in the control window of the beacon frame, and update their respective ACBLs based on the monitored control frame. In this paper, the interference definition of communication through retro-directive array antennas is defined as follows. Interference occurs if there are other transmitting nodes using the same channel in the beam coverage of a node that is transmitting data directionally. For example, Node B and Node A are transmitting data directionally in channel SCH1 and have a neighbor Node C (Fig. 8). If Node C also transmits with node E or D in channel SCH1, and its beam covers Node B or A, interference will be caused. To avoid such interference, nodes should understand the communication information of all the neighbors. They update ACBL based on the information and remain silent on the corresponding beam and channel during the beacon. Fig. 8 illustrates the mechanism mentioned above.

Nodes A and B shake hands successfully and then conduct directional data transmission on channel SCH1 through beam 1 of Node B and beam 3 of Node A. To avoid interference with the communication between A and B, beam 1 and beam 3 of node C are silent on SCH1 in this Data window. It means

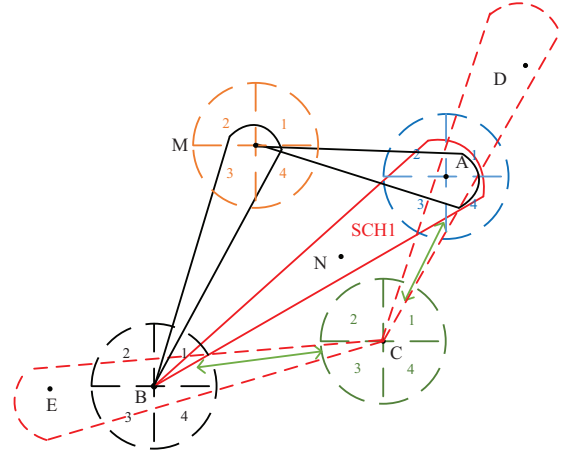


Fig. 8. Interference Example.

that in this beacon frame, if C needs to use beam 2 or 4 to transmit data, it can use SCH1. If C uses beam 1 or 3 for transmission, it cannot select SCH1 but only CCH or SCH2. Only after the nodes B and D finish transmitting and release the channel SCH1, the node C can use the SCH1 on the beam 1 and the beam 3. In addition, since with a large swarm of UAVs, UAVs that fly between two UAVs may act as scatters in the channel. For example, assuming that UAV N is the scatterer of the channel between source UAV B and destination UAV A. There are mainly two ways to deal with this problem. The first solution is that we can use multi-hop connection (i.e., using M or any other neighboring UAV as a relay) to complete the transmission from B to A. The second solution is that UAV B will back off until N moves out of the scattering range of the channel, and then B can communicate with Node A.

TABLE I
NODE C'S ACBL

Beams direction	Channel	State
1	CCH	1
	SCH1	0
	SCH2	1
2	CCH	1
	SCH1	1
	SCH2	1
3	CCH	1
	SCH1	0
	SCH2	1
4	CCH	1
	SCH1	1
	SCH2	1

In FA-MMAC, the nodes adopt the working mode of directional sending and omni-directional receiving, and send the circular directional control frames. In this scheme, the control frame is transmitted continuously in a circular manner until it scans all the area of sender. As mentioned above, it is assumed that the antenna has M beam directions. As shown in Fig. 9, we set M to four antenna sectors. Note that four sectors are just an example; they can be eight sectors, sixteen sectors, and so on. Furthermore, a pie is used to represent the antenna

beam sector for simplicity of representation. In the direction of beam 1, the sending UAV adjusts the antenna to send control frames directionally, then rotates the direction clockwise and send control frames in the direction of beam 2. Finally, the node has sent the control frames in all beam directions.

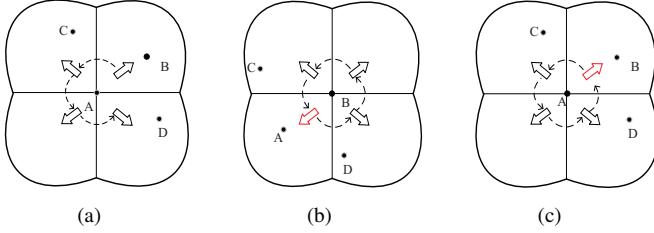


Fig. 9. Performance comparison of different protocols.

The principle of operation of FA-MMAC is illustrated in Fig. 9. We assume that Node A has data packets for node B. The key idea and main operation of FA-MMAC is highlighted next.

- 1) As shown in Fig. 9(a), the source node A sends RTS in each beam direction orderly to search for destination node, which carries the available channel information in this beams direction. Nodes can know the information from ACBL.
- 2) When the destination node receives the RTS, its retro-directive array antenna can align to the direction of the incoming wave automatically and then select the channel from the common available channel of the source node in this beam direction. The CTS carrying this information is sent in circular direction so that its neighbors can listen to the communication status. The transmission of the circular directional CTS starts in the alignment direction of the antenna and eventually returns to the alignment direction in Fig. 9(b).
- 3) When the source node receives the destination node's CTS, its retro-directive array antenna can align to the destination node. The source node confirms the reserved beam and channel information, and send the circular directional RES carrying the information so that its neighbors can listen to the communication status. The transmission of the circular directional RES starts in the alignment direction of the antenna and eventually returns to the alignment direction in Fig. 9(c).
- 4) The neighbors of source node and destination node update their ACBL based on the overheard CTS and response (RES) messages. When they overhear the message, they update the beam and channel status of the incoming wave in the ACBL.
- 5) As shown in Fig. 10, through the transmission of circular directional control frames in CW, the communication parties complete the beam alignment and channel reservation and then can transfer data directionally in DW. In addition, the protocol has designed an ACK acknowledgement and retransmission mechanism to ensure reliable data arrival. After receiving the data correctly and waiting for a short interframe space (SIFS), the receiver replies the

ACK frame to the sender. The sender can determine that the data transmission is successful only after receiving the ACK frame. Otherwise, it will send the data again. We set an upper limit for the number of retransmissions. If the times of data retransmission reaches this upper limit and it still fails, the data will be discarded.

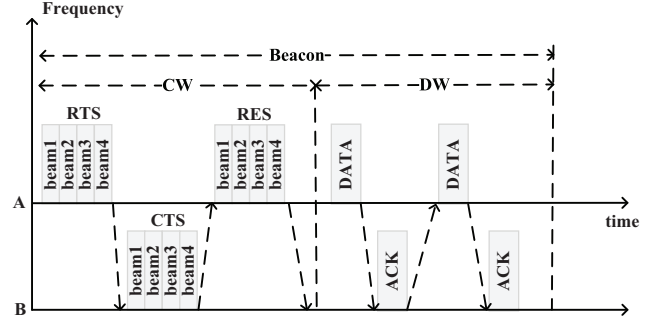


Fig. 10. Frame structure of FA-MMAC.

The main steps in a beacon frame of the FA-MMAC protocol are illustrated in Fig. 11.

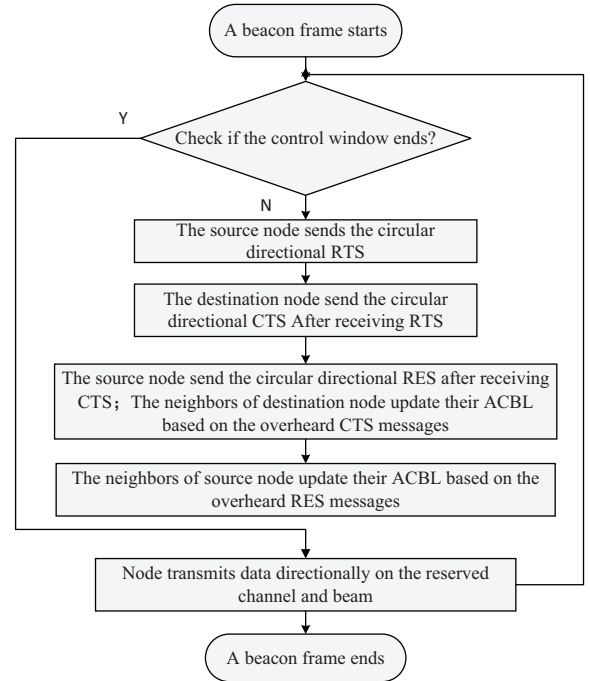


Fig. 11. Flowchart of the proposed FA-MMAC algorithm.

Nodes compete for access to channels according to the 802.11DCF mechanism in CW and their backoff counters are frozen in DW, which means that the competition will not be affected by the operation of the DW. The virtual process of channel negotiation among nodes during the CW is shown in Fig. 12.

- 1) At the initial moment, the backoff counters for nodes G, A and C are 2, 3 and 6. When the channel idle time reaches DIFS, the three nodes resume the backoff process.

- 2) After two backoff slots, the backoff counter of node G is reduced to 0. At this point, the node G sends RTS to the destination node and starts the first negotiation with it.
- 3) When the free time of the channel reaches DIFS again, node A and C continue to retreat. It should be noted that node G has already negotiated the channel and beam, it will not compete for the channel again during this beacon.
- 4) After one backoff slots, the backoff counter of node A is reduced to 0, and it initiates the second negotiation.
- 5) At this point, the control window ends. Node G and A switch to the negotiated channel for data transmission, and node C freezes the backoff counter until the next CW.

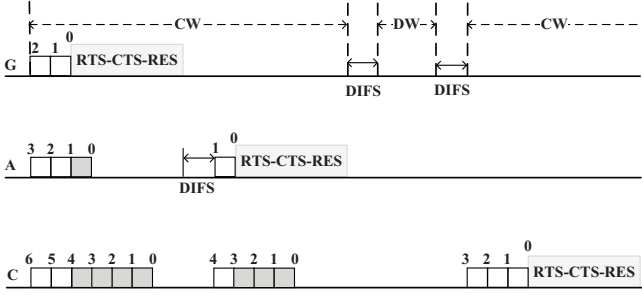


Fig. 12. The channel negotiation process of FA-MMAC.

IV. PERFORMANCE EVALUATION

In this section, we evaluate the performance of the proposed FA-MMAC protocol using JAVA simulator. The throughputs of 802.11-based and multi-channel MAC protocols are also presented for comparison purposes.

A. Performance analysis

The FA-MMAC protocol considers the freezing of the backoff counter and the maximum number of retransmissions. The Markov chain model is shown in Fig.13. The only non-null one-step transition probabilities are

$$\begin{cases} P(i, k|i, k+1) = 1 - p_c, & k \in [0, W_i - 2], i \in [0, m] \\ P(i, k|k) = p_c, & k \in [0, W_i - 1], i \in [0, m] \\ P(i, k|i-1, 0) = p/W_i, & k \in [0, W_i - 1], i \in [1, m] \\ P(0, k|i, 0) = (1-p)/W_i, & k \in [0, W_0 - 1], i \in [0, m-1] \\ P(0, k|m, 0) = 1/W_0, & k \in [0, W_0 - 1] \end{cases} \quad (1)$$

Let the stable distribution of Markov chain be $b_{i,k} = \lim_{t \rightarrow \infty} P\{s(t) = i, b(t) = k\}$, we can obtain

$$b_{i,0} = b_{i-1,0} \cdot p = p^i b_{0,0} \quad i \in [0, m] \quad (2)$$

$$b_{i,k} = \begin{cases} \frac{W_i - k}{W_i(1-p_c)} \left[\sum_{j=0}^{m-1} (1-p) b_{j,0} + b_{m,0} \right] & i = 0, k \in [1, W_i - 1] \\ \frac{W_i - k}{W_i(1-p_c)} b_{i,0} & i \in [1, m], k \in [1, W_i - 1] \end{cases} \quad (3)$$

$$b_{0,0} = \sum_{i=0}^{m-1} (1-p) b_{i,0} + b_{m,0} \quad (4)$$

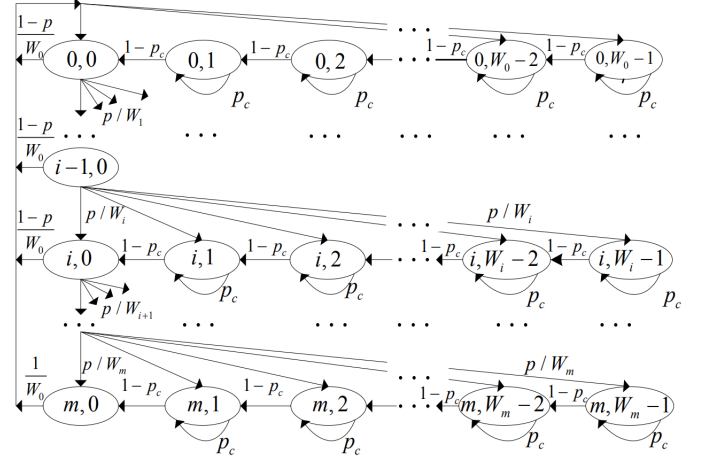


Fig. 13. The Markov chain description of the retreat process of a control channel.

$$b_{i,k} = \begin{cases} p^i b_{0,0} & k = 0, i \in [0, m] \\ \frac{W_i - k}{W_i(1-p_c)} b_{i,0} & i \in [0, m], k \in [1, W_i - 1] \end{cases} \quad (5)$$

From the complete event group, it can be known that:

$$\sum_{i=0}^m \sum_{k=0}^{W_i - 1} b_{i,k} = 1 \quad (6)$$

According to the Bianchi model:

$$p = 1 - (1 - \tau)^{N-1} \quad (7)$$

If a node detects that the CCH channel status is busy, it means that at least one of the other $(N - 1)$ nodes is using the CCH channel to transmit control frames. Assuming that all nodes are independent, then p_c is a binomial distribution of N and p :

$$p_c = \sum_{i=1}^{N-1} C_{N-1}^i \tau^i (1 - \tau)^{N-1-i} = 1 - (1 - \tau)^{N-1} \quad (8)$$

Then

$$p_c = p \quad (9)$$

$$\begin{aligned} 1 &= \sum_{i=0}^m \sum_{k=0}^{W_i - 1} b_{i,k} = \sum_{i=0}^m b_{i,0} \left[\sum_{k=0}^{W_i - 1} \frac{W_i - k}{W_i(1-p)} + 1 \right] \\ &= \frac{b_{0,0}}{2(1-p)} \left[W_0 \sum_{i=0}^m (2p)^i + (1-2p) \sum_{i=0}^m (p)^i \right] \end{aligned} \quad (10)$$

$$b_{0,0} = \frac{2(1-p)^2(1-2p)}{W_0(1-p)(1-(2p)^{m+1}) + (1-2p)^2(1-p^{m+1})} \quad (11)$$

The probability τ that node sends an RTS frame is

$$\begin{aligned} \tau &= \frac{1+p^{m+1}}{1-p} b_{0,0} \\ &= \frac{2(1-p)(1-2p)(1-p^{m+1})}{W_0(1-(2p)^{m+1})(1-p) + (1-p^{m+1})(1-2p)^2} \end{aligned} \quad (12)$$

N represents the number of competing nodes in the network; W is the minimum contention window; m represents the maximum number of retransmissions. We can obtain the

relationship between the number of competing nodes N and the conditional collision probability p is

$$N = 1 + \frac{\ln(1-p)}{\ln\left(1 - \frac{2(1-p)(1-2p)(1-p^{m+1})}{W_0(1-(2p)^{m+1})(1-p) + (1-p^{m+1})(1-2p)^2}\right)} \quad (13)$$

When W is 32 and m is 4, the relationship between the collision probability and the number of nodes is shown in the Fig. 14.

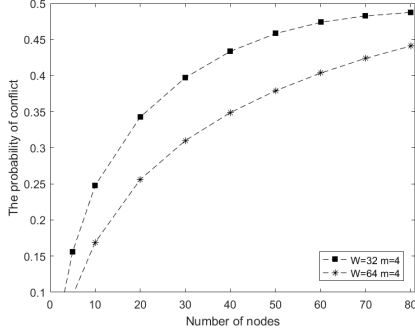


Fig. 14. The relationship between the collision probability and the number of nodes.

The average probability that the CCH is in the idle time slot P_{idle} , data transmission time slot P_s and negotiation collision time slot P_c are expressed as

$$P_{idle} = (1 - \tau)^N \quad (14)$$

$$P_s = N\tau(1 - \tau)^{N-1} \quad (15)$$

$$P_c = 1 - (1 - \tau)^N - N\tau(1 - \tau)^{N-1} \quad (16)$$

The source node sends the circular directional RTS. After the destination node receives the RTS frame, it waits for DIFS to reply to CTS. We set the waiting time for replying to CTS as the duration for a collision transmission

$$T_c = M * t_{RTS} + DIFS \quad (17)$$

M indicates the number of antenna beams, and t_{RTS} is the transmission time of one RTS. A successful negotiation includes the sending of RTS, CTS, RES frames and the inter-frame interval

$$T_s = M * (t_{RTS} + t_{CTS} + t_{RES}) + DIFS + 2 * SIFS \quad (18)$$

Each backoff is based on a backoff slot, so the idle slot is

$$T_{idle} = \sigma \quad (19)$$

The average time required for the last successful channel negotiation of CCH is

$$T_{neg} = \frac{P_{idle} * T_{idle} + P_s * T_s + P_c * T_c}{P_s} \quad (20)$$

The number of successful negotiation in CW is

$$N_{neg} = \min\left(\frac{T_{cw}}{T_{neg}}, N_{channel} * M\right) \quad (21)$$

Interference occurs if there are other transmitting nodes using the same channel in the beam coverage of a node

that is transmitting data directionally. In FA-MMAC, we use ACBL to avoid directional interference. Therefore, beams can be multiplexed when directional interference does not occur between the communication links. In this case, the number of nodes will affect the beam reuse probability. When the number of beams is M and the number of competing nodes is N , the probability of multiplexing k beams is

$$P_k = C_M^k \frac{S(N, k) * k!}{M^N} \quad (22)$$

C_M^k is a combination in mathematics, which means that m elements are selected from n elements without repeating. $S(N, k)$ is a Stirling number of the second kind. Its mathematical meaning is the number of schemes that divide N different elements into k sets. Considering the number of nodes, we get the number of successful negotiation

$$N_{neg} = \min\left(\frac{T_{cw}}{T_{neg}}, \sum_{k=1}^{N_{channel} * M} k * P_k\right) \quad (23)$$

Since the CW window size affects the number of successful ATIM handshakes, we can estimate the duration of CW and DW by maximizing N_{neg} . With the average length of data packet is L , the average aggregate in saturated condition throughput can be calculated as

$$S = \frac{N_{neg} * E(L)}{T_{beacon}} \quad (24)$$

TABLE II
SIMULATION PARAMETERS

Parameters	Value
Number of nodes	80
Number of channels	3
Number of beams	4
Control Window/Data Window	20 ms / 80 ms
SIFS / DIFS / Slot time	10 μ s / 50 μ s / 20 μ s
RTS/CTS/RES	16 bytes / 16 bytes / 16 bytes
Minimum contention window	32
Retry limit	4
Data rate	2 Mbps
Data packer size	500 bytes
The size of the node's data queue	8 Mb

Now, we validate our analysis through simulations. The simulation parameters are given in Table II. According to Equation (23) and (24), the length of CW will have an impact on performance. There are many existing research have studied this adaptive process, such as [31] and [32], and it is not the focus of this paper. So we set the duration of the control window as 20ms and the duration of the data window as 80ms in our simulation as an reprehensive example to conduct performance evaluation. We compare the analysis results with simulation results in the Fig.15, showing the match between the analysis and the simulation. $nbmc$ denotes n beams and m channels. When multi-channel is enabled, generally, the throughput will increase by times. One can observe that "1b3c" and "4b1c" (Fig. 15), the 4-beam 1-channel mode has higher network throughput than the omnidirectional 3-channel mode, which is enough to prove the advantages of the implementation of retro-directive antenna. In addition, comparing the scenarios

of 1b3c, 2b3c and 4b3c, one can observe that in the same condition of 3-channel, the throughput of 2-beam directional mode is twice than that of the omnidirectional mode, and the throughput of 4-beam directional mode is more than 3 times than that of the omnidirectional mode. These results verify the advantages of the implementation of retro-directive antenna.

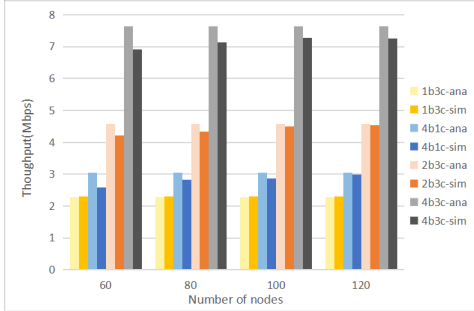


Fig. 15. Saturated throughput of FA-MMAC.

B. Simulation setup

To simplify the simulation model, we assume that the bit error rate in the physical channel is zero and there is no transmission delays. Coordinate positions of multiple UAVs are arbitrarily set in a $500\text{m} \times 500\text{m}$ area. We assume that all UAVs are flying at the same altitude and simplify the model to a plane problem. All UAVs use GPS to synchronize.

In the simulation we measure both throughput, packet delivery ratio and packet delay, as they are importance performance metrics in our study. The system simulation parameters are listed in Table II. The packet arrival at each station is a Poisson process with the same mean λ . In order to simulate different levels of congestion in the network, the simulation verifies the network throughput and packet success rates for various λ . The position of UAVs are set randomly in each simulation run, and we select half of the nodes in the area as source nodes and the other half as receiving nodes randomly. We assume that all nodes are within the transmission and interference range in our evaluation. Each simulation is executed for 10 seconds, and the results of various protocols are the average of 200 simulation executions. Any two UAVs in the communication range are matched into a transmission pair, that is, the destination and receiver are selected randomly.

C. Simulation results

Fig. 16 compares the throughput performance of the three protocols, namely 802.11-based, Multi-channel MAC(MMAC) [26], and FA-MMAC (2- and 4-beam). We found that at low arrival rates, the total throughput of the three protocols is close at low. However, as the network tends to be saturated, the combined multi-channel and retro-directive array antenna can achieve higher throughput. The throughput of 2-beam and 4-beam FA-MMAC is about 100% and 200% higher than that of MMAC, respectively. The reason is that multi-channel provides independent and non-interfering sub-channels for nodes to realize parallel

transmissions. FA-MMAC allows more node pairs to transmit in the same subchannel and therefore its spatial reusability and channel capacity are larger than MMAC. In addition, we simulated the performance of FA-MMAC in four and eight beams. We observe that the spatial reusability of the network is further improved with the increase of the number of antenna beams. In three-dimensional space, the retro-directive array antenna has more angle selection, which can greatly improve the spatial reusability of the network.

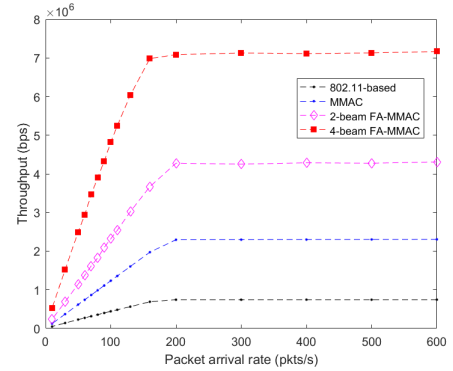


Fig. 16. Throughput performance of FA-MMAC.

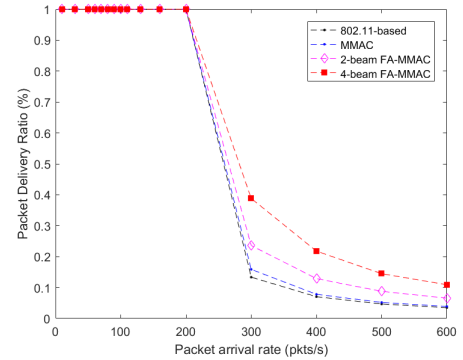


Fig. 17. The packet delivery ratio vs. packet arrival rate. Comparison of FA-MMAC (2 and 4 beam), and MMAC.

The packet delivery ratios for the three protocols are shown in Fig. 17. With the increase of data arrival rate, more and more nodes compete for the channel to send packets, which leads to the increase of collision probability and more packet losses. Besides, nodes have thresholds for the cache size of arriving packets, which is also an important reason for packet losses. Therefore, the packet delivery ratio decreases inevitably as the packet arrival rate increases. While both FA-MMAC and MMAC use multichannel technology, but the proposed FA-MMAC allocates the transmitting nodes to different sub-channels to reduce the probability of collisions. This allows more nodes to transmit packets at the same time, hence achieve better packet delivery ratio than 802.11-based protocol. In addition, the retro-directive array antenna further improves the parallel transmission capability in the space domain, and therefore, FA-MMAC achieves higher packet delivery ratios

than MMAC. Fig. 18 shows the effect of increasing the number of nodes on packet delivery ratios. As the number of nodes increases, the packet delivery ratio decreases about 10%-20% than that of MMAC, which means that the FA-MMAC protocol is excellent for large-scale FANETs applications.

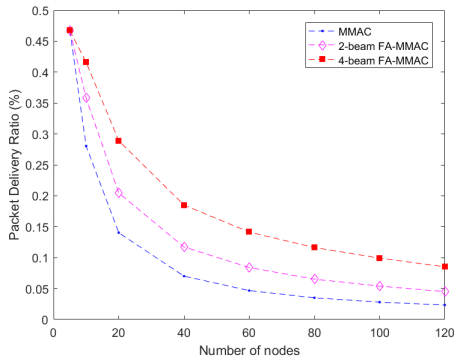


Fig. 18. Packet delivery ratio vs. number of nodes. Comparison of FA-MMAC (2 and 4 beam), and MMAC.

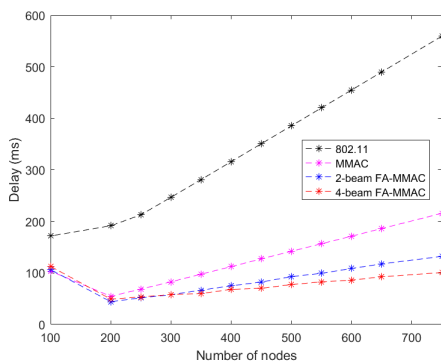


Fig. 19. Packet delay vs. number of nodes. Comparison of FA-MMAC (2 and 4 beam), and MMAC.

The packet delay for the three protocols are shown in Fig. 19. It can be seen that when the data packet arrival rate is low, the advantage of FA-MMAC is not obvious, and as the data packet arrival rate decreases, the delay increases. In IEEE 802.11, when a node has a data packet to transmit, it competes for the channel to transmit the data packet. In FA-MMAC, nodes need to wait for the data window to transmit data. Therefore, when the network load is very low, the delay performance advantage of FA-MMAC is not obvious. When the network load is high, the FA-MMAC protocol supports more concurrent data transmission, which makes FA-MMAC have a lower delay. The more beams, the more concurrent data transmission, the lower the delay.

Mobility is a challenging characteristic of FANETs. Therefore, it is useful to evaluate system performance in mobile environment. We measure node throughput in mobile environment. We also measure node throughput in static condition for comparison purposes. The mobility model of UAVs we adopted is based on Random Walk (RW) [33], which is a random-based model allowing mobile nodes, at each

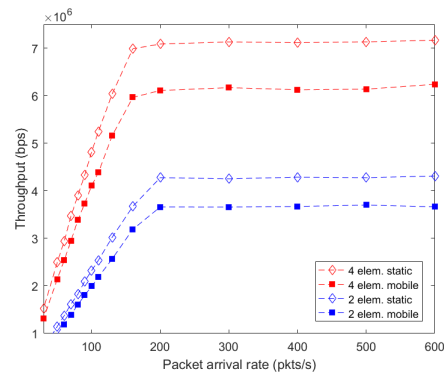


Fig. 20. Throughput for the random scenario.

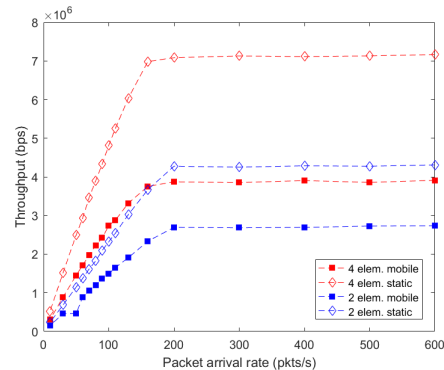


Fig. 21. Throughput for the random scenario.

fixed duration of time, to select a random direction, speed, and distance. If a mobile node reaches the area boundary, it bounces off the boundary with a new direction. In the simulation, we set a fixed moving speed for the nodes and compare the performance of different node speeds. Firstly, we set the node mobility to 10m/s in the mobile scenario. The simulation results are shown in Fig. 20. One can observe that the performance of FA-MMAC is affected by the mobility of the nodes as node throughput decreases slightly compared to static nodes. We also compare the throughput of 2-beam and 4-beam FA-MMAC in mobile environments. We observe that the decline throughput of 4-beam FA-MMAC is larger than that of the 2-beam. This is because of the coverage range of each beam is narrowed in 4-beam FA-MMAC and the nodes are easier to move out of the coverage range of the beam. Secondly, we set the nodes' moving speed to 50m/s and the corresponding simulation results are shown in Fig. 21. By comparing Fig. 20 and Fig. 21, we observe that the faster the node moves, the faster the throughput performance declines. This is due to the following facts. Due to the changes in the moving direction of the UAV during the communication process, its relative direction to the receiver will change, which is tolerable to a certain extent. Because of the directional beam has a certain width, small changes in its directions will not affect the transmission. However, if the node suddenly turns sharply during transmission, causing

its receiver to completely escape from the coverage of the directional beam, the transmission will be interrupted. In this case, the node will soon re-subscribe to the channel in the next cycle of the control window. In the performance simulation, we discussed the mobile situation of nodes, and the results show that this fact has an impact on system throughput performance. As shown Fig. 6 that when the number of beams is larger, it means that the beam width in a single direction is narrower, so the tolerance of node movement and steering is lower and the impact on the network capacity is greater. Therefore, we recommend appropriately increasing the width of the directional beam when nodes in the network move and turn too fast. However, the modest levels of degradation demonstrate the viability of our protocol in mobile scenarios. The simulation results also show that our protocol still has a significant advantage over omnidirectional transmission even for the case of under the influence of node movement.

V. CONCLUSION

A MAC protocol for FANETs (FA-MMAC) is proposed by combing the multi-channel MAC with retro-directive array antennas. FA-MMAC can avoid channel interference between transmitting nodes, and consequently improve the spatial reusability of channel. The trade-off here is that when you send the control frames by the circular directional transmission, the access delay and consumption increase. However, compared with the omnidirectional antenna, the retro-directive array antenna requires less power for the same transmission distance, which can save power consumption effectively. Besides, through the directional transmission of control frames and data frames, it can greatly improve the communication range of nodes and the reuse of the network. The simulation results obtained have shown that FA-MMAC can provide better network aggregate throughputs and packet delivery ratios than the existing 802.11 and MMAC protocols. The throughput of FA-MMAC is about 100%-200% higher than that of MMAC, and the decline rate of FA-MMAC's packet delivery ratio is about 10%-20% slower than that of MMAC. As further study, we will focus on the handoff problem of beams to reduce the influence of mobility in FA-MMAC.

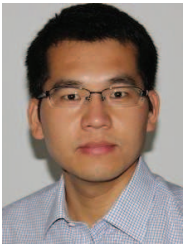
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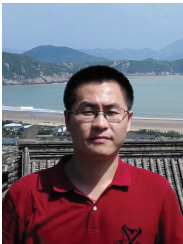


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