A Hybrid MAC for Long-Distance Mesh Network with Multi-beam Antennas

Xin Li, Fei Hu, Ji Qi and Sunil Kumar

Abstract In recent years, with the development of multi-beam smart antennas (MBSA), directional mesh networks is becoming more and more popular. With the popularity of UAVs and environment surveillance applications, airborne networks (ANs) have become important platforms for wireless transmissions in the sky. In this work we propose a hybrid MAC scheme for a hierarchical airborne network, which consists of high-speed, long-link, multi-beam aircraft nodes (in the higher level) and short-distance, high-density UAVs (in the lower level). Simulation results show that compared to existing 802.11 MAC schemes, our MAC has better performance in terms of network throughput and packet delay.

Keywords Airborne Mesh Networks · Multi-beam antennas · Heterogeneous MAC · Ku-band

1 Introduction

1.1 Two-Level Airborne Mesh Networks

In recent years, with the development of multi-beam smart antennas (MBSA), directional airborne network is becoming more and more popular in the sky. Aircrafts could be equipped with MBSAs instead of omni-directional antennas currently in use. With the help of MBSAs, each airplane in the airborne network would be able to communicate with its adjacent neighbors simultaneously in different beams. This would considerably improve the overall throughput of the network compared to

X. Li(✉) · F. Hu · J. Qi
Electrical and Computer Engineering, University of Alabama,Tuscaloosa, AL, USA
e-mail: xli120@crimson.ua.edu

S. Kumar
Electrical and Computer Engineering, SDSU, San Diego, CA, USA

S. Latifi (ed.), *Information Technology New Generations*,
Advances in Intelligent Systems and Computing 448,
DOI: 10.1007/978-3-319-32467-8_9

that in networks with omni-directional antennas. In practice, a number of UAVs (unmanned aerial vehicles) usually work within a specific region-of-interest (RoI). The distance between UAVs is roughly within a range from 500m to 10km. The flying height of UAVs is much lower than that of aircrafts. Thus the UAVs form a *low level* airborne network which has a large number of nodes working in a small space. Typically an UAV is equipped with both omni-directional antenna and single-beam directional antenna. The omni-directional antenna is used to carrier-sense signals from surrounding nodes while the single-beam directional antenna is used to send out information. However, the aircrafts distribution in the *high level* is sparse. The average distance between these aircrafts may be longer than 100km. Each of these aircrafts is equipped with a MBSA. The high level airplanes are used to manage the RoIs. One of the UAVs in each RoI serves as the UAV head which could communicate with the corresponding aircraft. Figure 1 shows an illustration of hierarchical airborne mesh network. The figure shows that the airborne network has a typical wireless mesh network (WMN) architecture. The aircrafts in upper level form a wireless backbone network. The nodes in backbone network are named mesh routers (MR). In this case, the MR nodes are considerably powerful and sparse. While the UAVs in the lower level serve as mesh clients (MC).

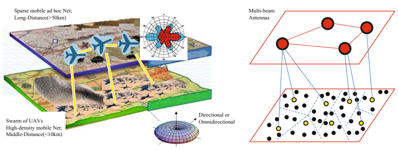

Fig. 1 An Illustration of Hierarchical Airborne Mesh Network.

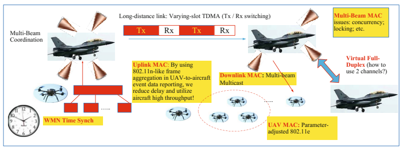

Fig. 2 Big Picture: Proposed heterogeneous MAC

Ku-band[1] spectrum, usually from 10GHz to 15GHz, was reserved for satellite communication. According to Shannon's equation, high frequency makes fast data rate. Ku-bands also provide better anti-interference capability, which means that the receiver node suffers less interference from other nodes. In addition, Ku-band signals are very sensitive to line-of-sight (LoS) blocking. Fortunately, airborne network nodes are set up in very high height with low blocking chance.

In this research, we target the MAC design in hierarchical airborne mesh network (HAMN). We propose an integrated, hybrid MAC for HAMN. There are three different types of links in a HAMN: Aircraft-to-aircraft (A2A), aircraft-to-UAVs (A2U) and UAV-to-UAV (U2U). For A2A links, we use a scheduled, TDMA-like multi-beam oriented MAC scheme to achieve high throughput transmissions. However, for U2U communications, we use the conventional CSMA/CA scheme with omni-directional antennas. The A2U links have a heterogeneous feature since these links connect the two network layers.

The rest of this paper is organized as follows: In Section 2, we first summarize the related work on MAC layer. In Section 3, we describe the system assumptions and then present the technical details of proposed heterogeneous MAC scheme.

Numerical simulation results will be shown in Section 4. Section 5 concludes the entire paper.

2 Literature Review

In the recent a few years, there has been plenty of research work on directional antenna oriented MAC for airborne networks [2]. Those MAC protocols are designed for real-time, high-throughput, low-delay transmissions.

The MAC used in long-distance aircraft communications is first mentioned in [3]. Most conventional 802.11 protocols are based on CSMA scheme. But the network based on 802.11 MAC has certain limitations. For example, it is only suitable to low-distance links (<500m). Now with the usage of new frequency such as Ku-band ($\sim$ 15GHz)[4],the long distance network becomes a reality. With Ku-band frequency, wireless communication links could have more reliability in transmissions. In practice the BER (bit error rate) is below 10^{-5}. Ku-band signals are less likely to scatter. Thus they are less likely to be interrupted by the noise.

There has been some work focusing on directional MAC protocols [5]. Unfortunately, the single-beam antenna model is considered in most of these studies. Some work did consider multi-beam MAC design. In [6], V. Jain proposed a hybrid MAC scheme in multi-beam networks. An enhanced point coordination function (PCF) is proposed in [7]. A distributed CSMA-based scheme is considered for multi-beam communication in [8].

In our work, we propose a new hierarchical multi-beam MAC protocol which is able to deal with the critical issues such as long distance, node deafness, sender polling, etc. The simulation results show that our proposed scheme could fully exploit the benefits of MBSA.

3 Heterogeneous MAC Design

Figure 2 shows the big picture of our MAC design. The distance between two nodes determines the performance boundary of CSMA-based and TDMA-like MAC. The random access scheme such as CSMA does not work well if the distance is too long. When the distance is larger than 50km, the round trip delay is 0.33ms. It is difficult to detect radio signal collision for such a long time. In addition, the long ACK timeout makes it difficult to achieve high throughput since it wastes too much time on ACK waiting. In this scenario, CSMA severely sacrifices the network throughput. While time-scheduled MAC protocols (TDMA-based) is more suitable to such a long propagation delay since it can use a dedicated time duration for data transmission.

In multi-beam antenna MAC design, our goal is to fully explore the multi-beam antennas to improve the network throughput. Theoretically, we could achieve N times of throughput improvement over a single-link case if each antenna has N beams. Compared to one-beam transmission, multi-beam transmission can take advantage of neighbors′ relay. We can use more neighboring nodes to help forward data. Thus a high throughput is achieved via multiple path. Below we would describe MAC operations in A2A and U2U links.

3.1 A2A MAC Design

Our A2A MAC is based on TDMA-like scheme. Each node is entitled with a number of time slots to send or receive data packets. The node with the right to transmit data is named as 'star' node. The slots could be assigned according to deterministic or statistical rules. The entire aircraft is synchronized based on the clock synchronization scheme [9].

Since the upper level aircraft network is sparse, it it easy to manage the slot allocation through a satellite-based global management. In our work, A2A MAC is different from pure TDMA-MAC in the following two aspects:

(1) Each phase is longer than that in conventional TDMA. As we know, the time duration in conventional TDMA is set to only hundreds of microseconds (μs). In our A2A links the time in each phase could be hundreds of milliseconds (ms) in order to deal with a large number of data packets.

(2)While in conventional TDMA-based MAC, each node is allocated with a fixed-length of time slots, in our A2A MAC the length of time slots is variable. Since it may cause much delay if the multi-beam antenna frequently switches between Rx and Tx modes, it is better to finish a window of packets in one slot (i.e., one Tx/Rx phase). The window size should be proportional to the traffic load in the node.

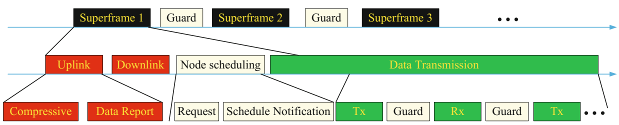

Fig. 3 Operation Phases in Each Aircraft

Figure 3 shows operation phases in each aircraft. As we can see, each superframe consists of three phases.

(1)Uplink/Downlink phase: In this phase, the node needs to determine the direction of the communication. For the uplink communication, the RoI nodes would first report their transmission durations to the aircraft through a compressive sensing based polling method. Then the center aircraft receives data packets from UAVs. For the downlink communication, the aircraft has to broadcast information to UAVs in its RoI.

(2)Node scheduling phase: In HAMN, if one aircraft wants to send messages to other nodes, it first sends request messages to a gateway node. which would determine the transmission order based on a hash function with node ID and times tamp:

$$Position(i) = Hash(ID(i), timestamp), i = 1, 2, ..., N \quad (1)$$

The value of the Hash function is normalized between (0, 1]. The variable $timestamp$ is the current time. A node with $ID = J$ wins the time slot only if the following equation holds true:

$$arg \max_{1 \le x \le b} Hash(ID(i), timestamp) = J \quad (2)$$

The Hash function is performed by each node. In this way, each node knows who is the current 'star' node and who will be the next. The Hash function is carefully chosen so that nodes have an equal chance to be the 'star' node.

(3)Data transmission phase: After the first two phases, the nodes enter scheduled communications. In this phase, we use a token-based [10] pipelined scheduling. Figure 4 shows an example of token handle process.

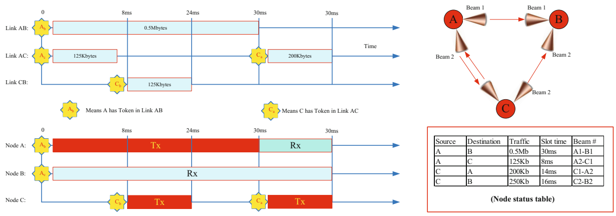

Fig. 4 Multi-beam Scheduled Transmission Process

As we can see from Fig. 4, although A cannot switch to Rx mode due to the longer Tx time in A-B link, it allows C to enter Tx mode after A-C transmission is done. Therefore, C can start to transmit data to B after 8ms. Such a scheme makes our MAC efficiently utilize each free link.

In addition, note that there is a node status table (shown in Fig. 4) which maintains the information on traffic amount in each beam of a node. In this example only two beams in each node are active. The beam status table is used to discover link quality and choose the proper beam to send out data packets. The gateway does not need to broadcast such a table to each node. It just needs to tell a node about its specific Tx /Rx timing information as well as the MAC address of its destination (when in Tx mode) or source (when in Rx mode).

3.2 U2U MAC Design

Compared to upper-level aircraft network, the UAV network has much higher node density. If we apply TMDA-based MAC in UAV network, we need a global coordinator as well as accurate timing synchronization among many UAVs. It is considerably difficult to manage such a global coordinator. Furthermore, using dedicated time slots could waste much bandwidth since the communications between UAVs are sparse. In most of the time, data transmission occurs between aircrafts and UAVs. Therefore, it is better to use a random access MAC scheme in UAV network. With a random access MAC, we do not need to consider any synchronization issues as well as global coordinators. Moreover, since the distance between UAVs is short (100m $\sim$ 10km, average 1km), it is less likely to have errors in carrier sensing as well as ACK timeout.

In this paper, the U2U MAC is designed based on existing IEEE 802.11 protocols. The latest 802.11 standards [11](such as 802.11e) recommend the use of point coordination function(PCF) for scheduling control of each neighbor′s transmissions.

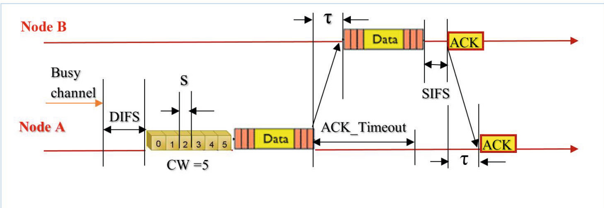

Fig. 5 Different CSMA time durations during DATA/ACK transmission

The timeline of the U2U MAC is shown in Fig. 5. Node A has a data packet for node B. According to CSMA scheme, node A first listens to the channel. If the channel is busy currently, it enters a backoff waiting phase. Once the channel is free, A would occupy the channel and sends out the packet. Here τ is the propagation delay. After B receives data packet, B waits for SIFS time and sends ACK to A. Note that the relationship between DIFS and SIFS is:

$$DIFS = 2 \times S + SIFS \tag{3}$$

In UAV network, we need to modify some parameters of 802.11e. The modifications are listed as follows:

(1) ACK Timeout: The latest 802.11 standard recommends that ACK timeout should include SIFS, S_{STD}(standard slot time) and PCLP (Physical layer convergence procedure). Here we adjust 802.11e $ACK_{Timeout}$ value as follows:

$$ACK_{Timeout} = SIFS + S_{STD} + PCLP + RTT \tag{4}$$

(2) Slot Time: The Slot Time (S) is defined as the maximum time needed to detect signal collision. In conventional 802.11, S must meet the following requirement:

$$S > (RTT/2) + CCA \tag{5}$$

Here CCA is the sum of all times except the light propagation time. In practical design, the constraint of S should consider the impact of the interference of a node on the ongoing link. In order to make sure that one node does not cause collisions to another one, we have:

$$S > (RTT/2) + 2 \times CCA \tag{6}$$

(3) DIFS: The purpose of setting SIFS and DIFS is to separate the transmission times between DATA, ACK, PCF control frames, and DCF data frames. After we adjust the slot time (S) based on the above formula, we can adjust the DIFS based on 802.11 recommendation:

$$DIFS = SIFS + 2 \times S \tag{7}$$

3.3 A2U/U2A MAC Design

In Fig. 3, we mentioned Uplink/Downlink phases. The links between UAVs and aircrafts are extremely important to a HAMN since the UAVs need to pass surveillance information data to aircrafts through uplink transmissions (U2A), and the aircrafts deliver command data via downlinks (A2U).

1. Uplink Transmission (U2A): The major issue in uplink transmission is the polling of each RoI UAVs about their data transmission requests. To quickly collect different RoI nodes requests, we propose to use compressive sensing (CS) concept to allow concurrent, uplink request transmission among a large amount of RoI nodes. CS scheme can simply ask all nodes to send out analog (instead of digital) signals in the air, and then the aircraft can use signal reconstruction to recover the original analog signal vector. Since we use analog signals to send out requests, those signals could simultaneously propagate in the air. And the aircraft can use CS signal reconstruction (again, this is analog operations) to recover the request of each RoI node.

2. Downlink Transmission (A2U): Unlike U2A transmission, in A2U we only need to broadcast the command messages. One challenging issue is multi-beam multicast (MBM) transmission. We cannot afford to lose any of those multicast messages since they are re-tasking commands. For A2U links, we propose to use link quality estimation. We require that each multicast UAV to piggyback their PER (packet error rate) and mobility information in their ACKs. After the aircraft collects the history link state parameters, it predicts the next link state via ARMA (Auto Regressive Moving Average) model.

$$\sum_{l=0}^{p} A_l y(t-l) = \sum_{l=0}^{q} M_l \epsilon(t-l) \tag{8}$$

Here A_0, A_1,..., M_0, M_1,... are all matrices of order $n \times n$, and $\epsilon(t)$ is a disturbance (noise) vector of n elements.

4 Performance Evaluation

In this section, we will show the simulation results of our proposed MAC protocol. Our results include network throughput performance, average packet delay and transmission time.

4.1 Simulation Setup

We consider an A2A network with 10 nodes. The nodes are uniformly distributed in a 300km-by-300km area. We use Ku-band signals with high data rate. The link capacity is set as 10Mb/s. As we mentioned before, in A2A network each node is equipped with a multi-beam antenna. In our simulation, each aircraft has an antenna with 4 beams, and each beam covers 90 degrees of area. Each packet contains up to 1500 Bytes of information. Each node has a buffer to store up to 30 packets. We conduct the whole simulation for 25 iterations. In each iteration, the simulation time is set to be 10s. Fist we test the overall throughput and delay performance of the A2A network. Then we simulate token scheme in Section 3.1. Finally, we test the A2U link and compressive sensing polling scheme.

4.2 Simulation Results

Figure 6 shows the throughput of the network with the average packet arrival rate. In Fig. 6 we compare our proposed A2A MAC protocol with traditional 802.11 DCF.

From the figure it is apparent that the overall network throughput with our proposed A2A MAC scheme is much better than that conventional IEEE 802.11. As we can see from the figure, when the average packet arrival rate is less than 100 packets/second/node, the two MAC schemes have similar performance. As the packet arrival rate goes up, conventional 802.11 network quickly saturates while our proposed MAC scheme could achieve almost twice throughput. The network starts to get congested when packet arrival rate is greater than 300.

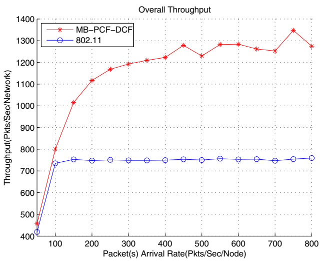

Fig. 6 A2A Throughput performance

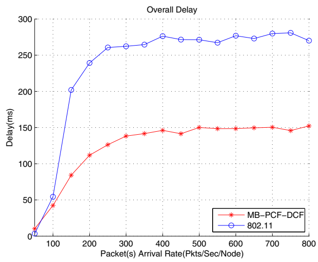

Fig. 7 A2A Delay performance

Figure 7 shows the average delay performance. It is also obvious that the proposed MAC has the lower average time delay, which could satisfy some of the QoS requirements (e.g, for video transmission the delay should be less than 200ms).

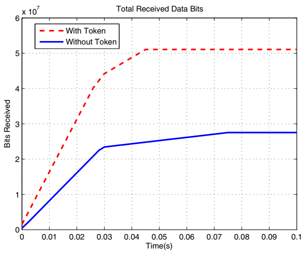

Fig. 8 Throughput of token-based scheme

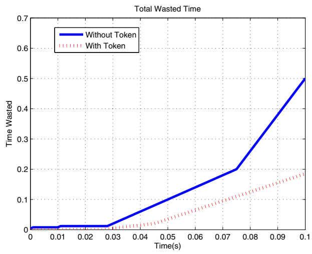

Fig. 9 Time Waste Performance

As we can see from Fig. 4, the network throughput is significantly increased with the token-based MAC scheme (almost doubled compared to non-token scheme). This is because any node can immediately switch to Tx (or Rx) mode after it finishes Rx (or Tx) phase, as long as it follows multi-beam antenna requirements (all beams should be in the same mode). Such a pipelined transmission also shortens the delay. As shown in Fig. 9, the delay is reduced for more than 50% after a certain time of communications.

5 Conclusion

In this paper, we proposed a two-layer hybrid MBSA-based MAC design for HAMN. In particular, we proposed TDMA-like A2A MAC for long-distance transmission. In UAV network, we modified the existing 802.11e to make it suitable for UAV communications. In addition, a compressive sensing based data polling scheme is used between the aircraft and its covered UAV nodes, in order to achieve fast multi-beam multicast transmissions. The above MAC scheme has important applications in practical airborne networks. Simulation results showed that compared to existing 802.11 MAC scheme, our MAC has better performance in terms of network throughput and packet delay. Our future work includes MAC design with full-duplex transmission and anti-jamming algorithm.

References

1. Nagase, F., Mitsugi, J., Nakayama, M., Ueba, M.: Ku band mobile multimedia satellite communications system for trains. In: ICSSC, AIAA-paper-2003-2205 (2003)
2. Cheng, B.-N., Block, F.J., Hamilton, B.R., Ripplinger, D., Timmerman, C., Veytser, L., Narula-Tam, A.: Design considerations for next-generation airborne tactical networks. IEEE Communications Magazine **52**(5), 138–145 (2014)
3. Bekmezci, I., Sahingoz, O.K., Temel, Ş.: Flying ad-hoc networks (fanets): A survey. Ad Hoc Networks **11**(3), 1254–1270 (2013)
4. Lee, H.-C.: Ku-band link budget analysis of UAV with atmospheric losses. In: 25th Digital Avionics Systems Conference, 2006 IEEE/AIAA, pp. 1–8. IEEE (2006)
5. Vilzmann, R., Bettstetter, C.: A survey on MAC protocols for ad hoc networks with directional antennas. In: EUNICE 2005: Networks and Applications Towards a Ubiquitously Connected World, pp. 187–200. Springer (2006)
6. Jain, V., Gupta, A., Agrawal, D.P.: On-demand Medium Access in Multihop Wireless Nnetworks with Multiple Beam Smart Antennas. IEEE Transactions on Parallel and Distributed Systems **19**(4), 489–502 (2008)
7. Chou, Z.-T., Huang, C.-Q., Chang, J.: QoS Provisioning for Wireless LANs With Multi-Beam Access Point. IEEE Transactions on Mobile Computing **13**(9), 2113–2127 (2014)
8. Bao, L., Garcia-Luna-Aceves, J.: Transmission scheduling in ad hoc networks with directional antennas. In: Proceedings of the 8th Annual International Conference on Mobile Computing and Networking, pp. 48–58. ACM (2002)
9. Hu, F., Li, X., Kumar, S.: Intelligent Multi-Beam Medium Access Control in Ku-band for Mission-oriented Mobile Mesh Networks. IEEE Transactions on (Submitted to) Mobile Computing (2015)
10. Nedevschi, S., Patra, R.K., Surana, S., Ratnasamy, S., Subramanian, L., Brewer, E.: An adaptive, high performance MAC for long-distance multihop wireless networks. In: Proceedings of the 14th ACM International Conference on Mobile Computing and Networking, ser. MobiCom 2008, pp. 259–270. ACM, New York (2008)
11. IEEE Standard for Information technology–Telecommunications and information exchange between systems Local and metropolitan area networks–Specific requirements Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications. IEEE Std 802.11-2012 (Revision of IEEE Std 802.11-2007), pp. 1–2793, March 2012