Airborne Networks with Multi-beam Smart Antennas: Towards a QOS-Supported, Mobility-Predictive MAC

Xin Li, Fei Hu, Lei Hu and Sunil Kumar

Abstract Airborne networks require throughput-efficient MAC for mission-oriented communications. The use of multi-beam smart antennas (MBSAs) could provide the network with better throughput performance since all beams can send out data concurrently. In this paper, we propose a two-layer MAC design for MBSA-based airborne network. In the upper layer, we use TDMA-like schedule control to separate the packet collision domains in multi-beam data transmissions. In the lower layer, we use the CSMA/CA based scheme that is compatible with conventional 802.11 protocols. Such a two-layer scheme significantly reduces the packet contentions and thus improves the throughput. In addition, in order to support mission priorities in the network, we introduce the QoS-oriented MAC control in both upper and lower layers. Furthermore, a mesh network time synchronization method is proposed to guarantee the beam synchronization. A Hierarchical Dirichlet Process (HDP) enhanced Hidden Markov Model (HMM) is used for mobility prediction in each beam (direction) of a node. These approaches could better exploit the benefits of MBSAs. The simulation results show that our proposed MAC protocol outperforms the standard 802.11 DCF and general MBSA-based MAC designs. The validation of the QoS control, synchronization and prediction schemes are also evaluated. It turns out that these schemes could greatly improve the overall performance of the airborne networks.

Keywords Airborne networks · Multi-beam smart antennas (MBSAs) · MAC · QoS · Synchronization · HDP-HMM

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1 Introduction

1.1 Multi-beam Antenna Airborne Networks

Airborne network performance is important in modern battlefields. Generally, an airborne network consists of wireless nodes (e.g., aircrafts, unmanned aerial vehicles (UAVs), etc). Figure 1 shows a typical scenario. Such a network has a wireless mesh network (WMN) topology. The large aircrafts serve as mesh routers (MRs). The nodes can change mission areas. The data to be transmitted in the WMN could be in multimedia format, such as video or images of different terrains. Those MRs form a wireless backbone with high data rate links among them. Other planes, usually UAVs, are regarded as mesh clients (MCs). MCs are connected to the closest MR directly or through other MCs to a MR.

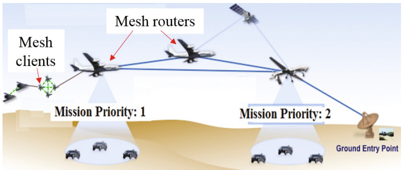

Fig. 1 An illustration of a mission-oriented airborne mesh network.

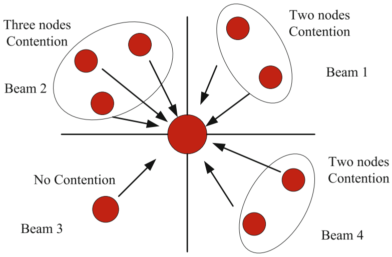

Fig. 2 Channel contention within beams

The Ku-band channel is used in today's airborne links. Ku-band[1], across 10GHz to 15GHz, has conventionally been reserved for satellite communication. Now it has been released for general long-range military or civilian applications. Its high frequency makes the data rate faster than Wi-Fi links. It also provides better anti-interference capability, which is due to its good directionality, especially after using directional antennas. But the main drawback is that it is difficult for such a short-wavelength signal to propagate through some objects such as trees, buildings, vehicles. This means that the signal can suffer from high path loss when no clear line-of-sight (LOS) is present.

Nowadays, the antenna technologies have made great progress. The size of the multi-beam antennas could be very small. It is feasible to equip the aircrafts in today's airborne networks with multi-beam smart antennas (MBSA). It enables cost-effective, concurrent multi-beam transmissions. Thus it significantly improves the WMN throughput.

1.2 Mission-Oriented Mobile Networks

The mission-oriented network has two important features: (1) Priority-aware communications: If any node captures important RoI data (such as an intrusion event), its traffic is marked with a higher priority than general scene data; (2) Predictable mobility trajectory: any node can establish a state transition model based on its history communication patterns. Unfortunately, none of the existing MBSA MAC protocols supports the above mission-oriented communications. Even though in higher layers such as routing layer and transmission layer, the protocols could support QoS, the performance of the network is still poor. There is a demand of the MBSA-based MAC layer which is able to handle both the QoS and node mobility.

In this paper, we propose an efficient MAC design for MBSA-based airborne networks. We design a hierarchical MAC for multi-beam antenna communications. In the lower layer, we propose the enhanced distributed/point coordination function (DCF/PCF) scheme. In the upper layer, we use time-slot-based overlay MAC control scheme. We then propose the time synchronization scheme to ensure the beam and node synchronization in multi-beam concurrent transmissions. Finally, beam communication pattern prediction model is used to predict the node mobility and plan the beam queue sizes.

The rest of the paper is organized as follows: In Section 2, we review some relevant work. The hierarchical MAC layer design is presented in Section 3. Section 4 provides our time synchronization scheme. Section 5 discusses the mission QoS control. The HDP-HMM based node mobility prediction is explained in Section 6. The simulation results are shown in Section 7. Section 8 has the concluding marks.

2 Literature Review

There has been much research work on directional antenna MAC designs. However, most of them simply assume that the antenna could communicate in only one direction each time [2]. With the development of antenna technology, researchers start to consider multi-beam antennas for high-frequency (such as millimeter-wave or Ku-band) communications. Among those works, [3] proposed a hybrid MAC protocol which assumed only 802.11 distributed coordination function (DCF) was used. This is not suitable to some contemporary MAC implementations (such as 802.11e) that emphasize the use of point coordination function (PCF).

In [4] a study on QoS-based MAC is conducted in Wi-Fi. It designed a set of polling-based MAC control protocols. Note that only PCF mode is improved in [4] compared to standard 802.11 protocols. The DCF mode has not been explored in multi-beam antennas. In [5] a distributed, receiver-oriented MAC with multibeam antennas, is designed. However, many practical MAC issues are not considered in [4] and [5]. The QoS support is not discussed there either.

3 Two-Layer Hierarchical MAC Design

3.1 Higher Level MAC

In the higher layer, we use a coarse time slot management to divide the time into different intervals. Each interval is called a superframe. It only allows one node to be the receiver or the sender. The reason of separating the collision domains (by only allowing one node to receive data from all beams), is that existing CSMA-based MAC tries to give each node equal chance to access the medium, which has been shown to significantly under-utilize the nominal network throughput [6], especially when there are very different sending rates among the neighbors. Another shortcoming of existing 802.11 protocols is that they do not give the nodes that need to help to relay other nodes$'$ traffic more opportunities to access the resource, and hence generate a suboptimal resource allocation. The TDMA-like MAC can also help to handle prioritized flows by controlling slot allocations among nodes.

We use a time slot T to divide the time into different superframes. Note that T is a very coarse time duration and is much larger than the clock synchronization error. Usually during time T, the node could send/receive several packets. If one node takes one role (e.g. being a receiver) in a slot, this node may not be the same role in the next slot, since the role selection is based on probability calculations. This approach thus guarantees fairness between different nodes.

As mentioned before, in each slot, there is only one node allowed to be the receiver and all the remaining nodes are transmitters. The receiver node is called as the ‘star’ node in this paper. The ‘star’ node could also be a transmitter. Obviously, being the ‘star’ node means that it could achieve the maximum throughput within the specific time slot T. Thus one main issue in the higher layer is how to choose the ‘star’ node. When we try to address this issue, we need to make a balance between the total throughput of the network, the data priority and the fairness between the nodes.

We assume that each node in the network has its own ID. For simplicity, we assign an unique integer number to each node ID. The IDs in a neighborhood are known to each node by using neighbor discovery protocols. Each node in a MAC neighborhood can calculate a pseudo-random hash function for each node ID nearby:

$$Position(i) = Hash(ID(i), timestamp), i = 1, 2, ..., N \tag{1}$$

The value of the Hash function is normalized between (0, 1]. The variable $timestamp$ is the current time. It serves as the random function seed. A node with $ID = J$ wins the time slot only if the following equation holds true. In other words, the node with the maximum hash result wins the slot occupancy.

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

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. When we need to consider the QoS for different kinds of data, we should make some nodes have higher chances to be the ‘star’ node than others.

3.2 Lower Level MAC

The latest 802.11 standards (such as 802.11e) recommend the use of PCF for schedule control of each neighbor′s transmissions. Such a centralized control can poll each node to ask for desired data rates for each neighbor. In our study, we also keep PCF phase in the superframe for a few reasons: first, the existence of PCF is compatible with the latest 802.11 MAC standards; Second, in the above-mentioned upper MAC layer, we have selected a node as the star node, which is the only receiver or sender in that time slot. Naturally the star node can serve as point coordinator (PC) in the PCF mode.

From the above PCF mode in the upper layer, it seems that we could establish an effective MAC layer scheme simply based on the hash function. However, there are still some challenging issues. Figure 2 shows one possible problems. From the figure we see that in beams 1, 2 and 4, there are more than one node that want to send packets to the star node. According to the basic principles of MBSA communication [3], each beam can only communicate with one node at one time. So the problem is how to solve the contentions within the beam. The lower MAC layer needs to be compatible with the traditional CSMA/CA backoff scheme. Meanwhile, the channel contention within the beam could be addressed by the CSMA backoff algorithm.

In this paper, we propose an enhanced PCF / DCF scheme for the lower layer, which is shown in Figure 3. In the enhanced PCF phase, the ‘star’ node first sends out QoS query messages to the other nodes within the beam area to ask for the QoS information. The transmitting nodes reply with the QoS response messages. If there are more than one sender in one beam, the contention is solved in the collision resolution phase. Then, the star node knows the priority level of the data from each beam.

In the enhanced DCF phase, the first enhancement we made (compared to conventional DCF) is that we control the backoff timer for concurrent multi-beam transmissions. Unlike the conventional 802.11 DCF operations that use random backoff after each DIFS, here we use multi-beam antennas that require all nodes to be ready for receiving data simultaneously. To achieve such a requirement, first, all neighbors which are supposed to receive the data from the star node should synchronize their clocks (later on we will discuss our clock synchronization scheme); second, we need to make the entire node (including all of its beams) perform CW-based backoff together, instead of performing backoff in each beam individually. This is because that we cannot guarantee that the entire node is under accurate timing control if each beam waits for different contention windows (CWs). Particularly, we need

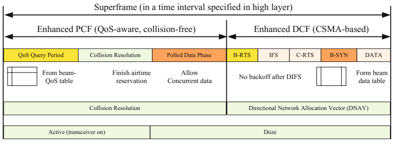

Fig. 3 Enhanced PCF and DCF in each superframe

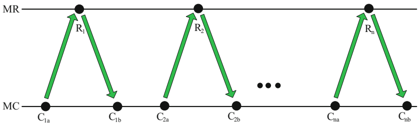

Fig. 4 Message exchange for synchronization

to remove CW-based backoff after DIFS for beam-synchronized communications. However, we still need to keep backoff timer for 802.11 compatibility.

The CW waiting time is expressed as:

$$W\_time = Random(seed) \times Delta\_Delay \tag{3}$$

4 Network Synchronization

As shown in figure 4, when a MR replies to a message from a MC, it checks the timestamp from the packet that contains the time at which this message is sent out. Meanwhile, MR knows its local time. So it is easy for the MR to figure out the time from the MC to MR. In the response message, MR tells MC the round trip time (RTT). The RTT is expressed as:

$$\varTheta_i = C_{ib} - C_{ia} \tag{4}$$

The clock offset of the ith round trip is estimated as the mean of the time difference between MR and MC, which is:

$$\varDelta_i = \frac{(R_i - C_{ia}) + (R_i - C_{ib})}{2} \tag{5}$$

The time in MC can be estimated as:

$$T_{MC} = T_{MR} - \varDelta + \varTheta \tag{6}$$

where $\varDelta = \frac{1}{N}\sum_{i=1}^{N} \varDelta_i$ and $\varTheta = \frac{1}{N}\sum_{i=1}^{N} \varTheta_i$.

5 Mission QoS Control

In airborne networks, the applications are mission-oriented, which means that different applications have different QoS requirements. So the MAC layer should support QoS control. Since our proposed MAC has two layers, we design QoS control for the two layers respectively.

5.1 Upper-Layer QoS Control

In mission-oriented networks, we assume that the applications have different priorities. In the upper layer, we assign nodes with different priorities with certain weights. According to [5], one of the effective approaches is that the priority is represented by the winning probability of the node:

$$P_i = H(ID(i), t)^{1/\omega_t} \tag{7}$$

$H(ID, t)$ is the function used in equation (1), while ω_t is the weight we assigned to the node.

5.2 Lower-Layer QoS Control

In the lower layer, our goal is to exploit the benefit of MBSA. For VBR, the desired airtime a node could have is [4]:

$$\Omega = \left(\mu + \sigma\sqrt{\frac{1-\xi_{VBR}}{\xi_{VBR}}}\right) \times \frac{SF}{R_{ch}} \tag{8}$$

Here ξ_{VBR} is the individual nodes tolerable degree ($0 \leq \xi_{VBR} < 1$) for insufficient airtime. SF is the length of SuperFrame, while R_{ch} is channel capacity.

Likewise, for CBR, the desired time will be:

$$\Omega = \mu(1-\xi_{CBR}) \times \frac{SF}{R_{ch}} \tag{9}$$

To sum up, based on equation (8) and (9), we could adjust the airtime of each node to meet QoS requirements.

6 Intelligent Communication via HDP-HMM

Airborne networks often transmit surveillance video streams among them. In the upper MAC layer, the entire interval should be dedicated to useful data transmissions. It will seriously decrease the communication efficiency if we ask the upper layer to exchange neighboring node arrival information frequently. Therefore, each node should use other ways to prepare the beam transmissions. The node state estimation and mobility prediction will be a good approach to low-overhead communications. A good news is, for mission-oriented communications the system typically has predictable mobility [7]. In the following descriptions, we will discuss our proposed HDP-HMM based prediction scheme.

HMM [8] can be used to deduce the internal state transition even if the observed values have noise or even missing data. In finite HMM, the system mode can only switch between pre-set finite number of states. Finite HMM can be simply described as a generative process as follows:

$$Z_t|Z_{t-1} \sim \pi_{Z_{t-1}} \tag{10}$$

$$y_t|Z_t \sim F(\theta_t) \tag{11}$$

We need to extend conventional finite-state HMM to an infinite-state scenario, where the number of states could change from time to time. Here we build *infinite* HMM via Dirichlet Process (DP):

$$G_0 = \sum_{i=1}^{\infty} \beta_i \delta_{\theta_k}, \quad \theta_k \sim H \tag{12}$$

The above DP-HMM adapts to *variable-state* Markov chain. However, it has a serious drawback: It assumes that the transition spectrum has non-overlapping support. This can cause large Markov state subspace and intolerable HMM convergence time. To reduce the prediction time and remove redundant states, we define a hierarchical specification $G_j \sim DP(\alpha, G_0)$, and G_0 itself is a draw from a $DP(\gamma, H)$. Therefore, we can extend (12) to a HMM with a prior distribution of hierarchical DP (HDP) as follows:

$$\begin{cases} G_0 = \sum_{l=1}^{\infty} \beta_i \delta_{\theta_k}, \ \beta|\gamma \sim DP(\gamma, H) \\ G_j = \sum_{l=1}^{\infty} \pi_{ji} \delta_{\theta_k}, \ \beta|\gamma \sim DP(\gamma, H) \end{cases} \quad and \ \theta_k \sim H \tag{13}$$

7 Performance Evaluation

In this section, we show the simulation results of our proposed MAC protocol. To evaluate the network performance, the two-layer MAC design in Section 3 is implemented. We also estimate the performance of the time synchronization and prediction schemes.

7.1 Simulation Setup

In our simulation model, we assume that there are 15 nodes in the network. Each node is equipped with a MBSA that contains 4 beams. All beams in one node could send out data simultaneously. The link capacity is set to be $2Mbps$ in each beam. So, ideally, the maximum data rate that one node would achieve is $2Mbps \times 4 = 8Mbps$. The size of each packet is 1500Bytes. The average slot length in the upper layer is 100ms. In the following results, we mainly use network throughput and average packet delay to be our performance indicators.

7.2 Simulation Results

Figure 5 shows the throughput of the network with the average packet arrival rate. In Fig.5 we compare our proposed MAC protocol with another two schemes: traditional 802.11 DCF and multi-beam DCF (MB-DCF).

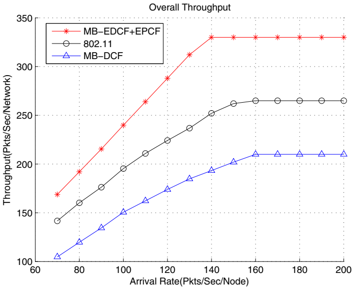

Fig. 5 Network Throughputs Comparison

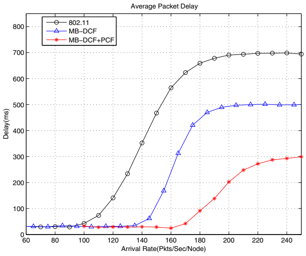

Fig. 6 Network Delay Comparison

We can easily see that our proposed scheme has the highest throughput compared to the remaining two ones. The conventional 802.11 DCF has the lowest throughput.

Figure 6 shows the average delay performance. It is also obvious that the proposed MAC has the shortest average time delay, while 802.11 DCF has the longest one.

In Fig.7, we show the benefit of the QoS control. In our model, all the nodes could send out data with 3 different priorities. The blue curves represent the throughput of data with different priorities when we do not have any QoS control in MAC layer. In that case the performances of those flows are similar to each other. However, with QoS control, the performance is greatly different with respect to priorities, which are shown in red curves. Our scheme could guarantee the QoS of the applications with higher priorities.

The synchronization scheme is also evaluated in this paper. Figure 8 displays the effect of using our proposed time synchronization algorithm. The throughput increases dramatically while the delay drops greatly. It is close to the performance under accurate clock synchronization.

Figure 9 shows the effect of using node state prediction schemes, including ARMA (Auto-Regressive Moving Average) and HMM based prediction schemes. As we can see, both HMM and ARMA achieve a higher throughput than no-prediction case. This is because each node can prepare the data queue better after predicting the

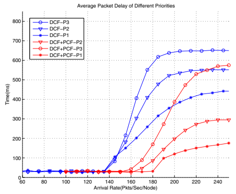

Fig. 7 Network Delay for Different Priorities

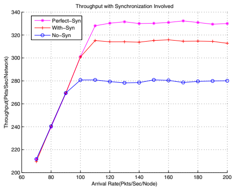

Fig. 8 Throughput with Synchronization

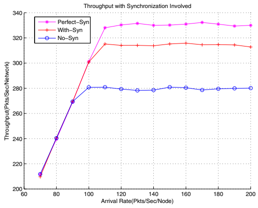

Fig. 9 State prediction Schemes

traffic profile and node mobility behaviors. Figure 9 also shows that both HMM and ARMA have the performance that is closer to the ideal prediction case. But HMM outperforms ARMA in most cases since it can overcome the impacts of noisy, missing or even erroneous measurements. HMM can deduce the internal state from the inaccurate measurements. While ARMA simply assumes that the measurement represents the internal true state.

8 Conclusions

In this paper, we have proposed an two-layer hierarchical MBSA-based MAC design. Out MAC layer protocols can be used in the MBSA-based airborne network. We presented the 2-layer MAC architecture. Then the QoS support and time synchronization approach were proposed, which could greatly improve the performance of the network. Finally we used HDP-HMM to predict the node mobility. This helps the star node to better prepare the queue content and schedule order. Our results have validated the proposed MAC designs.

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