Systematic Medium Access Control in Heterogeneous Airborne Networks With Multi-Beam and Single-Beam Antennas

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***Abstract*—In this research, we propose a throughput-optimal, heterogeneous (with both scheduled and random communications) medium access control (MAC) strategy for a typical airborne network with the following features: (1) *hierarchical topology*: the higher height level has a small number of powerful aircraft with multi-beam antennas and long-distance links (>50km); the lower level has high-density UAVs with <10km link distance and single-beam (directional) antennas. (2) *Ku-band (15GHz) links*: Such a cm-Wave frequency has better directionality but higher fading loss than 5.8GHz radio (used in the low-level UAVs). Our proposed MAC scheme allows the UAVs to use uplink/downlink MAC schemes to communicate with the high-level aircraft. It consists of 3 critical parts: (1) *Multi-beam, long-distance MAC for aircraft-to-aircraft links*: A dynamic, scheduled MAC is proposed to fully explore multi-beam features to achieve high-throughput transmissions. The beam locking/synchronization issues are also solved. (2) *Downlink/uplink MAC for aircraft-UAV communications*: In the uplink (UAVs to aircraft), we propose to use enhanced 802.11n with fame aggregation and compressive sensing based request polling; In the downlink, prediction-based, differentiated transmissions are used for reliable multi-beam multicast communications; (3) *MAC for UAV-UAV links*: among the high-density UAVs, we extend 802.11e DCF through parameter adjustment for 10km-link access. Our simulation results have shown the significant performance improvement over conventional MAC protocols.**

***Index Terms*—Medium Access Control (MAC), Airborne Networks, Multi-Beam Antennas, IEEE 802.11.**

I. Introduction

A. Directional Airborne Networks

With the popularity of unmanned aerial vehicles (UAVs) and environment surveillance applications, airborne networks (ANs) have become important platforms for wireless transmissions in the sky. Our research targets a typical hierarchical AN as shown in Fig.1. It has the following 6 features: (1) *Multi-level network*: In the lower level, a large number of UAVs form a high-density network with a link distance of 500m to 10km. They operate at 5.8GHz (or other free licensed bands). In the higher level, a small number of aircraft use higher power levels to reach a communication distance of longer than 50km. (2) *Multi-beam Antennas*: the aircraft are equipped with multi-beam antennas. Those antennas can *simultaneously* communicate with multiple neighbors located in different directions

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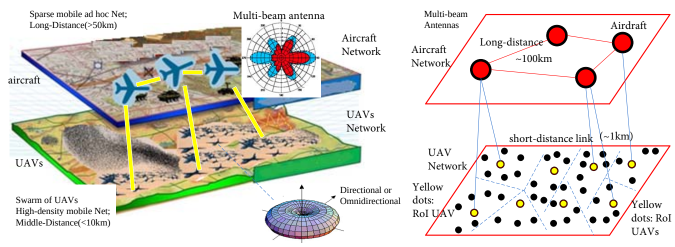


Fig. 1. Airborne Network: Multi-level, Directional, Mobile, High-frequency (Ku-band)

(beams). The lower level UAVs are equipped with simpler antennas, which are either omnidirectional or single-beam directional antennas. An UAV typically uses omnidirectional antenna to *carrier-sense* possible signal sources, and then uses directional antenna to deliver the data. (3) *Aircraft-UAV Information flow*: Some UAVs are selected as region-of-interest (RoI) nodes. Each RoI node typically flies in a pre-defined interested area. Other UAVs use multi-hop relays to send data to the RoI nodes, which then use uplink channel to send data to an available aircraft. An aircraft can use downlink channel to broadcast commands (such as assigning new surveillance tasks) to the UAVs. The aircraft use high transmission power to relay data among them, and one of them, called gateway node, can directly communicate with a satellite or a ground station. (4) *wireless mesh network (WMN) architecture*: a WMN typically consists of small number of powerful nodes (called mesh routers) and larger number of nodes (called mesh clients). As we can see from Fig.1, an AN has a typical WMN architecture. (5) *Ku-band links*: Compared to Wi-Fi, Ku-band ($\sim$15Ghz) signals are weaker to line-of-sight (LoS) blocking [1]. However, it has better *energy concentration*, that is, it can focus on specific direction with better signal quality. With the use of high-gain directional antennas, the Ku-band can easily reach $>$100km away with good signal directionality. (6) *Mobility*: The AN has a highly mobile topology. However, since each aircraft can reach $>$100km away with good signal quality, its topology control schemes can tolerate general flying speed ($<$600mph) [2] as long as the destination node is still within the signal coverage of a specific beam of its antenna.

In this paper, we focus on medium access control (MAC) design in the above airborne mesh network (AMN). The main goal of MAC protocol is to avoid transmission collisions among neighbors (typically 1-hop range). Achieving a high throughput is the main purpose of MAC design since a poor MAC scheme can significantly decrease network throughput due to frequent transmission collisions.

Obviously, we cannot just simply use scheduled or random access schemes in the entire AMN. For example, a carrier sense multiple access (CSMA) based random access scheme (such as IEEE 802.11 standards), may be effective in Wi-Fi. However, it will cause frequent collisions when used in long-distance links (such as aircraft-to-aircraft links) due to the potential misdetection of signals sent from 100km away. In such a long link, it takes "long" time (>0.1ms) for the remote signals to reach the current node, since the radio propagation delay cannot be ignored. Likewise, a scheduled access scheme (such as TDMA) cannot achieve high-throughput among high-density UAVs due to the difficulty of managing time slots among so many UAVs. It can also cause huge bandwidth waste when no data is sent for an allocated time slot.

Such a MAC should also be able to achieve the efficient uplink / downlink transmissions between an aircraft and its lower level UAVs. For example, since the aircraft link has higher throughput than the UAV links (the aircraft uses multi-beam, high-gain antennas), in the *uplink* (UAVs-to-aircraft), it is better to aggregate the UAVs' packets into one larger packet, in order to reduce the communication rounds of DATA/ACK packets. In the *downlink* direction, the MAC needs to support multi-beam multicast operation since an aircraft needs to tell a group of UAVs about new surveillance tasks. One issue of such multicast operation is, how do we adjust the bit rates in each beam (direction) based on its corresponding beam quality? Obviously we cannot simply use the same bit rate for each multicast beam.

To the best of our knowledge, there is no *systematic MAC* design that is suitable to the above AMN architecture (Fig.1). We will propose a new MAC scheme based on the above mentioned 6 features of AMN, especially its heterogeneous architecture with both multi-beam and single-beam antennas.

B. Heterogeneous MAC Solution

Our solution is to design an integrated, heterogeneous MAC to achieve high throughput in three different links (as shown in Fig.2): Aircraft-to-aircraft (A2A), aircraft-to-UAVs (A2U), and UAV-to-UAV (U2U). The A2U links include both uplink (from UAVs to a nearby aircraft) and downlink (from an aircraft to its covered UAVs) transmissions. It has *heterogeneous* nature since we use different medium access schemes based on the topology features of aircraft network and UAV network. Particularly, we use scheduled, TDMA-like, multi-beam MAC to achieve high-throughput, long-distance A2A transmissions, and use enhanced, CSMA-based MAC scheme for high-density, shorter distance (<10km) U2U communications.

Specifically, the **contributions** of this research consist of 3 important aspects listed as follows:

•**(A2A links)** *Multi-beam-oriented, token-and-schedule based medium access strategy for high-throughput A2A links*: First, the A2A communications fully explore the benefits of

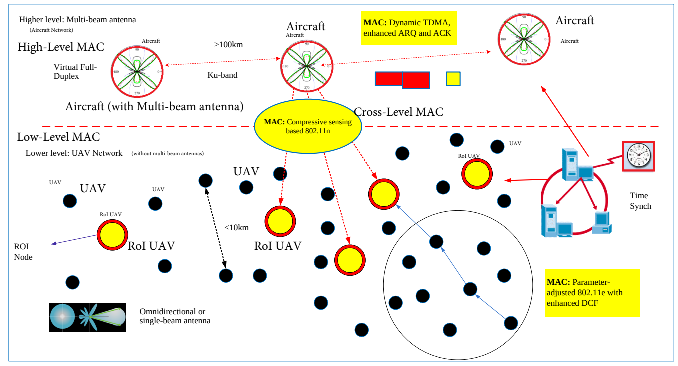


Fig. 2. Big Picture of Heterogeneous MAC

multiple beams to achieve *concurrent* neighborhood transmissions. Second, we propose to use both tokens and time slots to control the schedule of transmission (Tx) and receiving (Rx) phases in each A2A link. Here the time slot duration is over 10ms, which is longer than conventional TDMA slot length (<1ms). The *aggregated* traffic in one slot over the fast A2A link (>10Mbps) can be sent out for a long distance (>100km). We use variable slot durations in order to adapt to diverse traffic profiles. Third, we reduce the Tx/Rx switching operations to overcome the long round trip delay (RTT) of long-distance A2A links. Our goal is to maximize the link throughput and avoid data collisions among aircraft.

•**(A2U links)** *Compressive Sensing based CSMA extensions with multi-beam multicast considerations*: In the *uplink* direction (from RoI UAVs to the aircraft), to avoid time-consuming UAVs polling (i.e., asking each UAV whether or not it has data to send), we propose to use compressive sensing based 802.11n extension for fast polling response collection. The 802.11n supports frame aggregation, which fits the uplink traffic aggregation requirements. In the *downlink* (aircraft to RoI nodes), we focus on the multi-beam multicasting issue and propose to use channel quality prediction for beam-specific rate adaptation.

•**(U2U links)** *Directional CSMA extensions for high-density, middle-distance (500m 10km) UAV network*: The parameters such as ACK timeout in 802.11e, will be adjusted for better UAV-to-UAV communications. We will also overcome antenna-caused deafness and capture issues under single-beam directional antennas.

Other contributions: Our work will also address other issues in the above heterogeneous MAC design, such as *beam locking problem*, which refers to the fact that an aircraft cannot switch to Tx mode if one of its beams is still receiving data (in Rx mode).

Paper Organization: In section II, other related work is summarized; Section III describes some system assumptions. The heterogeneous MAC is detailed in Section IV. Section V then provides performance analysis results, followed by Section VI conclusions.

II. RELATED WORK

An airborne network typically has multi-level topology for complex environment surveillance applications [2]. It needs novel MAC protocols for real-time, high-throughput, long-distance aircraft communications [3]. Today, Ku-band (∼15GHz) has been applied to non-satellite applications [1]. By using high-gain, directional antenna, Ku-band links could have a high wireless communication reliability ($BER < 10^{-5}$), even for a distance of over 200 km [1]. Ku-band signals have better signal focusing capability than Wi-Fi signals due to its less signal scattering. Thus they have less interference to neighbors since the signals do not diffuse in a wide scope. But they are weak to LoS (line-of-sight) blockage due to their shorter wavelength than Wi-Fi. This fact requires that MAC design should pay more attention to the coordination among neighbors (such as scheduling *concurrent* data transmissions in multiple beams), instead of just focusing on the interference avoidance as what conventional 802.11 does.

Directional MAC schemes have been studied in some works (see [4] for a good survey). However, most of them assume a *single-beam* antenna. That is, the antenna can steer its beam to one direction only at any time. In our AMN targeted here, we assume the use of multi-beam antennas for A2A communications. All beams are synchronized to send or receive data each time. We do not allow some beams to send (Tx) and others to receive (Rx), due to the *inter-locking* nature among all antenna elements [5].

There are only a few works on multi-beam MAC design. In [5] a hybrid MAC is proposed to achieve *concurrent packet reception (CPR) and concurrent packet transmission (CPT)*. It changes conventional 802.11 distributed coordination function (DCF) to beam-oriented DCF with beam RTS/CTS exchanged between nodes. In [6], point coordination function (PCF) is enhanced with beam-specific data scheduling. A distributed CSMA-based scheme is considered for multi-beam communication in [7].

All the above multi-beam MAC schemes have big drawbacks when applied in our AMN. First, they do not consider the support of long propagation delay (in long-distance A2A links). Second, they do not have synchronized node coordination scheme for *concurrent* multi-beam sending or receiving. Third, they do not support the multi-beam multicast between the aircraft and UAVs with beam-specific data rate adjustment. Up to this point, there is no work on the MAC design that is suitable to the hierarchical AMN architecture shown in Fig.1.

This work is a significant extension of our previous short conference paper [8]: (1) Completeness: While in [8] it has only provided a basic MAC scheme with a few simulation results, this paper has a complete A2A, U2U, and A2U MAC solution with comprehensive simulation-based protocol validations. (2) Pipelined transmission and beam blocking /non-synchronization issues: We have also solved the multi-beam pipelined transmission issues in A2A MAC such as ACK non-synchronization problem. (3) Using Rateless codes: This work has seamlessly integrated Fountain codes with multi-beam forwarding, and provided the detailed fountain codes based transmission scheme; (4) Parameter adjustments in U2U MAC and deafness problem solution: While in [8] it just simply mentioned a CSMA-based U2U MAC, this paper has detailed CSMA parameter adjustment plan as well as the corresponding solution to deafness problem; (5) Compressive sensing based A2U communications: We have also introduced the compressive sensing based MAC polling concept to greatly reduce the communication overhead in A2U MAC protocol.

III. System Assumptions

We assume that the AN forms a WMN with mesh routers (aircraft), and mesh clients (UAVs). A RoI node is a special UAV that flies in the center of a particular region called RoI. The coverage of any region is pre-defined based on surveillance requirements. Usually, the military UAVs are flying at the height around 500 meters. Each UAV only covers a small RoI. Nevertheless, the aircraft in the higher level are able to reach as high as 1000 meters. Most of the time these aircraft are flying between 7000 and 10000 meters. The multi-beam antenna deployed on each aircraft has 4 beams which enable the node to either transmit data to or receive data from at most 4 other nodes.

Due to their good line-of-sight (LoS) signal propagation in the sky with GPS satellites, the airborne nodes can easily use GPS receivers to achieve global time synchronization among them. If GPS is not available, many synchronization schemes could be used [9] [10]. Note that we do not need an accurate synchronization scheme here since our time slot model uses coarse time resolution and has long duration (>10ms).

A *multi-beam antenna* has the following important features [5]: (1) it can easily detect the incoming signals in any beam by using Direction of Arrival (DoA) estimation. (2) If it wants to switch from transmission (Tx) to receiving (Rx) mode, or from Rx to Tx mode, *all beams must be switched together to the same mode.* This is mainly because the all antenna hardware elements are under the same antenna coefficient matrix's control. If one beam is in Rx while another beam is in Tx, the main lobe of the Tx beam will seriously interfere with the side lobe signals of the Rx beam.

Once the multi-beam antenna switches to Tx mode, it is important for all neighbors that are supposed to receive data from this node, to synchronize their communications. That is, all those neighbors should switch to Rx mode simultaneously, in order to efficiently utilize the bandwidth. If a neighbor enters Rx late, it may miss some data from the sender. Likewise, if the multi-beam antenna is in Rx mode, all neighbors that have data for this node, should prepare their sending data concurrently.

On channel model: In this research we assume the channel model is Rayleigh fading model, which is also called as small-scale fading model. It can describe the poor channel conditions experienced due to fading. Due to the fast movement of aircraft/UAVs, it is reasonable to use such a channel model in each radio link.

IV. Heterogeneous MAC Design

A. Big Picture

The big picture of our MAC design is shown in Fig.3. Our design follows 3 principles as below:

Principle 1: Uplink MAC with frame aggregation can serve as the bridging point from the UAV network to the aircraft network: The UAV network has much lower data rate than the aircraft network due to two reasons: First, an UAV has

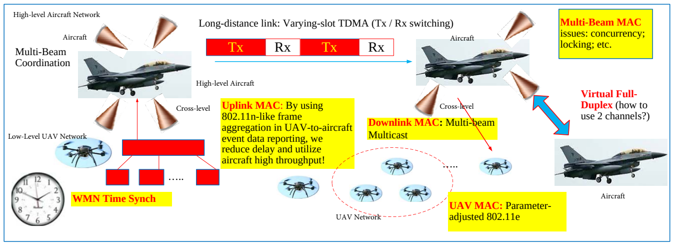


Fig. 3. Proposed heterogeneous MAC solution

much smaller size and more limited communication capability than an aircraft. Second, the multi-beam antenna in each aircraft enables high-speed links (>10Mbps in each beam). The aircraft can easily pump a big amount of data into the high-speed Ku-band links.

Principle 2: The link distance determines the performance boundary of CSMA-based (random) MAC and TDMA-like (scheduled) MAC: The link distance matters. When the distance is too long (>50km), the random access based MAC schemes cannot work efficiently since it is difficult to detect the radio signal collisions.

Principle 3: The MAC scheme should fully explore the multi-beam capacity to improve the network throughput: The biggest benefit of multi-beam antennas is that we can improve the throughput for N times (in ideal case) if an antenna has N beams that all send out data at full capacity. If we integrate such a multi-beam data distribution with Rateless codes (RC), we will have a higher efficiency since RC can decompose a packet into multiple pieces that go to different beams.

B. MAC for Aircraft Network (with A2A links): Multi-Beam, TDMA-like (Scheduled) Communications

Although long-distance wireless communications have been investigated in some works, especially in long-distance Wi-Fi (WiLD) for countryside networks [11] [12] [13], our system has a few challenging issues not considered in previous works: (1) *Explore multi-beam antenna's benefits* (2) *Overcome beam locking* (3) *Overcome ACK non-synchronization*

Here we emphasize that our A2A MAC is just TDMA-*like*, not the same as conventional pure TDMA scheme, due to the following two reasons:

(1) *Longer slot duration*: Although we also define time slots and schedule different Tx/Rx phases, each phase (a slot) is much longer than the slot in conventional TDMA: instead of using only hundreds of micro-seconds (μs) as the slot length, each slot in our scheme that is allocated to a Tx or Rx phase, could be hundreds of milli-seconds (ms) long to handle the aggregated traffic from RoI nodes.

(2) *Variable slot length*: Here we use a variable-length Rx/Tx phase, which could be tens or hundreds of ms long depending on the amount of data to be handled in each phase. It will cause much delay if the multi-beam antenna frequently switches between Rx and Tx modes. Figure 4 shows two cases that should not use equal sizes of Tx and Rx phases. The first case shows that the reverse direction has just tiny ACK packets, which means that node A should operate in Tx for a longer time than in Rx mode. The second case shows that an aircraft that relays data from two upstream nodes is supposed to spend longer time in Tx than in Rx (assume that A and B send out the same amount of traffic). This is because that C can use *separate* beams to simultaneously receive (Rx) the data from A and B. But it only uses one beam to send (Tx) the aggregated traffic to node D. Thus it needs longer time in Tx.

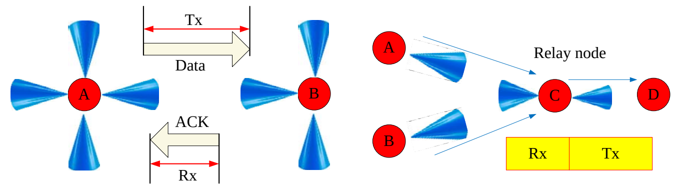


Fig. 4. Examples on unequal-time Rx/Tx modes

1) Aircraft MAC Operation Phases: Basically, there are two operation phases in the aircraft MAC. In node scheduling phase, each aircraft sends tiny messages (thus they can easily get through the network) to the gateway. Such a message tells about its transmission request, and includes required Tx time and QoS parameters. Then the gateway notifies each node about their Tx and Rx schedules. Note that each node just needs to report Tx time instead of Rx, since other nodes may have data for this node. The data transmission phase includes alternate Tx and Rx modes with guard time between them (to account for multi-beam antenna switching delay and other processing time).

(1) Node Scheduling Phase: After a gateway node receives the data request from each node, it can simply determine each node's transmission order based on a hash function with the input parameters of node ID and the timestamp:

$$Order(i) = Hash\left(ID\left(i\right), timestamp\right), i = 1, 2, \ldots, N \tag{1}$$

Here the hash function is a special function with the result between 0 and 1 [14]. Timestamp is the current clock time in the whole network. Using timestamp as a seed, we can make the result become a random value. A node with $ID = J$ is the winner of the current transmission cycle if it gets the maximum hash value:

$$arg \max_{1 \leq i \leq N} Hash(ID(i), timestamp) = J \tag{2}$$

If a node is the winner, its data can get out first. As shown in Fig.5, node 1 has the maximum hash value (=1), it will use 3 beams to concurrently send out data to nodes 3, 2, and 5. Note that in the meantime node 4 can send data to node 2 since node 2 is in Rx mode anyway. In Fig.5 we can see that node 2 can now send data to node 1.

To determine which node should transmit data next after node 1 finishes Tx phase, we can simply check the second highest hash value and let it transmit data (in Fig.5 it is node 3). likewise, we can continue to check the third highest hash value, and so on.

Node priority: If different nodes are assigned different weights (ω_i) to reflect their QoS demands and node priorities

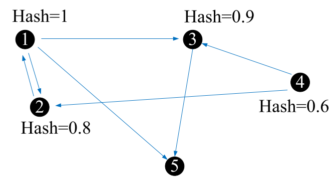


Fig. 5. Hash function based node Tx priority

in an aircraft network, we can use the following hash function to calculate the winning probability of any node with $ID(i)$:

$$P_i = Hash\left(ID\left(i\right), t\right)^{1/\omega_i}, \sum\nolimits_i \omega_i = 100\%$$

The reason of using the above exponential format is because the winning probability of a node i is proportional to its weight percentage, that is [15]:

$$P\left[arg \max_{1 \le n \le N} Hash(ID(n), t) = i\right] = \frac{\omega_i}{\sum_{n=1}^{N} \omega_n} = \frac{\omega_i}{100\%} \tag{3}$$

Therefore, a node with higher weight will have higher chance to get the maximum hash value (=1).

(2) Data Tx/Rx Phase: after the gateway node notifies each node about its Tx/Rx schedule, the nodes enter TDMA-like, scheduled communications. The gateway arranges the nodes' Tx/Rx modes based on a token-based, pipelined transmission (see Fig.6). It follows 3 rules as below:

Rule 1: Multi-beam antenna oriented transmissions: Any node can use all of its beams to concurrently transmit or receive data. In Fig.6, if node A is scheduled to send out data with higher priority (based on the above hash results), it should communicate with both B and C at the same time instead of just one of them. Otherwise, node A wastes its multi-beam capacity. Even though $A-C$ link time is shorter than $A-B$ time, A cannot switch to Rx mode until it finishes the longest Tx duration (here it is $A-C$ link).

Rule 2: Token control: In any link (say $A-B$), there is a unique token (a tiny control message). A node cannot enter Tx mode until it has held the token for that link. The token ensures that a node alternates between Tx and Rx modes (i.e., accessing the channel in a TDMA-like pattern). It immediately releases the token if it finishes data transmission.

Rule 3: Pipelined scheduling: As we can see from Fig.6, 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, Fig.6 also shows that a gateway maintains a *node status* table, which has the profile information on traffic to be sent in each beam of a node. 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). A node can use neighbor discovery process to easily find out which neighbor can be reached in which beam. For example, a notification message may have the following fields: 0ms, To B; 1.1ms, From C; 1.5ms, To D;...

2) Handle "Beam Locking" Issue: Although multi-beam significantly improves a node's capacity by pushing data to multiple directions simultaneously, there exists the beam locking issue. As shown in Fig.7, node A has a big amount of data to be sent in a particular beam. The entire node is locked in Tx mode, and other beams cannot receive data (i.e., enter Rx mode) even though they have finished Tx phase. This is because that they are waiting for the ending of the big data beam in node A. Node B is also locked (in Rx only) since one of its beams continuously gets data from A.

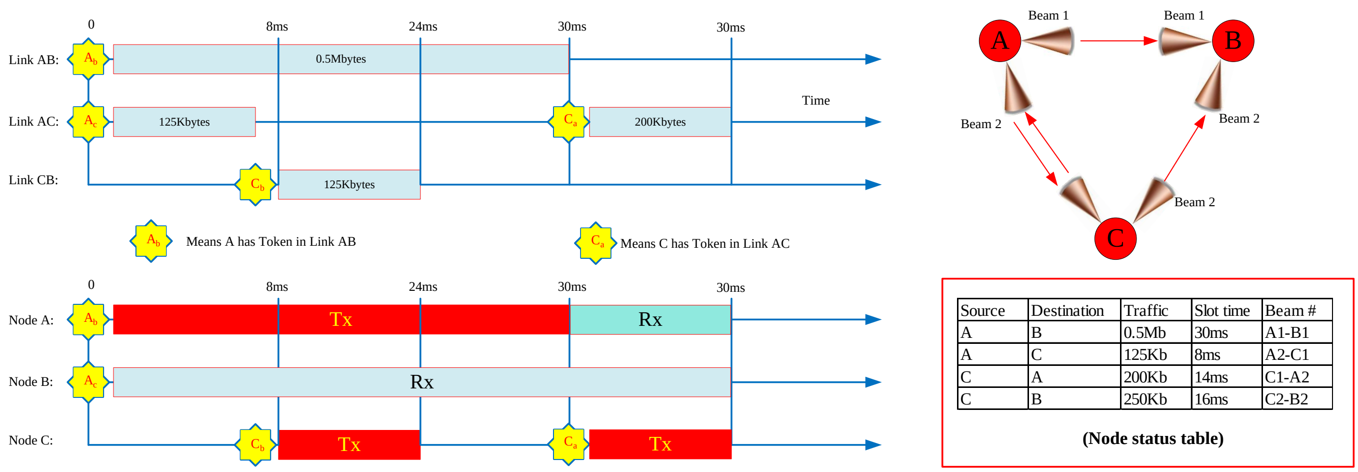
To avoid such an issue, we propose the *detour beam* concept. As shown in Fig.8, each node maintains a table called *beam channel status table* (BCST). The BCST includes not only its own channel quality (measured in SNR or BER) in each beam, but also the channel conditions in the nodes that are the neighbors of both itself (node A) and the destination (node B). For example, nodes C and D all have beams facing B. We call C and D as *detour nodes*. Then node A's BCST should maintain the channel conditions in $C-B$ and $D-B$ links.

3) Handle ACK Non-synchronization Issue: This issue is related to the above beam locking issue. It can occur in the following two cases: (a) many-to-one, and (b) one-to-many transmissions, as illustrated in Fig.9.

In either case, as long as there is a significant difference among beam link qualities or sending rates, we could have ACK non-synchronization problem. This is because any multi-beam node cannot switch Tx/Rx modes until it has finished transmissions in all beams. In Case (a), node C cannot send ACK back until it has finished Rx phase. However, *the slow rate in the poor-quality channel* (which is the $A-C$ link), makes C unable to switch from Rx to Tx until its data is finished. But the ACK transmissions require that node C switches from Rx to Tx. Since node B may set up a fast ACK timeout due to its good link quality (in link $B-C$), it cannot wait so long. Thus it will have one or multiple ACK timeouts and then performs unnecessary retransmissions.

To overcome the above issue, we propose the following solution: (1) first, each link should estimate its link quality based on the receiver's feedback. For example, node C in Case (a) can piggyback the BER value in its ACK packets. Then each sender should adjust its sending rate and traffic load in order not to hold the channel for too long. (2) Second, we require that all senders use an ACK timeout value not based on its own channel quality. Instead, they use the maximum possible RTT value among all links. By this way we can avoid the ACK timeouts in fast channels.

4) Explore Multi-Beam Relay via Enhanced Fountain Codes: Another important contribution of our work is: we further explore the benefit of multiple beams by integrating multi-beam transmissions with our invented *priority-aware Raptor codes* [16], to achieve real-time, reliable data transmission. As shown in Fig.10, our Unequal Error Protection (UEP) based Raptor codes can use outer/inner encoding schemes to protect different data flows with multiple priorities. The higher priority packets have more coding redundancy to achieve a



Source	Destination	Traffic	Slot time	Beam #
A	B	0.5Mb	30ms	A1-B1
A	C	125Kb	8ms	A2-C1
C	A	200Kb	14ms	C1-A2
C	B	250Kb	16ms	C2-B2

Fig. 6. Multi-beam Scheduled Transmission Process (an example)

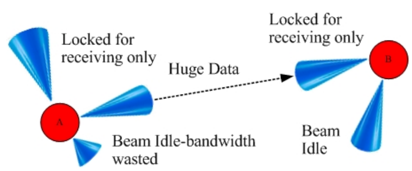
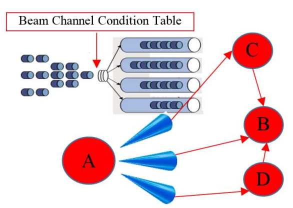


Fig. 7. Beam Locking issue



	Attribute	Helping Timer	Channel quality to source	Channel quality to Target	Max Data Rate
B	Target	-	BER =10^{-4}	-	3Mbps
C	Detour	40ms	BER =10^{-3}	BER =10^{-4}	4Mbps
D	Detour	20ms	BER =10^{-2}	BER =10^{-2}	2Mbps
E	Detour	Busy	-	-	-

Fig. 8. Detour beams to solve beam locking

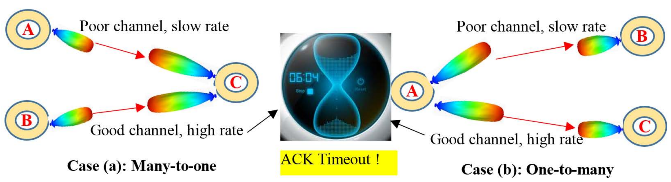


Fig. 9. ACK Non-synchronization Problem

higher reliability (i.e., with stronger packet recovery capability in the receiver side). *Then those encoded packet pieces are dispatched to different beams of a node*. The beams with better link quality (lower BER) are allocated with more of higher priority packet symbols.

In general Raptor codes, we first decompose the packet into pieces (called *symbols*). Those symbols pass an outer encoder (typically a LDPC code), and then pass a weakened LT code as the inner code. They can be parameterized by (K, C, $\Theta(x)$), here K means the number of the source symbols, C is the outer code result (with block size L). Thus we have L intermediate symbols after outer encoder. The last $L-K$ symbols are redundant symbols. $\Theta(x)$ is the degree distribution of LT codes. The L intermediate symbols are encoded with LT code to generate N encoded symbols. Those N symbols pass the lossy wireless channel. Even some of them are lost, we can still recover the original K source symbols as long as enough number of symbols are received. Assume N_r is the number of received encoded symbols. The decoding failure probability, $P_\epsilon(\xi_r)$, is very low. Here $\xi_r = N_r - K$ reflects the encoding overhead (redundancy level) of Raptor codes, and we have [17]:

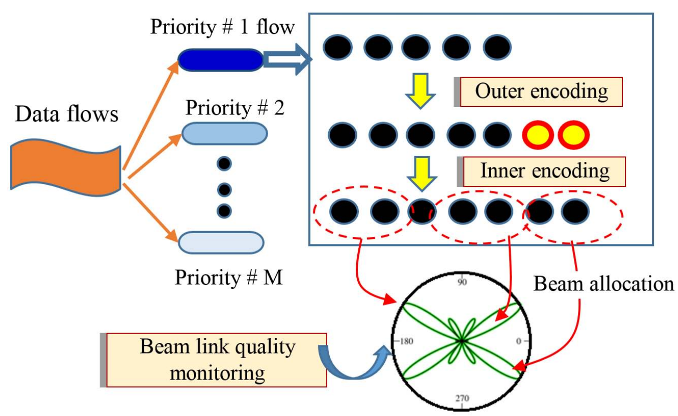


Fig. 10. Prioritized Raptor Codes based multi-beam data allocation

$$P_\epsilon(\xi_r) = 0.85 \times 0.567^{\xi_r} \tag{4}$$

The average received overhead ρ, is the percentage of the extra added symbols among the source symbols. It is [17]:

$$\rho = (1/K)\sum_{i=0}^{\infty}(i \cdot (P_e(i-1) - P_e(i))) \approx 2/K \tag{5}$$

As we can see, we just need to use 2 extra symbols to achieve a nearly 100% success recovery rate since the extra added symbols (in average) should be: $K \times \rho = 2$.

In our *priority-based Raptor codes*, we generate more extra symbols for higher priority symbols, and those symbols should be sent by the beam with higher link quality. Suppose L_1

represents the highest priority, L_2 the second, and so on. And we have K_i source symbols with priority L_i. Also denote $\xi_r(K_i)$ as the number of extra symbols for priority L_i. Then the minimum coding overhead $\rho(K_i)$, which is the percentage of extra symbols among the total source symbols for priority L_i , should be:

$$\rho(K_i) = \frac{K_i \times PER + \xi_r(K_i)}{(1 - PER) \times K_i} \tag{6}$$

Here PER is the packer error rate (PER). Our UEP-based Raptor coding scheme [16] can use PER feedback from the receiver to adaptively adjust the overhead of Raptor codes for data with different priority levels. The higher priority symbols can be dispatched to the beam with better link condition in that direction.

C. MAC for UAV Networks (with U2U links): Parameter-adjusted 802.11e Enhancement

The UAV network has much higher density than the aircraft network, and the above TDMA-like MAC is difficult to manage since distributed TDMA in a large-scale UAV network needs a global coordinator as well as an accurate timing synchronization scheme among many UAVs. Moreover, the data exchange among UAVs is not very often since most times they just send data directly to the higher-level aircraft. Thus using dedicated time slots could waste much bandwidth in the UAV network. Random access MAC (such as CSMA-based one) is a better option since it does not need a global schedule manager, and the short UAV links ($< 10km$) will not bring many signal transmission collisions due to its short propagation delay (this is different from the long aircraft links).

We propose to extend IEEE 802.11e protocol to support U2U communications. The 802.11e has an improved DCF mode (compared to 802.11b) for better QoS support. However, 802.11e does not support 10km links well due to its assumption of 300m Wi-Fi coverage. It also does not have efficient support of directional antennas. Since UAVs could be equipped with single-beam antennas, deafness and capture issues have to be solved in the enhanced 802.11e.

We first discuss some popular parameters used in 802.11 protocols. As shown in Fig.11, when node A has a DATA packet for node B, it first listens to the channel. It must finish the channel sensing within DIFS (Distributed Inter Frame Space). If the channel is busy, it enters a backoff waiting phase. The duration of waiting time is called a CW (contention window). It consists of a series of small time units, called Slot Time (S). This is the *quantum* (minimum time unit) for defining other durations (such as DIFS). S is PHY-dependent constant. In 802.11b it is $20\mu s$, while in 802.11e it is only $9\mu s$ [18]. Note that S is different from general time slot length. Here S is a shorter time unit than general TDMA slots ($> 100\mu s$) or Tx/Rx durations (>20ms).

In Fig.11, τ is the propagation delay (light speed). 2τ is the RTT. After node B receives DATA, it sends out ACK after SIFS (Short Inter Frame Space). SIFS separates the end of the DATA reception and the start of the ACK transmission. Note that we have the following relationship:

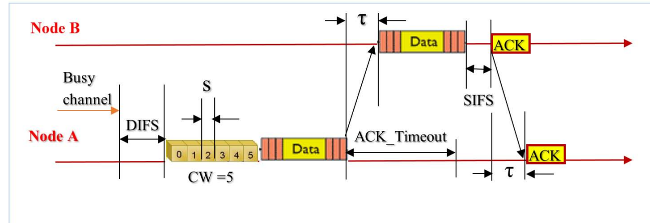


Fig. 11. Different CSMA time durations during DATA/ACK transmission

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

As we can see from Fig.11, conventional 802.11 standards set up ACK timeout value based on short Wi-Fi link distance (<300 meters). For longer U2U links, we will have frequent ACK timeouts, and then node A will retransmit the frame after the timeout.

The 802.11 protocols assume that the signal propagation time, which is defined in *AirPropagationTime* variable, has a maximum value of $1\mu s$ (only enough for 150m). When ACK timeout occurs, the default maximum retransmission times is 7. IEEE 802.11 uses RTS/CTS to handle hidden terminal issue. The RTS sender waits for CTS timeout interval for the return of CTS. Again, CTS timeout can occur when the distance is too long. And the maximum repeated RTS retries is 4 times by default.

1) Adjustment of ACK Timeout: The latest 802.11 standard [19] recommends that ACK timeout should include the following 3 components: (1) *SIFS*. The receiver needs a minimum of SIFS between the reception of DATA and the ACK feedback; (2) S_{STD} (standard slot time, $9\mu s$ in 802.11e); (3) *PCLP* (Physical layer convergence procedure), this refers to the processing overhead of PHY-to-MAC data passing (in the sender) and the overhead from MAC to PHY (in the receiver). 802.11 requires that the PHY layer passes an *aPHY-RXSTART-Indication* message to MAC layer before *ACKTimeout* expires (Fig.12). Otherwise, the ACK will be discarded. 802.11 expects that the RTT is less than $1\mu s$. But it also recommends the margin of $5\mu s$ for the CCA *(Clear Channel Assessment)*. Here CCA time is the sum of all times except light propagation delay. $5\mu s$ is good for 750m of light propagation. Therefore, the standard *ACKTimeout* value is not enough for U2U links longer than 750m. We thus adjust 802.11e *ACKTimeout* value as follows:

$$ACKTimeout = SIFS + S_{STD} + PCLP + RTT \tag{8}$$

2) Adjustment of the Slot Time: The motivation of defining slot time (S) is as follows: if two nodes transmit data in different slots (maybe those two nodes have the maximum distance to each other, which is around 750m in 802.11), they should have enough time to detect signal collisions, and then freeze and backoff to avoid the collision. Therefore, the slot time S should be at least larger than the sum of the following components: (1) time to allow CCA, (2) Tx/Rx

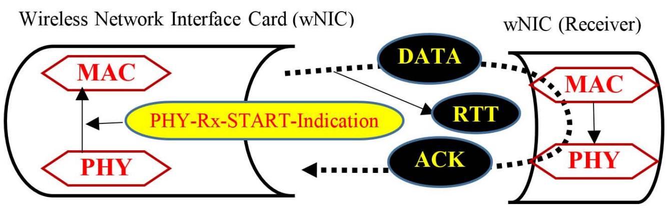


Fig. 12. Calculation of ACK Timeout

switching delay, (3) the light propagation time (single-trip, for signal collision detection), and (4) local protocol (MAC/PHY) processing delay.

3) Adjust DIFS: The purpose of setting SIFS and DIFS is to separate the transmission times between DATA, ACK, PCF control frames, and DCF data frames. It can prevent the collisions between the transmission of DATA and the reception of ACK. DIFS is longer than SIFS. Since it needs to consider the waiting time of ACK (for the last DATA frame), it needs to be longer than RTT. Therefore, after we adjust the slot time (S) based on the above formula, we can adjust the DIFS based on 802.11 recommendation: $DIFS = SIFS + 2 \times S$.

4) Deafness Avoidance for UAVs with Single-Beam Antennas: MAC design under single-beam directional antennas has been studied for some years (please refer to [19] for a good survey). Deafness is a serious issue in directional MAC. Assume a 3-node communication scenario as shown in Fig.13. When a source (node A) wants to send data to the destination (node B), it needs the help of a relay node (R). Ideally, we wish to see that R alternates between A and B, in other words, R talks with A to get some packets, then changes its antenna direction to talk with B to relay the data.

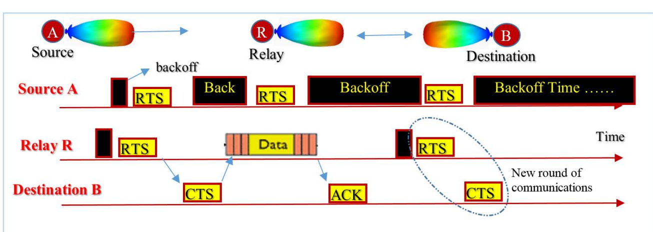


Fig. 13. Deafness under Directional Antennas

However, the deafness can occur as follows: when R uses *4WH* (4-way handshake: RTS/CTS/DATA/ACK) to talk with the destination B, the source A tries to hold the relay node R after it finishes one round of 4WH. However, when A tries backoff a few times (because it cannot receive CTS from R), its backoff window can become large. As shown in Fig.13, when it finishes the long-time backoff, and sends RTS again to R. Thus R maybe get engaged again with B for a new round of communications. R's single-beam antenna still faces B. Thus A will not be able to communicate with R.

The real issue is that R's single-beam antenna always faces B during its 4WH communication, and A does not know what time R finishes its 4WH. A's backoff window gets exponentially increased each time that R's antenna is not facing itself (no CTS is sent back to A).

Note that deafness issue can cause cascading effect since the higher layer (such as TCP) may think the link has congestion and stops to send out new packets. Deafness can cause path delay chain effect (i.e., increasing the accumulative delay after multiple hops) in large-scale networks [20].

Our solution to R's antenna deafness is to utilize a low-cost *analog signal detection technique*, called *tone-based energy detection*. Tone signal is not a *digital* signal. It can be broadcasted via low-cost *analog* circuit. And any nearby node can easily detect such a narrow-band analog signals with specific frequency (f_{tone}) and a narrow bandwidth (B_{tone}, less than 1KHz) [19] [20]. Such a narrow-band tone does not need to pass demodulator and decoder since it is not a digital signal. In our targeted airborne network applications, we have noticed that the CDL (common Data link) at Ku-band has enough unused bandwidth for the generation of multiple tone signals [21].

In this work, we propose to generate multiple tone signals in such a band. And we can ask each RoI node to maintain a table that holds the mapping relationship from a tone signal $[f_{tone}, B_{tone}]$ to a node ID. The RoI node can broadcast such a tone identification table to its nearby UAVs. Thus each UAV knows which node ID launches each tone after using a simple analog circuit to detect the tone energy.

In our scheme, as shown in Fig.14, each time a sender-receiver pair finishes a 4WH round, they can immediately launch a tone signal. Then the source node can detect those tone signals even when it is in backoff state, since the tone signal just needs *analog* circuit to detect the signals. Then S can terminate its backoff phase earlier, and issue a RTS for R. It thus has a higher chance to capture R than the case shown in Fig.13. Note that in UAV network each node has a low-cost omni-directional antenna to detect the incoming traffic from all 360° directions. R can capture A's RTS and turns its single-beam antenna to A. Then A sends data to R, which later on relays the data to B.

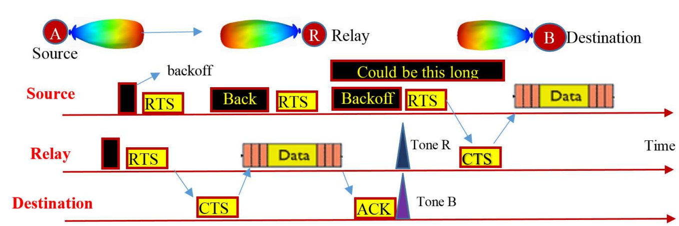


Fig. 14. Avoid Deafness via Ku-band Tones

D. MAC for Aircraft-UAV Links: Frame-Aggregated, Compressive CSMA Communications

The critical links in the airborne network are the ones between aircraft and UAVs since those links deliver surveillance data via uplinks (U2A) and command data via downlinks (A2U). An aircraft keeps certain time in each of its operation phases for uplink and downlink communications.

1) Uplink Transmission (U2A - from UAVs to the aircraft): There are some challenging issues in uplink transmissions, especially about the polling of each RoI UAV to collect their data transmission requests. There could be dozens of (or even more) RoI nodes in the broadcast coverage of an aircraft. If the aircraft simply polls each RoI node one-by-one to ask whether they have data to send, it will waste much time and cause high protocol overhead, especially when there are many RoI nodes. Moreover, those RoI nodes cannot send out their requests simultaneously. Otherwise, there will be many collisions since those nodes generate RF interference to each other. Although 802.11 can use backoff scheme to reduce collisions, when there are many RoI nodes, the CSMA scheme seriously degrades the link throughput. In other words, CSMA does not scale well with the UAV network size due to its random access nature and exponential backoff scheme.

To quickly collect different RoI nodes' requests, we propose to use *compressive sensing* (CS) concept to allow concurrent, uplink request transmission among large number of RoI nodes. CS-based MAC has been shown to be able to significantly reduce the data polling time in a large-scale wireless LAN [22]. This is mainly because 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 operation) to recover the ROI requests. Thus we do not need to worry about the signal collision issues in the air. It is a *concurrent* transmission (thus it is fast). And the aircraft can quickly handle the signals since analog signals do not need digital signal processing (such as demodulation, decoding, etc.)

Particularly, we propose a CS-based uplink data collection scheme as shown in Fig.15. As shown in Fig.15, since the multi-beam antenna allows simultaneous reception in all directions, we can avoid beam-by-beam polling. If there are multiple nodes in any beam, the previously broadcasted schedule information tells which node should go first in that multi-request beam. Finally, the aircraft broadcasts an aggregated ACK, which tells what requests have been successfully received from which node IDs.

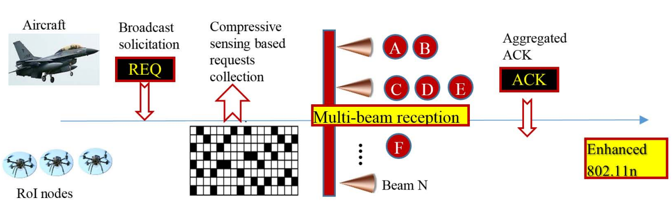


Fig. 15. Uplink: Compressive sensing based request polling

The compressive request signal model is shown in Fig.16. Here $h(\tau, t)$ is the *channel impulse response function* for each U2A link. $\mathbf{X} = [x_1, x_2, \ldots, x_N]$ is a binary signal vector. When a node has data to report, $x_i = 1$; otherwise 0. Note that we do not need to know the exact math model of $h(\tau, t)$ since it has only two cases: zero (no request), and a non-zero value (with request). Therefore, a simple threshold detection can find which nodes have data requests. In Fig.16, $\mathbf{A}$ is compressive sensing measurement matrix (also called sensing matrix). As long as the sensing matrix $\mathbf{A}$ meets restricted isometry property (RIP), we can exactly recover the signal $\mathbf{X}$, which is a sparse signal with sparsity K, that is, it has only K significant elements. This fits practical airborne surveillance application where only a small number of RoI nodes have important RoI data to report. For example, a UAV stores most sensing data *locally*. Only when it detects an abnormal event (such as an environment intrusion event), it will immediately tell its RoI node. In Fig.16, $\mathbf{n}$ is the noise vector. We can use l_1-norm to recover $\mathbf{X}$ to know which nodes have requests:

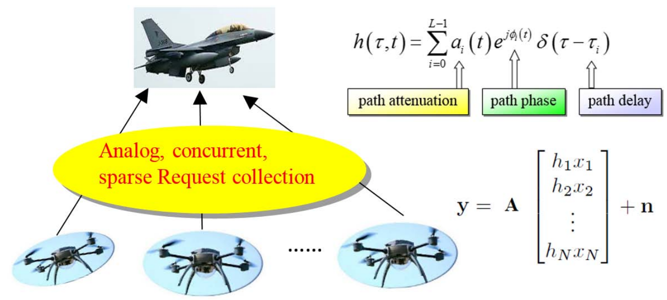


Fig. 16. Principle of compressive sensing based signal collection

$$\min_{\mathbf{X}\in R^N} |\mathbf{X}|_{l_1}, s.t.\ \mathbf{Y} = \mathbf{AX} + \mathbf{n} \tag{9}$$

2) Downlink transmissions (A2U links: Aircraft to UAVs; using multi-beam multi-cast): In the downlink direction, we can simply use broadcast to announce a message, or use unicast to allow an aircraft to pinpoint a specific RoI node. We need to use *multi-beam multicast (MBM)* transmissions. A highly reliable 1-to-M communication scheme is required in order to deliver important commands to a specific group of RoI nodes. For example, we may need to ask some specific RoI nodes to change their surveillance tasks, or change the sensing modes, or even update their information filtering models in order to detect different abnormal event patterns in those RoIs. We cannot afford to lose any of those multicast messages since they may hold re-tasking commands.

It is necessary to adjust the power level and sending rates in each beam direction based on the link channel quality. For higher quality links, we can use lower power levels (thus save some energy). We can also increase the sending rate in a good link to more efficiently use its bandwidth. In some beam directions, if the link quality is poor, we need to increase the power level to overcome the noise impacts, and use a lower data rate to avoid link congestion and reduce the packet loss.

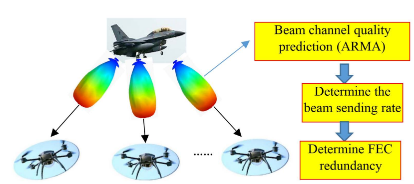


Fig. 17. Downlink MAC: Proactive multi-beam multicast

In any case, it is necessary to use a *link-quality-adaptive* MBM scheme. We thus propose a proactive MBM as shown in Fig.17. Since the link quality estimation needs some type of feedback from the receivers (RoI nodes), we require that each multicast UAV to piggyback their PER (packet error rate) in their ACKs. They should also indicate their mobility speed and absolute position in the ACK such that the aircraft can predict its next position (such as leaving the current beam or not). After the aircraft has the history link state parameters (including PER, mobility, etc.), it will use vector (i.e., multi-variable) AutoRegressive Moving Average (ARMA) model to predict the next round of link state:

$$\sum_{l=0}^{p} A_l y(t-l) = \sum_{l=0}^{q} M_l \epsilon(t-l) \tag{10}$$

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. For analysis convenience, we can convert the above equation to a state-space model involving a transition equation. Thus conventional first-order Markov process can be used. If the aircraft predicts that an UAV will leave its current beam next time, it will store the data in a buffer until it knows the next beam scope that the UAV will move into. It can also increase or decrease its power level based on the new position prediction results.

V. Performance Evaluation

A. A2A MAC Performance

We first test the efficiency of our long-distance A2A MAC protocol that explores multi-beam capacity and uses TDMA-like scheduling. We consider an A2A network with 10 nodes. The distance between nodes is in the range of 100km to 300km. Since the Ku-band A2A links have high data rate, here we set the link speed *in each beam* as 10Mb/s. The packet size is set to 1500 Bytes. Each node has a 4-beam antenna (thus the entire node can have 40Mb/s of data rate) as well as a buffer to store up to 30 packets.

Figure 18 shows the throughput comparisons of those two MAC schemes. Both schemes reach a ceiling after the network gets congested. Here "MB-PCF-DCF" means our proposed multi-beam (MB) MAC scheme with enhanced PCF and DCF functions. The term "LD-TDMA" is referred to as a MAC scheme designed for long distance (LD) transmission. Unlike the proposed MAC scheme in this paper in which the nodes compete for time slots by hash values, the TDMA-like scheme simply assigned the time slots evenly to each node, which is quite resource wasting because some nodes have a lot of packets ready to send while others don't have that many. This could result in waste of time and throughput. In the beginning when the node data rate is less than 100 pkts/sec/node, our scheme has the same performance as CSMA since the network does not have high traffic amount for both schemes. After the node data rate is higher than 150 pkts/sec/node, LD-TDMA throughput is much better than that of CSMA scheme: it is nearly twice as CSMA throughput. Figure 19 shows the delay performance. The average delay of CSMA is always larger than that of LD-TDMA. We can see that CSMA gets congested earlier than LD-TDMA: CSMA starts to have drastic delay increase after 100 pkts/sec/node; while LD-TDMA starts congestion until the rate reaches 300 pkts/sec/node.

B. A2A QoS Performance

Figure 20 shows the throughput performance for different types of data (video, audio, and text). Here we apply our LD-TDMA MAC scheme. In section IV-B we have introduced the use of hash function to determine the transmission order among all nodes. By introducing a weight in the hash function we can give video data a higher priority to access the Ku-band. The audio data has the second highest priority while the text data has the lowest one. In this part of simulation, we suppose 50% of the packets generated by one node are video data packets; while audio and text data occupy 30% and 20% of the total data, respectively. The maximum waiting time in the packet queue is set to 200ms, 500ms, and 1000ms, respectively, for video, audio and text data. If the waiting time is longer than the transmission time of one packet, this packet is automatically dropped in the queue. As we can see from Fig.20, video data has the highest throughput.

Figure 21 shows the delay performance of LD-TDMA with multimedia data. We can see that their delays have similar trends: after reaching the congestion point, they have drastic increase. The video has the lowest delay. However, their delay difference is less than the throughput case. This is because we use the frame aggregation (802.11e) when the UAVs send data to the aircraft. And each aircraft sends out all data during the Tx phase, no matter the data is video, audio, or text.

C. Beam locking scheme

Figure 22 shows the delay performance of beam locking scheme. Please refer back Fig.8 on the concept of detour beam to overcome beam locking issue. As we can see, the delay goes up more quickly if not using beam locking scheme. By using 2-path beam detour, we can decrease the delay for more than 40% when the data amount is larger than 3M bytes. By using 3-path beam detour, we can have more options to deliver blocked traffic. Figure 22 shows that the 3-path delay is less than half of the original non-detour case.

D. On efficiency of TDMA-like A2A MAC scheme

For long-distance A2A communications, we have modeled the *time efficiency* of TDMA-like, scheduled transmissions in section IV-B. Here we evaluate our MAC performance in terms of handling the input/output traffic asymmetry issues in the case of relay communications. The relay node needs to have higher throughput than other non-relay ones in order to forward the aggregated traffic, see Fig.4. Note that here we are not simulating the entire network. We use the scenario shown in Fig.4 (right part) to evaluate our time efficiency model.

Figure 23 shows the time efficiency with different Tx and Rx allocation ratios. The *x-label* represents the ratio of Tx time over Rx time. And the *y-label* is the measurement of *time efficiency* of the relay node. It means the percentage of *effective* transmission time (note that part of allocated Tx/Rx duration may be idle if not enough data is transmitted). We could find that the time efficiency first goes up and then decreases. There exists a peak point.

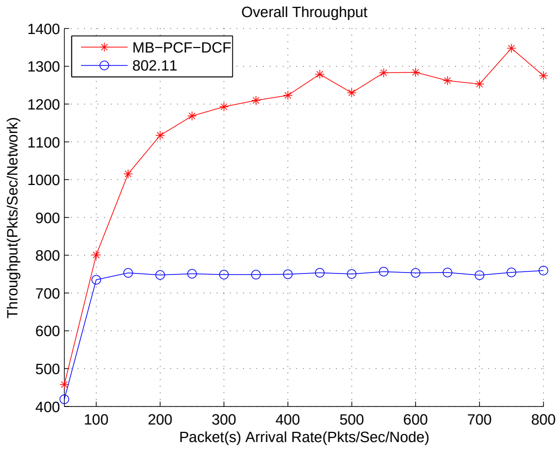


Fig. 18. Throughput performance

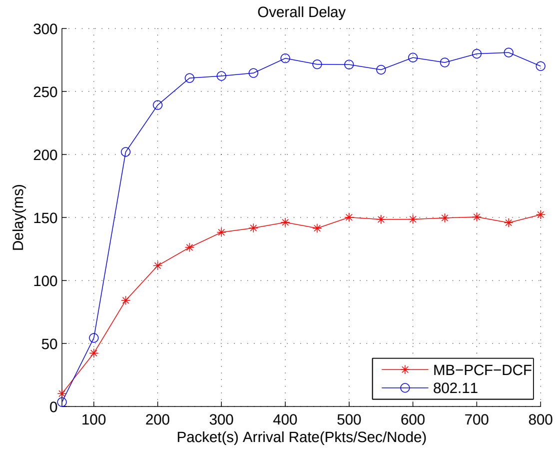


Fig. 19. Delay performance

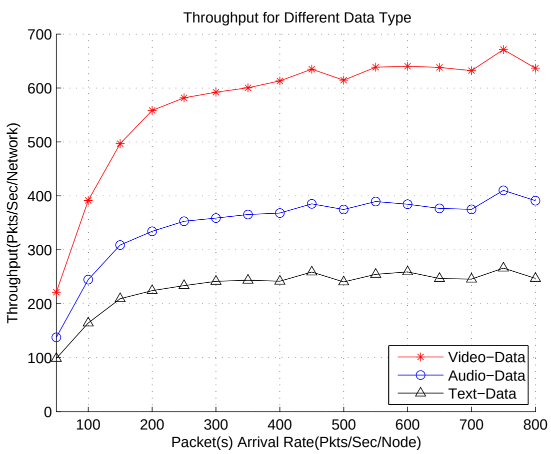


Fig. 20. Throughput of multi-class data

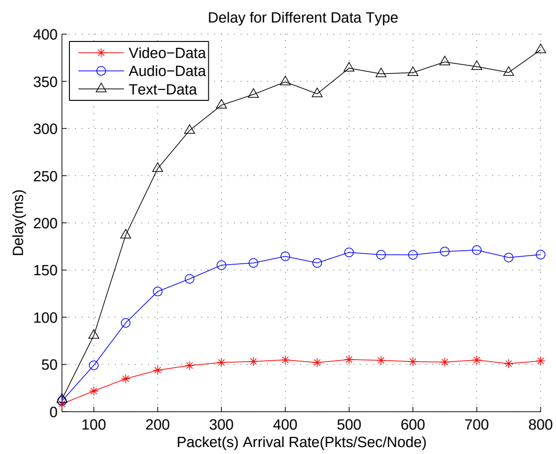


Fig. 21. Delay performance of multi-class data

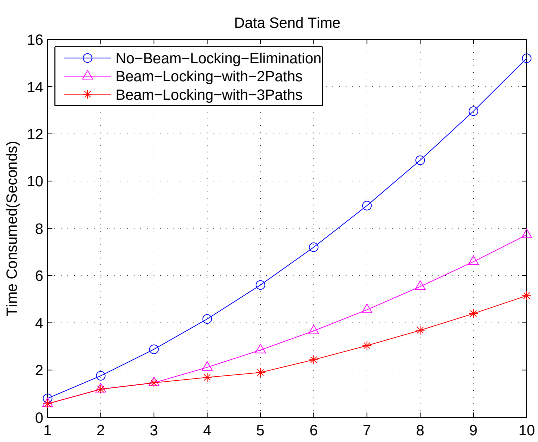


Fig. 22. Beam locking: delay performance

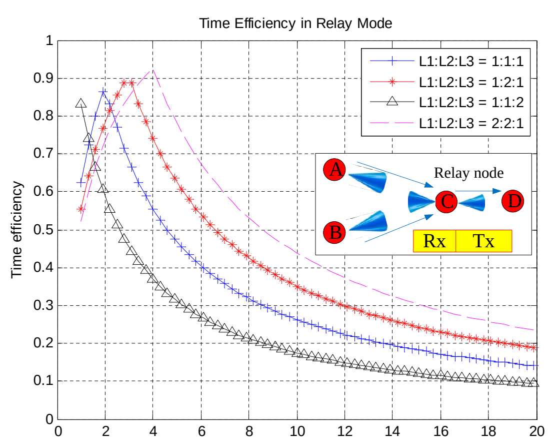


Fig. 23. Delay performance of TDMA-like A2A MAC scheme

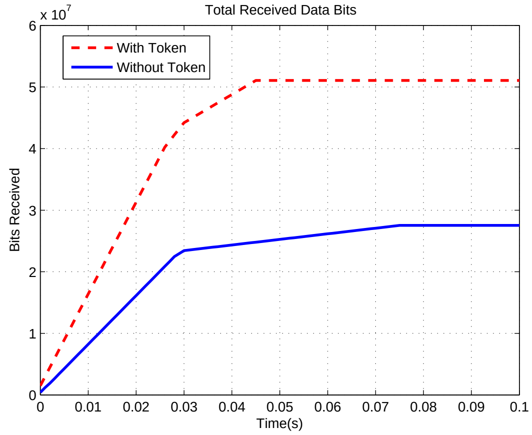


Fig. 24. Throughput of token-based scheme

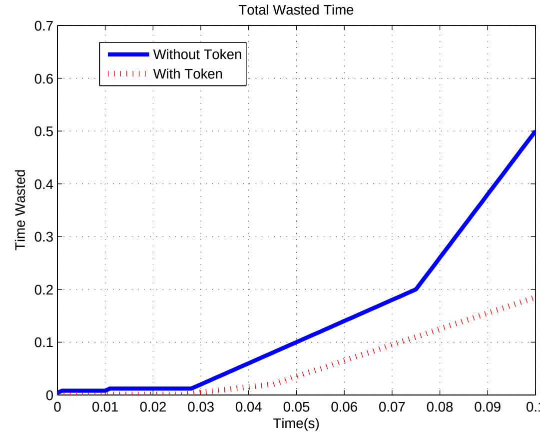


Fig. 25. Delay performance

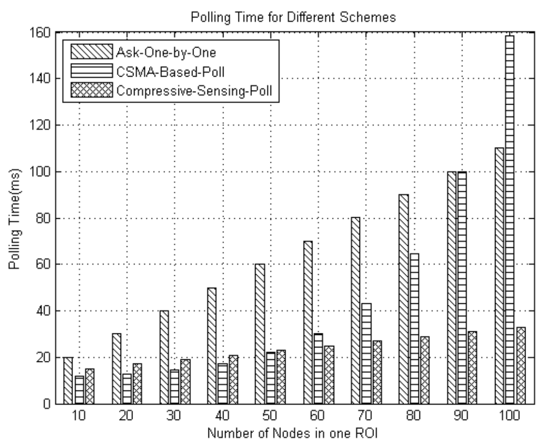


Fig. 26. Polling time comparisons among 3 schemes

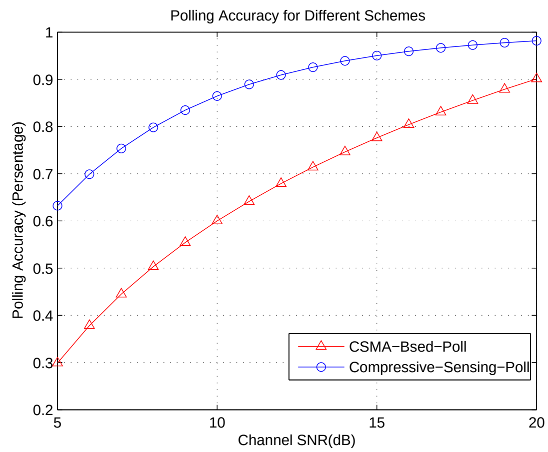


Fig. 27. Polling accuracy

E. Token-based A2A MAC scheme

We then evaluate our pipelined, token-based, scheduled A2A communication scheme (please refer to Fig.3 on an example scenario). Here we present the simulation results, as shown in Figs.24 and 25.

As we can see from Fig.24, The token-based MAC scheme can significantly increase the throughput (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.25, the delay is reduced for more than 50% after a certain time of communications.

F. Compressive sensing based uplink MAC (UAV aircraft) polling control

As described in Section IV.D on the *uplink* transmission (from UAVs to the aircraft), the aircraft will first poll the UAVs to see which nodes have data to send. We have used compressive sensing based polling scheme, which scales well in high-density UAV network. Here we use simulations to verify the throughput efficiency of our scheme.

Figure 26 shows the polling time comparisons between 3 schemes: (1) our *compressive sensing* based polling; (2) *naive one-by-one polling*: in this scheme, the aircraft polls each UAV (in its coverage) one by one to see whether the UAV has data to send in the uplink direction; (3) *CSMA-based polling*: In this scheme, the aircraft first broadcasts a querying message to ask which nodes have data to send. Then the UAVs use CSMA to compete for the channel access. If any UAV wins, it sends its response to the aircraft.

As shown in Fig.26, the compressive sensing based polling scheme has very low overhead (thus has little polling time) even when the network scale is over 100 nodes in the coverage of an aircraft. Simple one-by-one polling scheme has a linearly increased polling time, which is much higher than compressing sensing based scheme when the network size is more than 20 nodes. The CSMA-based scheme has good performance when the network scale is small (<50 nodes). However, when the node density is too high, there will be too many MAC transmission collisions among the nodes due to CSMA's random channel access nature. Thus it has the highest polling time when there are over 100 nodes.

Figure 27 shows the polling accuracy comparisons for CSMA-based and compressive sensing based polling schemes.

Here we use the percentage of correctly reported UAVs among all nodes as the polling accuracy. We aim to verfy that compressive sensing based polling can still accurately find out what nodes have polling requests even though it uses sparse analog signal sampling.

As shown in Fig.27, as the channel SNR becomes larger, the polling accuracy of both schemes keeps growing until reaching 100%. This is an expected result since better channel quality brings more successful uplink communications. The compressive sensing based polling is constantly better than that of CSMA. The reason is similar to the above mentioned one. Moreover, in CSMA based scheme, the response message is transmitted in the form of digital signals (i.e., packets), and thus suffers from many bit errors from fading channels. While in compressive sensing based scheme, the response messages are collected through the sparse, analog signals that suffer less from channel quality. As we can see, when the SNR is 20dB, its polling accuracy reaches 97%.

VI. Concluding Marks

In this work we have proposed a systematic 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). We propose to use variable-length Tx/Rx time slots and scheduled, pipelined communications for sparse, long-link aircraft networks. We have also solved the beam locking issue in multi-beam links. The UAV network uses an enhanced CSMA protocol to adapt to 1km links. 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. No single MAC scheme is the sole winner in such a complex, hybrid network. This is the motivation that we use a hybrid TDMA/CSMA scheme in the whole network. There are still some interesting issues unsolved in the airborne network MAC designs. Next step we will design a new anti-jamming, mission-adaptive MAC for airborne mesh networks.

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