C-ICAMA, A Centralized Intelligent Channel Assigned Multiple Access for Multi-Layer Ad-Hoc Wireless Networks with UAVs

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Abstract

Multi-layer ad hoc wireless networks with UAVs is an ideal infrastructure to establish a rapidly deployable wireless communication system any time any where in the world for military applications. In this tactical environment, information traffic is quite asymmetric. Ground fighting units are information consumers and receive far more data than they transmit. The up-link is used for sending requests for information and some networking configuration overhead with a few kilobits, while the down-link is used to return the data requested with megabits size (e.g. multimedia file of images and charts). Centralized Intelligent Channel Assigned Multiple Access (C-ICAMA) is a MAC layer protocol proposed for ground backbone nodes to access UAV (Unmanned Aerial Vehicle) to solve the highly asymmetric data traffic in this tactical environment. With its intelligent scheduling algorithm, it can dynamically allocate bandwidth for up-link and down-link to fit the instantaneous status of asymmetric traffic. The results of C-ICAMA is very promising, due to the dynamic bandwidth allocation of asymmetric up-link and down-link, the access delay is tremendously reduced.

1 Introduction and Background

To fulfill the Army’s vision of the 21st century digital battlefield[10], we proposed a Multi-Layer Ad-Hoc Wireless Networks with UAVs [6], which will make extensive use of wireless technology, with high bandwidth (45Mbps) links transporting high volumes of multimedia information to ground mobile backbone units. Ground mobile backbone nodes transport to individual soldiers for the multi-area theater.

In this infrastructure using the embedded ad hoc networking mechanism, nodes are able to transport packets across the network in a multi-hop fashion. On top of the multi-hop ground radio network, we propose to construct dynamically a point-to-point embedded mobile backbone network which connects (using separate frequencies from the ground radio network) properly elected backbone nodes using directive antennas. The mobile, embedded backbone network serves a single area (say, a few kilometers in diameter). Multiple UAVs form a Aerial Mobile Backbone to connect different ground mobile backbones. This multi-level physical heterogeneous multi-hop network will provide communications on-the-move for all fighting units in the entire multi-area theater while both “ground backbone” and “aerial backbone” are moving.

Each UAV will support a single area with Phased Array Antenna (PAA) technology to project multiple beams to the ground in a typical cellular pattern. All mobile backbone nodes on the ground within the same beam will use this channel to send and receive information to and from this UAV. In the real tactical environment, ground mobile fighting units are information consumers most of the time. They receive far more data than they transmit. This will cause highly asymmetric traffic between up-link and down-link radio channel of UAV access net. There are three different types of traffic through UAV, (1) UAV relays the traffic from one ground mobile backbone node to another within the same area. (2) UAV forwards the packets from the ground mobile backbone node in it’s own area to the ground mobile backbone node in another area. (3) ground nodes send request packets for information. For example, when soldiers get into a new area, they might send requests with a few kilobits worth of IP packets for geographic information, and the return data is most likely a multimedia file of images and charts of megabits size. So it will be very inefficient to assume in our design a symmetric model for this full-duplex IP data connection.

In this paper we propose a new MAC Layer protocol, Centralized Intelligent Channel Assigned Multiple Access (C-ICAMA) for ground mobile backbone nodes to access UAV. C-ICAMA is also a contention-based channel reservation protocol. All the mobile nodes will compete during the contention period by sending request packet to make reservation. A successful packet will join the polling queue and wait...
and backbone nodes. A variety of clustering algorithms have been proposed for the dynamic creation of clusters and the election of cluster heads in ad hoc wireless networks [11]. The only modification needed here is, that backbone nodes have higher priority to be selected as cluster heads than regular nodes. Spread-spectrum radios permit code division multiple access (CDMA) and spatial reuse across clusters. Within a cluster, we use 802.11 as the Medium Access Control (MAC) layer protocol.

2. level 2: Ground Embedded Mobile Backbone network: Due to the poor performance of ad hoc wireless network where many hops are involved, an embedded mobile backbone was introduced. In the tactical environment, special fighting units like trucks, tanks may carry a lot more equipment than individual soldiers. These mobile nodes, with the help of beam-forming antennas, can offer high-speed point-to-point direct wireless links. So if we select those mobile nodes as backbone nodes, we can establish a ground mobile backbone embedded within the ground ad hoc wireless network.

In this level, we only have ground backbone nodes. Direct point-to-point wireless links are used for the communications among the neighboring backbone nodes.

3. level 3: Aerial Mobile Backbone Network: Each UAV can maintain a station at an altitude of 50 to 60 thousands feet by flying in a circle with a diameter of around 8 nautical miles. With the help of Phased Array Antennas, it can provide the shared beam to the ground to keep line-of-sight connectivity for one area of operation down below. Multiple UAVs fly in the sky to form a mobile backbone with beam-forming technology to connect to each other. With the aerial mobile backbone, we can connect multiple areas of operations together to provide theater-wide communication. All the ground backbone nodes in the same area will access UAV using the MAC layer protocol, Centralized Intelligent Channel Assigned Multiple Access (C-ICAMA). C-ICAMA has an intelligent scheduling algorithm, which can dynamically allocate bandwidth for up-link and down-link to fit the instantaneous status of asymmetric traffic.
3 C-ICAMA in Multi-Layer Heterogeneous Ad Hoc Wireless Network with UAVs

3.1 Existing MAC Layer Protocols

The access to the radio channel is a key issue in an efficient design of UAV Access Net. The protocols used to determine who transmits on a shared channel belongs to a sublayer of the data link layer called the MAC (Medium Access Control) sublayer. Among the many protocols, there are two extremes. One is the "purely-random access" type in which nodes normally send arrival packets right away. The other extreme is the "perfectly scheduled" type in which there is some order allowing nodes receive reserved intervals for channel use. The first approach has a very small delay, but suffers from low throughput. The second approach will have the maximum throughput closed to 1, in order to achieve this, it must pay the expense of the delay for making reservation.

Random access solutions have been widely used for single packet data access. They deal with contentions and collisions by using retransmission of a collided packet at the MAC level. The most effective random access protocols, such as CSMA-CD, can not be used for UAV Access Net because the radio interface can not perform the Collision Detect function.

A good solution combine those two extremes, which is a contention-based channel reservation protocol. Roberts [7] is the first one to propose this type of multiaccess protocol for satellite use in 1973. In his protocol, multiaccess channel is partitioned into reservation and data subchannels by means of time division. Using the Slotted Aloha protocol, each ready station first sends a mini reservation request packet over the reservation subchannel to join a global queue which schedules the reserved time on the data subchannel for the station to transmit its data message. This protocol is very efficient for long propagation delays. However, due to the fixed subframe partition, data slots could lie idle when the global queue is empty, decreasing the bandwidth efficiency of the protocol.

In 1989, Goodman proposed the Packet Reservation Multiple Access (PRMA) [5], which is a merger of slotted ALOHA and TDMA. It uses a slotted channel structure, with time slots grouped into frames. When a mobile station (MS) becomes active, it randomly transmits the first packet of "periodic" information in a nonreserved slots. Once its transmission is successful, the MS keeps that slot in subsequent frames until the current message transmission is completed. This protocol is good for voice, but it lacks the flexibility required to integrate data and voice. Based on PRMA, Giuseppe Bianchi[2] etc. proposed the centralized PRMA, a natural enhancement of PRMA, in which the base station (BS) plays a central role in scheduling the transmissions of mobile stations (MS's). Unfortunately, neither of those two can be directly applied to UAV Access Net due to the large propagation delay. The assumption of the two separate physical channels make it very difficult to adjust the bandwidth ratio of up-link and down-link based on the instantaneous traffic condition.

Capture Division Packet Access (CDPA) [3] is a packet-oriented architecture to support the constant bit rate traffic and variable bandwidth on demand necessary for multimedia traffic. The modified version of CDPA for Aeronautical Telecommunication Network was proposed for this single physical channel environment[4]. It has two channels ATG(Air to Ground) and GTA(Ground to Air), both of them use the same frequency because all transmissions are under control of the GS(Ground Station). The GS can decide when using the frequency for GTA transmission and when using it for ATG transmission (by using commands). However, it can not scalable to support large number of ground mobile nodes in tactical environment.

In this paper, we propose a new MAC Layer protocol, Centralized Intelligent Channel Assigned Multiple Access (C-ICAMA), for ground mobile backbone nodes to access UAV.

3.2 C-ICAMA Protocol

C-ICAMA is a packet-switching multiple-access protocol especially devised for the UAV Access Net of Multi-Layer Heterogeneous Ad Hoc Wireless Network with UAVs. Within a single area, each UAV will provide multiple beams on the ground. Within a single beam, there is a one physical chan-
The channel is divided into time slots whose duration is equal to the transmission time of a data packet. The slots are organized into frames with a fixed $N_f$ slots in each frame. Each frame consists of down-link data subframe with $N_d$ slots, up-link data subframe with $N_u$ slots and reservation subframe with $N_r$ slots. All those sizes for subframe are variable based on the traffic condition. Each slot in the reservation subframe is further subdivided into $N_m$ minislots. The minislots are for reservation packets to be used on a contention basis with the slotted Aloha protocol. The slots in the two data subframes are for reserved data packets.

When a ground mobile backbone node generates a packet or a multipacket message, it transmits a reservation packet which contains the number of packets for this message. If the UAV receives this reservation packet successfully, it will store the packet into UAV up-link queue. Any packet generated from UAV will be stored into UAV down-link queue. The queue sizes for UAV up-link queue and down-link queue represent the traffic load on this channel. Therefore, if we adjust subframe sizes based on the ratio of UAV up-link queue size to down-link queue size, C-ICAMA will be able to dynamically allocate the bandwidth ratio between an up-link and down-link to fit the asymmetric data traffic.

As in the figure 3, frame structure for C-ICAMA is a heterogeneous TDMA frame. The last subframe, reservation frame, has all unused data slots grouped together. Each slot in this subframe is further divided into minislots to allow all ground backbone nodes sending reservation minipacket via Slotted Aloha protocol for slot reservation.

The very first slot in the frame is specially for FRAME-START packet. This packet has three fields as follow:

1. The first field contains the number of consecutive down-link slots in down-link data subframe.

2. The second field is the order list of up-link slots positions in up-link data subframe for all the active ground nodes which have reserved the channel in the corresponding slots.

3. The third field has the number of slots in reservation subframe. If this field is zero in any frame, that implies the channel is too busy and all backlog nodes have to wait for later frame to compete. Whenever there are some minislots advertised in the FRAME-START packet, ground nodes which have backlog packets can start to compete for reservation right after the end of up-link data transmission. UAV acknowledges whether the reservation packet’s competition in last minislot is idle (0), success (1), or collision (e).
4 Performance Evaluation

Our simulation environment is the GlomoSim library 1.2.3 [8] written in the parallel, discrete-event simulation language PARSEC [1]. The ground radios model reflects commercial radios, such as Lucent's WaveLAN. The data rate is 2 Mbps. The MAC layer protocol used among ground radios is IEEE802.11. Each ground backbone node has three different physical interfaces: (1) ground radio interface, which is used for communications among regular ground nodes and from regular ground nodes to backbone nodes; (2) directional point-to-point wireless links among backbone nodes and (3) radio interface for accessing UAV aerial backbone nodes.

In our simulation, we use one UAV with 100 ground backbone nodes in a single area. The backbone nodes are moving at very slow speed at 2 m/sec. Traffic sources are CBR (continuous bit-rate). The size of data payload is 512 bytes. We make each pair of CBRs on UAV and ground backbone node with a different rate to generate asymmetric traffic for the simulation. The network consists of 100 mobile nodes in a 1000x1000 meter square.

In figure 5, We compared the efficiency of our C-ICAMA with DAMA and Slotted Aloha. C-ICAMA achieves high efficiency as other contention-based reservation protocols, like DAMA. If we take look in detail, we will find something more interesting as in figure 6. When the channel traffic increase from 0.8 to 0.94, the efficiencies of downlink (DL) and uplink (UL) also increase. However, the efficiency of reservation channel has something really interesting. It got increased first then decreased when channel load is larger than 0.94. This is because, the more active nodes, the more collision in competition minislots.

For most of the contention-based reservation protocols, long access delay is the price they have to pay in order to have high efficiency. C-ICAMA, with it's capability of dynamic channel allocation, can adjust itself to fit any asymmetric traffic condition to retrieve low access delay as in figure 7. From there, you will also see that access delay will suddenly go high when traffic load is over 0.94. This is exactly the same as the traffic load to retrieve the highest efficiency of reservation channel. This is a very important trade-off point for the performance of UAV Access Net.

5 Conclusion

We have introduced the Centralized Intelligent Channel Assigned Multiple Access (C-ICAMA) in hierarchical, heterogeneous multi-layer ad hoc wireless networks. The C-ICAMA is the contention-based reservation protocol with an
intelligent scheduling algorithm. It can dynamically adjust the bandwidth ratio between an up-link and down-link to fit the highly asymmetric data traffic in this multi-layer heterogeneous environment. From the simulation, we have seen it can tremendously reduce the access delay and keep the high efficiency at the same time. The trade-off point at 0.94 traffic load can be used as reference for the system design. Since this can guide us to decide the right number of ground backbone nodes the system can support in order to retrieve the best performance.

References

