Fundamental Issues in Systematic Design of Airborne Networks for Aviation

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Abstract—Airborne networks are special types of ad hoc[1,2] wireless networks that can be used to enhance situational awareness, flight coordination, and flight efficiency in civil aviation. A unique challenge to the proper design of airborne networks for these applications is the dynamic coupling between airborne networks and flight vehicles. This coupling directly affects the operations and performances of both the networks and the vehicles. Accordingly, an appropriate method of airborne network design must consider its interactions with vehicle flight maneuvers and vice versa. In this paper, fundamental issues in the systematic design of airborne networks for civil aviation are addressed. We particularly focus on the issues that cover various aspects of the design such as establishing the airborne network, maintaining the network, and evaluating the performances of the network.

TABLE OF CONTENTS

1. INTRODUCTION

Airborne networks are special types of ad hoc wireless networks that can be used on air vehicles, moving platforms, and ground stations to enhance situational awareness, flight coordination, and flight efficiency. These features are achieved through the exchange of state information among individual vehicles in a timely, reliable, and secure fashion. When properly designed and applied, airborne networks can greatly enhance the safety, efficiency, and convenience of air travel for civil aviation.

Unique challenges to the proper design of airborne networks for situational awareness and flight coordination are presented by the dynamic coupling between airborne networks and air vehicle flights and the integration of airborne networks with other systems such as ground control systems, satellite communications systems, etc. The coupling directly affects the operations and performances of both the networks and the air vehicles. Indeed, the high speed nature of air vehicle flights changes the network topology rapidly as illustrated in Figure 1, whereas the network topology affects performances of the airborne networks, which in turn have a direct impact on the ability of individual vehicles to achieve situational awareness and flight coordination through networks. As a result, an appropriate method of airborne network design must consider its interactions with flight vehicle maneuvers and vice versa.

The integration of airborne networks with other systems introduces the other dimension of the systematic design issues. For instance, in a low dense flight region, one air vehicle could communicate with a ground station that uses a terrestrial network to consolidate the information set and rebroadcasts to other air vehicles in case the air vehicle cannot communicate with other air vehicles directly. This

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requires that the air vehicle be able to choose the air-to-air and/or air-to-ground communication mechanisms automatically to maintain the connectivity with other air vehicles. In addition, the system design requires the integration of the airborne network with the terrestrial network and provides the synchronized information to air vehicles consistently. In this paper, we primarily focus on the issues that cover various aspects of the design of airborne network such as establishing the airborne network, maintaining the network, and evaluating the performances of the network. We leave the systematic design of integration of airborne networks with other systems for future study.

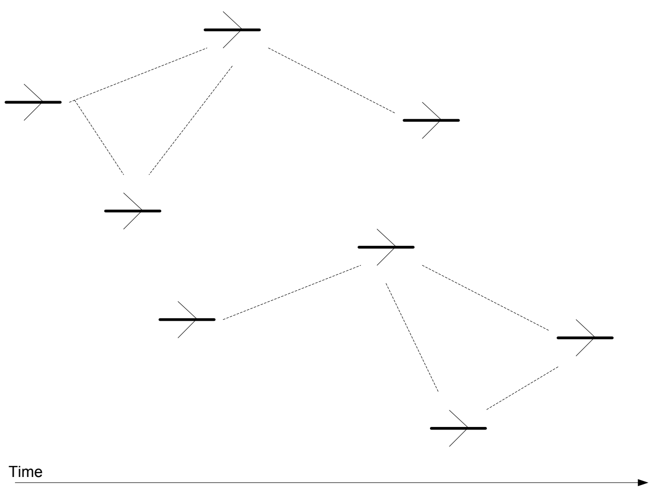

Figure 1 – Dynamic Coupling between Airborne Networks and Air Vehicle Flights

In order to develop an appropriate method of airborne network design, we need to understand the fundamental issues associated with both the design and the operation of airborne networks. In this paper, we address the challenge of airborne network design based on the simultaneous considerations of several inter-related aspects of the airborne system including requirements of civil aviation flights, flight vehicle dynamics and states, basic components of airborne network systems such as physical layer, data-link layer, and network layer, and network performance evaluations.

Specifically, the physical layer aspect includes the selection of transmission frequency, transmission power, etc. The data-link layer aspect includes the design of transmission protocols and algorithms. The network layer consideration addresses the interaction of flight vehicle dynamics and network connectivity. Finally, the network performance evaluation criteria are defined based on integrated consideration of both network performances and their benefits to intended vehicle flights. The design of airborne networks for the self-separation of commercial aircraft is then used as an example to further explain these issues.

This paper is organized as follows. We first present a basic airborne network and discuss flight vehicle dynamics and states potentially involved in network transmission. Next we examine design considerations of an airborne network for civil aviation. We then explore approaches to and identify issues for airborne network architecture and performance criteria. A summary is given at the end.

2. A Basic Airborne Network and Flight Vehicle Dynamic And States

A basic airborne network (AN) consists of a number of air vehicles that can communicate with each other through wireless communication as shown in Figure 1. Distinguishing characteristics of airborne networks are expected to be different for different platforms [1] and uses. For example, an airborne network for civil aviation is different from a military airborne network due to the fact that the movement of civil flight vehicles is highly regulated and managed, and the traffic of civil flight vehicles is thus much more predictable.

Air vehicles can perform three different roles in an AN. (1) The first role is to act as users of the AN that receive necessary information from the AN. (2) The second role can be to serve as sources of the network and send necessary information into the network. (3) The third role is to perform routing/relaying functions by relaying information from some users/vehicles to other users/vehicles as shown in Figure 2.

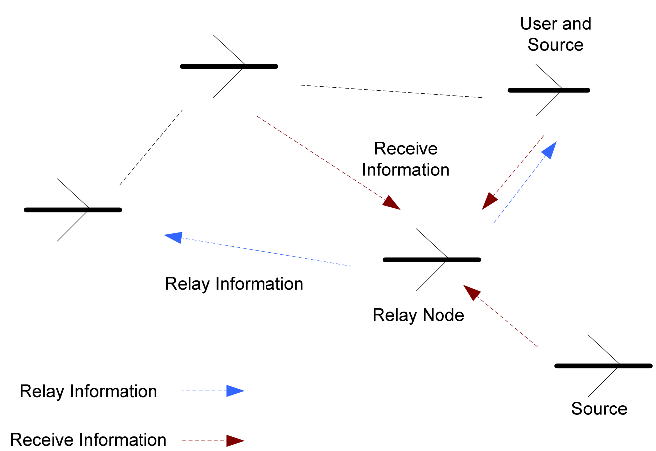

Figure 2 – Three Roles for an Air Vehicle in an Airborne Network

Air vehicles are required to perform different functions when serving in different roles. In this paper, we use the Open Source Interconnection (OSI) reference model to represent the different functions at different protocol layers. Figure 3 shows the protocol layers for the different roles. Role 1 and Role 2 require the full protocol layers from Layer 1 to Layer 7 in order to support the user and source functions. In comparison, only the first 3 layers are needed to support Role 3 functions.

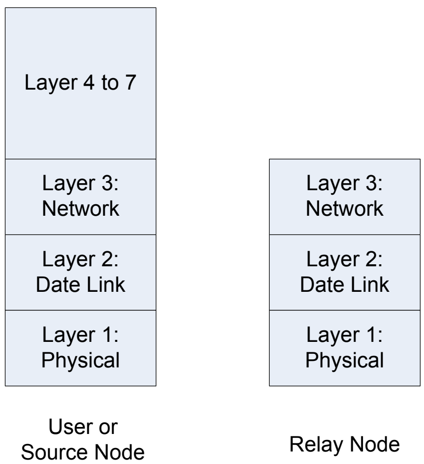

Figure 3 – OSI Protocol Layers for Different Roles

The states of air vehicle describe the vehicle dynamics. The vehicle dynamics directly affect the airborne network topology. To model the vehicle dynamics, we treat each vehicle as a point mass with the following properties:

Position Vector: A vehicle's current position can be described by its horizontal location along the East and North, as well as its height above the ground.

Velocity Vector: The velocity vector of a given vehicle in general contains three components: its speed, heading, and flight path angle, or the three components of the velocity vector along another defined frame of reference.

Flight Intents: There are different ways to express the flight intentions of a certain vehicle. In the short term, these intentions may be described by the three components of its acceleration vector. The current levels of control actions (thrust, lift, and bank angle) can equivalently specify the current acceleration components. In the medium term, planned trajectory points (desired future positions plus possible future velocities at a series of time instants) can define the intended trajectories of the vehicle over an established certain time frame. In the long term, desired final destinations, desired arrival time, and/or company policies of vehicle operations (i.e. minimizing fuel consumption whenever possible) can be used to predict the entire flight trajectory of a given vehicle.

Environmental Conditions: Flight vehicles in an airborne network can also be used to collect environmental conditions around them. These condition variables can include values of local temperature, pressure, wind velocity components, and/or air density. When transmitted over the airborne networks, these variables can help other vehicles develop a more accurate knowledge of the regional atmospheric conditions to assist their planning of efficient flight trajectories.

If available, the position, the velocity, and the acceleration vectors can be interpolated kinematically to predict the changes of network topologies over time. In addition, the network system can also suggest future positions for individual aircraft in order to guarantee desired network connectivity.

The airborne network can be designed in such a way that would allow individual aircraft not only to communicate their own state information, but also to relay received information of other aircraft; thus forming a multi-hop ad hoc system. This airborne network is shown to be able to greatly enhance the range of reach-ability of aircraft state information transmission.

3. Basic Design Considerations For Aviation

There are several key drivers to the design of an airborne network that provides real-time situational awareness and facilitates flight coordination in civil aviation. Basically, the most important motivations in employing airborne networks in civil aviation are to enhance safety and efficiency.

Safety is the primary consideration in commercial flight. The airborne networks can be used to enhance situational awareness among the flight vehicles and therefore, to improve the safety for the vehicles. In other words, one vehicle needs to know the positions and flight conditions of nearby vehicles in order to ensure adequate separations. Safety may further be improved through the exchange of flight intentions among neighboring vehicles in their coordination of planned maneuvers, for example, for conflict resolutions or scheduled arrivals at certain waypoints. To this end, airborne networks can be employed to transmit flight states among neighboring vehicles.

For example, there is a minimum safety envelope around each aircraft that is defined by the required time of maneuver in the event of a potential conflict as shown in Figure 4. Essentially, a vehicle needs to know the relevant states of all other vehicles before they enter its safety region in order to ensure adequate separations from each other. In general, shapes and sizes of these regions depend on traffic density, aircraft performance capabilities, and typical pilot's response characteristics. The minimum safety region for a given vehicle may be spherical or of a special shape designed for its operational safety. In any case, airborne networks should provide reliable and secure connectivity over the minimum safety region for each vehicle.

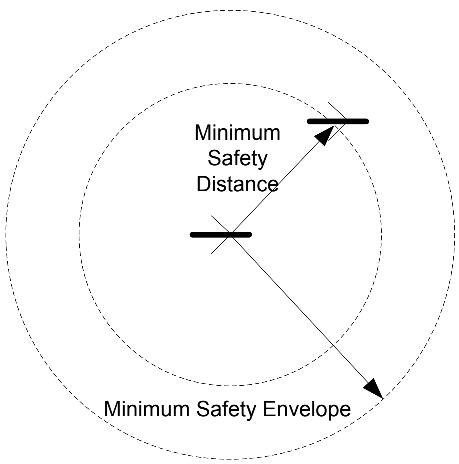

Figure 4 – A Minimum Safety Region and Minimum Safety Envelope for an Aircraft

Thus, there exists a "minimum safety envelope" around each vehicle such that the airborne network nodes on two approaching vehicles can receive each others signal, perform whatever initialization is required and transmit/receive the other vehicle's position, course and speed before the approaching vehicles reach the minimum safe distance for each vehicle.

Efficiency becomes an important consideration when safety can be guaranteed. Efficiency can be improved through the use of airborne networks or other means both on an individual vehicle and/or for the entire traffic over a certain region. For example, individual vehicles can improve their flight efficiency by getting a better knowledge of environmental conditions over the region of their intended flight. These environmental conditions may include wind velocity components, air density, pressure, and temperature. A modern vehicle can measure these quantities at its current position fairly accurately. Therefore, if every vehicle in a region can broadcast its local measurements of these quantities, other vehicles would be able to develop better estimates of the atmospheric conditions in their flight regions, and thus plan optimal flight trajectories to save fuel and/or flight times.

Assuming every vehicle is planning and flying its own optimal flight trajectory, the less the disruptions to the planned trajectories of individual vehicles the more efficient the entire traffic system would be. Therefore, the second level of efficiency comes from the coordination and expedient flow of the entire traffic over a certain region, for example, to reduce potential delays and/or deviations from nominal trajectories for individual vehicles. Airborne networks can then be used to disseminate state information of various vehicles among themselves for self-separation and self-scheduling, or to the ground stations for central traffic management.

Reliability and security are also important considerations in designing airborne networks, because in all cases, the reliable and secure transmissions of needed state information are essential. State information transmissions must be reliable because erroneous information can cause potential dangers among air vehicles. In this case, reliable transmissions mean accurate and timely broadcast, as well as accurate and timely receptions of intended information. At the same time, security is also important here because these vehicle states should not be known by un-authorized parties.

Based on the above discussions, airborne networks for civil aviation should have the following features:

- Air vehicles (network nodes) should maintain some minimum distances (minimum safety envelope) between each vehicle pair.
- Air vehicles should be able to relay necessary information from other nodes or sources in a reliable and secure fashion.
- The vehicle dynamics and states are time-sensitive information. The network performance criteria should be developed in such a way as to insure that the network can provide real-time delivery of these information to the users.
- The air vehicles should be able to perform all three roles, e.g. users, sources, and relays as indicated in Section 2. The capability of the network can be determined based on the predicted topology and predefined roles.
- Due to the highly managed aviation traffic, the topology of the networks is not completely random, but it is not static either. In normal situations, the topology can be predicted and modeled.

- Although in the normal case, the topology can be predicted. However, due to the dynamic nature of the air vehicle flight, the network should have the capability of self-forming, self-healing, and self-organizing among the air vehicles in order to provide a highly available and reliable network.

4. SYSTEMATIC DESIGN APPROACHES AND ISSUES

Feasible airborne network design methods need to be able to achieve the features identified above. For the purpose of discussing potential methods of AN design, we consider the relay roles of the air vehicles only. Specifically, we propose the following systematic design approaches for the selections of various AN components as shown in Figure 5.

The design requirements should pass through the three layers, i.e. physical, data, and network in the selection of proper components from suitable technologies. The three layers should also be considered in an integrated manner to meet any specified performance metrics. Potential components for each layer are discussed below:

1. Physical Link Layer Components: These components provide the physical layer support and can include the considerations of spectrum, radio transmission rates, transmission powers, etc. in order to maintain the physical communication connections among the air vehicles.

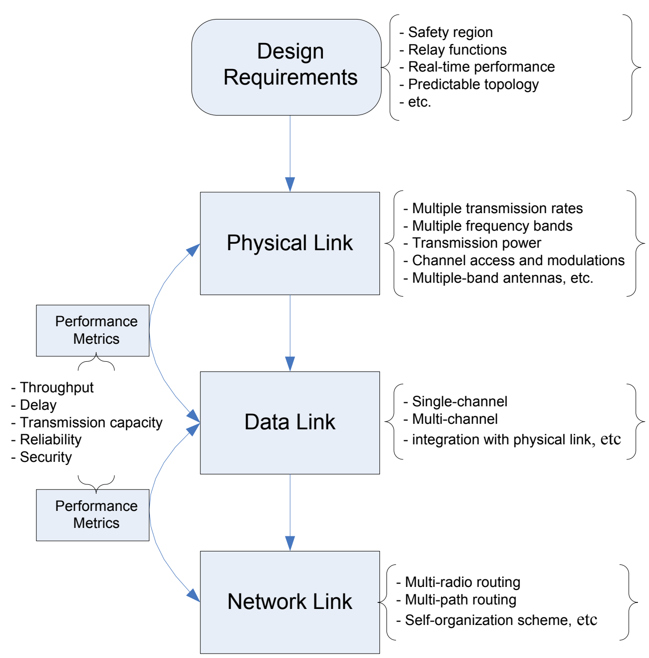

Figure 5 – Systematic Design Approaches

2. Date-Link Layer Components: These components include the considerations of multiple data-link connections, frame delimiting, alignment, flow control, detection of transmission, format, and operational errors on a data link, recovery from errors, etc.

3. Network Link Layer Components: These components provide the routing and relaying functions, network connections, multiplexing, congestion control, error detection, etc. for maintaining and changing of the network topology.

4. The performance criteria should be established to meet the needs of the civil aviation users.

In the following, we describe the potential issues associated with the components in detail.

4.1 PHYSICAL LAYER COMPONENTS

One of the primary functions of physical layer components is to establish and maintain communication connectivity among the flight vehicles. Especially it must maintain the connectivity within the specified minimum safety envelope. In order to provide the adequate transmission capability for flight vehicles to establish the connections with other flight vehicles, it is required that the physical layer components be able to adjust the transmission power based on the various positions of the flight vehicles. This requires the development of the feedback mechanisms.

Frequency selection is also an important issue to be considered. Due to the large movement range of flight vehicles, the fight vehicles most likely cannot use a single frequency/channel to communicate with other vehicles throughout their entire flight journeys. Therefore, the physical layer components should be able to switch transmission frequencies or channels at different locations while still maintaining the network connectivity.

Due to the high speed nature of flight vehicles, the handoff from one moving node to another as well as the high speed movements themselves can cause potential problems.

4.2 DATA-LINK LAYER COMPONENTS

A moving node should be able to create and maintain the multiple data link connections with adjacent nodes in the network. To maintain such connections, the data-link layer components in the sending and receiving nodes should be able to adapt to changing environments. This requires network self-organization for desired collaboration between neighboring nodes and nodes in multi-hop distances [3].

Due to the dynamic change of the air vehicle positions, it is desirable to have an air vehicle to work on multiple channels instead of only on a single fixed channel. In this way, the vehicle can provide a smooth transition from one position to another position in the network while maintaining the connection. Depending on hardware platforms, different multi-channel Medium Access Control (MAC) protocols need to be developed or adopted [3].

To provide a seamless integration between the physical and data-link layers, and between the data-link and network layers, certain cross-layer design has to be employed among the various components.

4.3 Network Layer Components

For a highly dynamic and yet predictable network topology, the airborne network is required to provide fast routing and relaying functions among the network nodes. In the environment where the routes are frequently changed, links are frequently handed-off from one node to another, and the air vehicles are moving fast, the routing convergence time and route setup delay have significant impacts on path availability and throughput loss [2].

Correspondingly, the routing protocols should be able to dynamically update the changes of the network topology. The routing information will constantly be updated due to the movement of air vehicles. This calls for the modifications of existing routing protocols or the developments of new ones. For example, many existing routing protocols use minimum hop-count to select the routing path. This selection may be sufficient for fixed or some slow mobile ad hoc networks. However, the status of hop-count may be changed rapidly due to the fast movement of air vehicles.

It is desirable to establish multiple channels from one node to adjacent nodes in order to maintain the high connectivity with the network. The multi-path routing performs the multiple path selections. In case the primary path fails, the backup path route can be chosen without introducing any excessive delays. Therefore, the selections of network layer components should consider these various factors in order to meet the design requirements.

4.4 Performance Evaluation Criteria

Airborne networks for civil aviation can be evaluated based on the following performance criteria:

1. Basic network standalone criteria

Throughput, average delay, information transmission capacity (bits per second), least transmission ability (bottleneck). These criteria define the basic performance metrics for an airborne network.

2. Availability and reliability of the network over a specified region

Network availability should be defined over selected regions. For example, in a high dense flight region, the availability of the network should be higher than that in a low dense flight region. The network should be highly reliable in order to maintain the minimum safety envelope among the air vehicles.

The airborne networks can be integrated with other communications systems such as satellite communications system, air-to-ground communications system to enhance the network availability and reliability.

3. Integrated performance criteria

Network performances should be evaluated in terms of their contributions to the needs of civil aviation such as situational awareness and flight coordination. For example, an airborne network may be measured with the probability of reliable transmissions of specified vehicle states (position, velocity, maybe intents, maybe environmental information) from all vehicles within a specified region around a given aircraft and the reliable reception of these states by the given aircraft.

4. Network security

The network should be protected to prevent any unwanted parties to intercept and/or relay the information transmission. This may require the transmission messages, communication channels, etc. of the network to be encrypted at different layers.

5. Examples of the Approaches

We now consider the design of airborne networks for the self-separation of commercial aircraft as an example to illustrate the proposed design approaches and issues.

In commercial aircraft operation, for example, it is essential for pilots and/or ground controllers to maintain a high level of situational awareness of neighboring traffic. The Automatic Dependent Surveillance-Broadcast (ADS-B) concept has emerged as a feasible and low-cost system for such purposes. In ADS-B, an aircraft automatically broadcasts its position, velocity, and other information on a regular basis (every one second or so) via a digital data link. All properly equipped aircraft within a certain range can receive this information. Because an aircraft only broadcasts its own state information periodically, however, the current ADS-B concept is essentially a single-node operation scheme and its range is limited to the direct transmission range of the airborne antenna.

In order to increase the transmission range, a network extension of the ADS-B concept was proposed, in which individual aircraft not only broadcast their own state information, but also relay received information of other aircraft; thus forming a multi-hop broadcasting system. This airborne network is shown to be able to greatly enhance the range of reach-ability of aircraft state information transmission.

In this application scenario, desired network connectivity is first defined as the continuous network connectivity among a team of air vehicles over a certain time frame starting from the current time in order to account for vehicle mobility. This time frame should at least be larger than the broadcast interval. This definition will ensure that broadcast powers are varied in anticipation of potential aircraft movement within the specified region to maintain connectivity.

In order to examine the behaviors of airborne network concept in practical operations, two performance measures are now defined. The coverage ratio is introduced to measure the impacts of timely end-to-end transmissions from message generation to reception. Specifically, it is the percentage of all aircraft within a certain range around a given aircraft whose state information can be received by the given aircraft over a certain time. The closer the coverage ratio is to one, the better the situational awareness is for a given aircraft. In addition, the average power consumption per transmission is defined over the specified minimum safety envelope to measure the energy efficiency of any adjustable network algorithm.

The development of decentralized algorithms for adjustable range broadcast network can then be formulated as an optimization problem that minimizes the total broadcast power of participating aircraft within the specified region, while maintaining the desired connectivity.

In the practical implementations of any decentralized algorithms, individual aircraft need to communicate with one another in adjusting broadcast powers. Three feedback mechanisms can be considered. In the first scheme, a receiver airplane sends back a signal to notify the sender airplane that the signal is too weak. However, the sender may also get a weak signal from the receiver due to the large distance. In the second scheme, a receiver airplane sends a signal to the ground station or satellite to request the sender to increase its broadcast power. Due to the fast motion of air vehicles, the latency of this scheme can be substantial. Finally, senders and receivers can continuously handshake with each other. If the noise-to-signal ratio increases to a certain level, a sender can increase its transmitting power to bring the noise-to-signal ratio down to a certain level. This scheme seems to be the most promising one.

Finally, hardware selections of the airborne network system can be made based on minimizing the transmission power requirement, subject to satisfactory performance of the airborne network with the decentralized algorithm implemented and constraints of spectrum limitation.

6. SUMMARY

We have explored some key considerations for designing airborne networks for aviation use. Desired characteristics of airborne networks for civil aviation are described. Based on these characteristics, a framework for the systematic design of airborne networks is laid out and associated issues discussed that touch upon various aspects of components of an airborne network design. These components include different layers such as physical, data, and network. Potential performance criteria for evaluating the network are also presented.

Significant work is still needed to make the design of airborne networks for civil aviation mature. In order to understand the behaviors of airborne networks in civil aviation, it is highly desirable that integrated simulation studies be conducted. For instance, in order to examine the behaviors of an adjustable range broadcast airborne network concepts in practical operations, simulation should be conducted on the performance of the proposed algorithms and comparisons of different feedback mechanisms. In these simulations, dynamic motions of individual aircraft need to be simulated simultaneously and uncertainties in the transmissions and receptions in the airborne networks need to be considered.

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BIOGRAPHIES

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