Wireless Communications for Low Altitude Aircrafts
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Introduction
Advances in flight controls, avionics, and airborne sensors will drive large increases in wireless communications with manned and unmanned low altitude aircrafts. Use cases on the uplink (ground to air) include transmitting weather, traffic, and entertainment data for manned aircrafts, and control inputs for unmanned aircrafts. Use cases on the downlink (air to ground) include transmitting images, video streams, and sensor data. However, current wireless networks are primarily geared towards communications between terrestrial base stations and terrestrial mobile endpoints. On a traditional cellular network, the cell tower occupies the highest geographical position, and therefore receives the highest interference. On a aerial network, the situation is reverse. On a traditional cellular network, shadowing and fast fading greatly affect the channel model. On an aerial network, shadowing and fast fading are secondary to the attenuation due to distance.

Recently, major airliners have partnered with satellite or ground based wireless network operators to offer in flight wireless service, but these technologies are largely unsuitable for low altitude flying vehicles. Airliners can carry heavier equipment, transmit at higher power settings, and fly above the cloud. An aircraft flying in low altitude will have constrained hardware, a different channel model than a terrestrial endpoint, and a different link budget calculation. Consequently, an aerial endpoint optimized network could be significantly different than a terrestrial network.

Regulations and Common Practices in Aviation
In the United States, The Federal Aviation Administration (FAA) sets rules and regulations for unmanned, general and commercial aviation, and the codes are referred to as the Federal Aviation Regulations (FARs). According to FAR Part 91.119 [7], airplanes should fly at least 1000 feet above ground (AGL) over congested area, and at least 500 feet AGL over not congested areas, but are permitted to fly under 500 AGL over open water and sparsely populated areas. The FAA is currently working towards regulations for unmanned aircrafts, and FAA Advisory Circular 91-57 [8] states that model aircrafts are permitted under 400 feet. In practice, most helicopters fly between 500 and 1000 feet AGL, general aviation aircrafts between 3,000 and 25,000 AGL, and commercial scheduled airliners between 35,000 and 45,000 feet AGL. For the purpose of this project, it is assume that a cellular base station is 100 feet above ground, and a hand held base station is 10 feet above ground.

Channel Model
The free space model is an attractive channel model for uplink (ground to aircraft) signals when the airplane is more than an order of magnitude higher than the cellular base station. By pointing the antenna skywards, the directional antennas will attenuate the amount of energy reflecting off the ground by 10dB [2]. Additionally, reflections from nearby high rises is geometrically unlikely to be directed towards a far away object. Refractions and scattering will attenuate the power to a negligible amount.
The 2 Ray model is the best channel model for downlink (aircraft to ground) signals because of reflections from buildings and features near the cellular tower. However, the Elnoubi found that the cellular ground station experiences 4.38 times less interference compared to the aerial end point [3], because the higher vantage point increases the radio line of sight (RLOS) distance. Therefore, even with increased multipath, the downlink channel is the same or better than the uplink channel.

The channel model for communications between cellular base station and an aircraft flying less than 1000 feet is the empirical model with shadowing and rich multi-path. Similarly, the channel model for communications between a hand held base station and an aircraft flying less than 1000 feet is also an empirical model, but additional link margin needs to be budgeted because none line of sight communications should be expected.

The delay spread for the two ray model should have a maximum value of
\[ \sqrt{\frac{2}{c}} \times 100 = 1.44 \times 10^{-7} \text{ seconds} \]
where \( c \) is the speed of light in feet per second, and \( \sqrt{\frac{2}{c}} \times 100 \) results from a reflection close to the cellular tower. On a hand held controller with a height of 10 feet, the delay spread is \( 1.44 \times 10^{-6} \) seconds.

<table>
<thead>
<tr>
<th>Channel Model Between Base Station and Aircraft at Varying Altitudes</th>
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</thead>
<tbody>
<tr>
<td><strong>Base Station</strong></td>
</tr>
<tr>
<td>Tower Uplink</td>
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<tr>
<td>Tower Downlink</td>
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<tr>
<td>Hand Held</td>
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</tbody>
</table>

**Minimum Base Stations for Complete Coverage**

An aerial end point will have a much longer line of sight range than a terrestrial end point, thus allowing for fewer number of base stations to cover the entire United States. The radio line of sight (RLOS) is a function of height, and is limited by the curvature of the earth. Below is the full derivation of the closed form solution, which is confirmed by [2,3].

Let \( R = \frac{4}{3} \text{ radius of earth} \)
Let \( h = \text{height of airplane} \)
Let \( r = \text{RLOS distance} \)
\[
(R + h)^2 = R^2 + r^2
\]
\[
r = \sqrt{2Rh + h^2}
\]
\[
r \approx \sqrt{2Rh}
\]
\[
r / \sqrt{R} \approx \sqrt{2h}
\]
\[
\sqrt{R} \approx 5280 \text{ feet}
\]
\[
r \approx \sqrt{2h}
\]
where \( r \) is in miles and \( h \) is in feet
Based on the RLOS distance, we can calculate the minimum number of base stations necessary to cover the entire United States at each height by dividing the total square mileage of United States, 3,806,000, by the area covered by a base station, \( \pi r^2 \) square miles, where \( r \) is the RLOS range in miles. In the chart below, the blue series shows the relation between the minimum height and the RLOS range, and the orange series shows the relation between the minimum height and the minimum number of base stations needed for full coverage. From the chart below, we see that the base station count is a function of \( 1/h \). There is a precipitous drop in the number of base stations as the minimum altitude of the aircraft increases from 250 feet to 1000 feet.

McGrath proposes two plans for covering continental USA at 850 MHz: 73 three sector cellular towers, or 59 three sector cellular towers and 124 size sector cellular towers [2]. Continental US has roughly 3500000 square miles. With 73 cellular towers, the average coverage radius should be 123.5 miles, and with 183 cellular towers, the average coverage radius should be 78 miles. While McGrath does not explicitly state the range of cellular tower, the proposed data rates have a 24.1 dB range between the lowest and highest \( E_c/N_t \), which could reasonable cover 123.5 miles.

**Link Budget**

*Long Range*

Elnoubi calculated the link budget for signal at 800 MHz, a distance of 105 km, 10db of Eb/N0, 10db of link margin, 3db of noise floor, and a data rate of 270.8 kb/s [3]. I extended it for frequencies from 100 MHz to 10 GHz, distances of 35 km, 70 km, and 105 km, and a data rate of 1 mbps. From this link analysis, if one assumes that the EIRP is 10 W, a reasonable assumption for an airliner, the highest frequency at 30 km is 2.5 GHz, the highest frequency at 70 km is 1.2 GHz, and the highest frequency at 105 km is 800 MHz.

\[
\begin{align*}
EIRP &= EIRP_{min} + 10 \\
EIRP_{min} &= FSL + RSL \\
FSL &= 32.44 + 20 \log (\text{distance in km}) + 20 \log (\text{frequency in MHz}) \\
RSL &= C/N_0 - 204 + NF \\
C/N_0 &= 10 + 10 \log (\text{data rate in bps}) \\
NF &= 3
\end{align*}
\]
The results show that at long distances, the data rate is severely constrained by the transmit power. For regions below 10 dBw EIRP, where there is a surplus of link budget, each 3 dBw of surplus link can be utilized to double the data rate. However, most of that region exists below 1 GHz. Airliners typically provide high data rate through the use of satellite communications at frequencies above 10 GHz because there is no cloud cover or rain at 45,000 feet AGL, but that is not feasible for low flying aircrafts because of the presence of cloud cover and rain. Additionally, satellite communications suffer from long latency, and is less than ideal for safety critical real time two way communications, but is acceptable for streaming entertainment content. In the chart below, the radius of the cellular coverage per tower is compared with the minimum aircraft altitude and minimum cellular tower count. In practice, the lower bound on the minimum altitude is 1000 feet, because that is the minimum altitude where the free space channel model is valid.

### Cellular Tower Range, Minimum Tower Count, and Minimum Altitude

<table>
<thead>
<tr>
<th>Max Distance from Cell Tower</th>
<th>Minimum Aircraft Altitude in Feet</th>
<th>Minimum Cellular Tower Count</th>
</tr>
</thead>
<tbody>
<tr>
<td>35 km / 21.75 miles</td>
<td>327</td>
<td>2561</td>
</tr>
<tr>
<td>70 km / 43.5 miles</td>
<td>946</td>
<td>640</td>
</tr>
<tr>
<td>105 km / 65.25 miles</td>
<td>2129</td>
<td>285</td>
</tr>
</tbody>
</table>
Short Range
For low altitude aircrafts flying below 1000 feet, the channel model is expected to be empirical. For purposes of this analysis, I modify the distance component of the free space loss such that it attenuates the signal proportional to the cube of the distance, and plotted the EIRP as a function of the carrier frequency at different ranges. From this link analysis, if one assumes that the EIRP is 3 W, a reasonable assumption for an unmanned aircraft or a light manned aircraft, the highest frequency at 3 km is 9 GHz, the highest frequency at 10 km is 1.45 GHz, and the highest frequency at 15 km is 700 MHz.

\[ FSL(db) = 32.44 + 30 \log(distance\ in\ km) + 20 \log(frequency\ in\ MHz) \]

Comparing the long range model to the short range link budget model, we see that reducing range for increased carrier frequency or data rate is much more favorable in the short range model. This is because attenuation is proportional to the square of the distance in the long distance model, but attenuation is proportional to the cube of the distance in the short distance model. On the other hand the effects of frequency and data rate are the same for both models. Additionally, we see that 5 GHz is the upper limit of the carrier frequency for both the long and short range model. For extended range, sub 1 GHz is required. Also, note that the long range model assumes a minimum height of the aircraft due to the effects of the curvature of the earth. On the short range model, the curvature of the earth does not effect the link budget calculations.

Modulation Schemes
TDMA
In air-to-ground papers from the 1990 and early 2000s, research was focused on reducing the reuse distance because the dominant form of communications was GSM, which uses GMSK modulation with TDMA [3,4,5]. By reducing the reuse distance, fewer channels are needed, thus reducing the bandwidth of the system. The reuse distance was found to be [3]

\[ D = 5R \text{ if } RLO > 4R \]
\[ D = RLOS + R \text{ if } RLOS < 4R \]

where D is the minimum distance between cell towers on the same frequency, \( R \) is the range of the cell tower, and RLOS is the maximum radio line of sight distance from an aircraft. Curious, the author concluded that TDMA was superior to CDMA and TDMA, because he assumed a static channel [3].
CMDA
In air-to-ground papers from the late 2000s, research was focus on interference because the dominant form of communications changed to CDMA [1,2]. In CDMA, all transmitters and receivers use the same frequency band, and differentiate by using different PN codes. In the presence of too much interference, the receiver will not be able to decode the PN codes correctly. The author concluded that as the cell radius increased or aircraft height decreased, interference and outage probability decreased [2].

FDMA
In current standards such as LTE and WiFi, OFDM has become the favored modulation scheme because of it's spectral efficiencies. One challenge when applying OFDM to air-to-ground communications is correctly sizing of the guard interval [6]. If the guard interval is too short, there will be inter symbol interference. If the guard interval is too long, capacity will be reduced. In the calculations above, the maximum delay spread in long range air-to-ground communications is $14.4 \text{us}$. The maximum delay spread in short range air-to-ground communications is $1.44 \text{us}$.

In WiFi, the guard interval is $0.8 \text{us}$, which is unsuitable for air-to-ground communications. IEE802.11 AX is planning to extending the guard interval to $3.2 \text{us}$, which is suitable for short range air-to-ground communications. In LTE, the guard interval is variable, with the longest one $17 \text{us}$, which is suitable for both short range and long range air-to-ground communications.

Conclusion
In a terrestrial network, the bottleneck is the uplink from the mobile to the cellular tower. Coverage and capacity can often be improved by increasing the number of cellular towers. On the other hand, the bottleneck on an aerial network is the uplink from the tower to the aircraft. Increasing the number of towers could decreases capacity by adding interference because each high altitude aircraft has a line of sight link to multiple cell towers. This constrains the maximum data rate for a long range high altitude network because most of the link budget is used to combat attenuation due to distance. However, a network of several hundred cellular towers is enough to cover the entire United States. On a short range low altitude network, the channel model retains the line of sight properties, while reducing the interference from operating at a low height. It is also suitable for a variety of commercially available platforms, such as CDMA, LTE and Wifi, and can operate across a large range of carrier frequencies and data rates.
References


