Delivering Real-Time Weather Maps to Aircraft by Hybrid Uni-cast/Broadcast LEO/GEO Satellite Communications *

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Abstract

In this paper we focus on the modeling and evaluation of next generation satellite communications technologies to support future aeronautical communications. Recent studies identified an important future aeronautical application as the delivery of real-time high resolution weather maps to the cockpit. Focusing on this application, we investigate the use of Low- and Geosynchronous- Earth Orbit (LEO and GEO) satellite networks for efficient delivery of the data. We propose a hybrid uni-cast and broadcast communication technique reducing the required communication bandwidth. We quantify our results through simulation and compare them with other methods.

1 Introduction

The introduction of Next-Generation Satellite Systems (NGSS) into the global telecommunications landscape offers the potential to revolutionize how consumers and business entities communicate in the future. Aviation is also currently undergoing major changes in its telecommunications infrastructure with modernization efforts underway to convert from the current analog, primarily voice-based system to a digital voice and datalink system for both Air Traffic Management (ATM) as well as airline operational (AOC)-type communications. The future air-ground aeronautical

*This work was supported by NEXTOR, the National Center of Excellence for Aviation Operations Research, based on funding from the Federal Aviation Administration and the National Aeronautics Space Administration. Any opinions expressed herein do not necessarily reflect those of the FAA, the U.S. Department of Transportation or NASA.

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telecommunications infrastructure will be a hybrid, made up of numerous terrestrial and space-based links such as VDL-Modes 2 and 3, Mode S, SATCOM, HF [1]. Each of these will have their own specific link characteristics in terms of technical performance and cost as well as applicability to aircraft platform. Traditionally, air-ground aeronautical communications in domestic airspace has been considered primarily from the ground based provider perspective. The application of NGSS systems for aviation offers the potential to greatly change how aeronautical communications is performed in the future. NGSS stands to offer a new alternative to the mix of candidate communications links for future ATM and AOC communications.

In this paper, we focus on the real-time delivery of high resolution weather maps to the cockpit. We identify this application as a candidate for future aeronautical applications requiring more intensive processing and higher communications bandwidth. Furthermore, the delivery of up-to-date weather maps to the cockpits will have profound effects both from aeronutical operations and safety point of views. Recent studies at NASA have identified weather as one of the most important safety issues. Over 30% of aviation accidents are consequences of weather related events. In addition to safety, weather has economic consequences. Weather is responsible for approximately two-thirds of air carrier delays- a four billion dollar cost, of which 1.7 billion dollars are considered avoidable [9]. Rather than the implementation issues, we investigate the communications requirements of this new application in this paper. It is often the case that the communications requirements are neglected while aeronautical applications are designed. Thus, we hope to fill this void by our current work. In this paper, we quantify the communications requirements associated with possible future applications by taking the delivery of high resolution weather maps as an example. We rely on a recent study performed by NEXTOR for determining the data requirements for this application [2]. We show that the bandwidth requirements are massive, and the current and possibly the future ground-based aeronautical communications infrastructures seem inadequate. NGSS with proposed broadband capabilities provides an alternative for future aeronautical communications. We develop a hybrid uni-cast and broadcast architecture via LEO/GEO satellite networks for the delivery of high bandwidth information.

The paper is organized as follows: In section 2, we give a brief overview of the system and discuss the relevant issues. In the following section, we define our system model. In section 4 we determine the communications and processing requirements under this model. We give numerical results in section 5 and discuss the results in the concluding section 6.

2 Overview of Communications Requirements

We can generally classify aeronautical communications applications into those that are specific to a single aircraft and those that are of interest to multiple aircraft within a geographic region. An exchange related to a route modification would fall into the former category and dissemination of weather information would fall into the latter. Both types of communications could be sent to an aircraft via a uni-cast link, which we define as a private communications channel between two parties. However, a broadcast link, which provides communications from a single party to many parties within a region of interest, may offer a more attractive alternative for the latter type of communications. We develop bandwidth requirements associated with next generation aviation communications applications for both the case of uni-cast-only links and the case of a hybrid uni-cast/broadcast architecture. In the hybrid case, we specifically take into account the characteristics of next generation satellite systems.

We model the broadcast applications by associating a region of interest (ROI) with each aircraft at any particular time during its flight. We assume that all required broadcast information can be represented as attributes of this (geographic) ROI. The ROI can be conceptualized as a map whose attributes are dynamically updated over time and whose center changes as the flight moves through space. As the flight progresses the ROI would change. In general, an aircraft could be interested in three different ROIs: a tactical ROI, a near-term strategic ROI and a far-term strategic ROI. At certain times during a flight the pilot and/or aircraft control systems could be interested in any one the three ROIs, while at other times, e.g. during final approach, there would be only one of interest. We model the requirements of each separately and implicitly assume that overall bandwidth requirements are obtained by summing the requirements of each application. We leave to future research methods for efficiently handling the three simultaneously. We assume that each of the three ROI types have appropriate sizes, which increase as one progress from tactical to near-term strategic to far-term strategic and resolutions, which decrease as a function of the same progression. A refresh rate would also be associated with an ROI. This is the frequency at which the information in the ROI is updated. Since between successive updates some of the underlying information will remain the same, we also associate an update factor for this process, which is the fraction of the ROI's information content that must be changed between successive updates.

The principle focus of our analysis is the modeling and evaluation of next generation satellite communications technologies to support future aeronautical communications. However, we will also be able to draw some conclusions related to terrestrial cellular communications systems.

Next generation satellites are equipped with directional antennae with multiple spot-beams. Thus, the footprint of a satellite is covered by multiple cells, each of which is served by a spot-beam (see [3] for background). LEO/MEO satellites have steered antennae so that as the satellites move along their orbits, the area illuminated by their spot-beams remain fixed with respect to Earth coordinates. For example, the Teledesic proposal [4], [5] describes such a system. Thus, both GEO and LEO/MEO satellites cover the Earth with multiple stationary cells. From the perspective of our model, the only difference between the two is the size of the cells. As the aircraft (or user of any sort) traverses different cells, it is handed-over to different spot-beams or satellites. In this work we assume that hand-over issues such as call-blocking and call-dropping are solved by employing similar hand-over strategies developed for terrestrial cellular networks [6], [7].

In the next three sections we describe a model for determining the bandwidth requirements for the down-link to an aircraft for successful on-time delivery of weather information. Thus, we treat the case of communications applications that can be transferred by either broadcast or unicast channels to determine the appropriate architecture and requirements for these applications. This analysis can then serve as the basis for the determination of overall requirements for both application

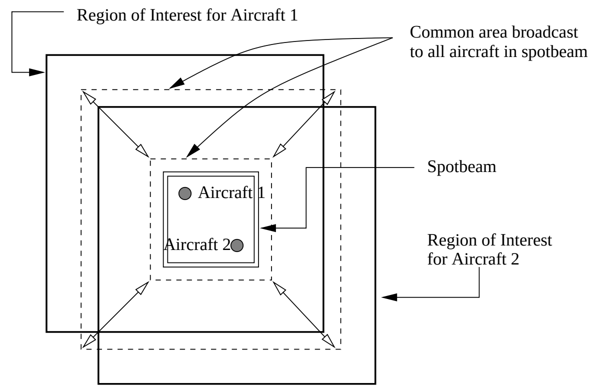

Figure 1: Region of Interest of different aircraft in a spot-beam.

types.

3 Communications Model

We model the ROI as a square with the aircraft at the center of this square. Thus, the aircraft is interested in the region ahead of it as well as the region it has passed. During take-off and final approach, the aircraft generally will be interested in the on-going events (in this case weather information) in all directions, since the air traffic density in these regions is high, which may cause the aircraft to make frequent maneuvers to approach/leave the airport. However, during the en-route portion of a flight an aircraft is likely to be principally interested in a very large area ahead of it and a relative small portion of the area that it has already passed. Thus, this assumption represents a somewhat coarser approximation in the en-route case.

We consider LEO and GEO satellites and compare the bandwidth requirement of the two. The LEO satellite spot-beam is also modeled as a square with an area of 2500 km^2, while the GEO satellite spot-beam has an area 40000 km^2. These numbers are representative of typical or proposed architectures (see [3] and [8]) . The size of ROI for tactical, near-term strategic and far-term strategic weather applications are 47000 km^2, 424000 km^2 and 2700000 km^2 respectively [2]. Thus, spot-beam sizes are usually much smaller than ROI. We consider the aircraft traffic to be uniformly distributed in a spot-beam. For those aircraft in the same spot-beam, there is substantial overlap for ROIs that can be exploited for efficient delivery of information.

Each aircraft has two active channels: broadcast and uni-cast. In the hybrid communications case, which is the subject of our optimization model, any aircraft-specific communications would be carried over the uni-cast channel, while the communications of interest to multiple aircraft would be sent using a combination of the broadcast and uni-cast channels. Every aircraft in the same spot-beam tunes in to the same broadcast channel. A large portion of information that is common to all ROI of the aircraft in the spot-beam is delivered on this channel. However, the uni-cast channel of each aircraft is specific to that aircraft; it is used to transmit the information for the portion of the ROI not transmitted over the broadcast channel. Our objective is to determine the optimal size of the area that needs to be broadcast over the broadcast channel for optimal bandwidth and processing efficiency.

We consider two factors in determining the optimal broadcast area (BA) per each spot-beam: Bandwidth and processing costs. The bandwidth cost is the total amount of information transferred to the aircraft per unit time. This is the usual metric that considers the bandwidth of the pipe from the satellite. The processing cost is the amount of processing that has to be performed to convert the received information into a format that is suitable to be displayed on a cockpit monitor. In our work, we assume that the weather information is transmitted from a central processor to the aircraft in a format that is ready to be displayed. A processing cost must be incurred because the amount of information transmitted is greater than the amount needed by the aircraft (i.e. a portion of weather map is out of the scope of ROI); the excess information must be filtered out by the aircraft. Since we are dealing with future applications, one can only speculate as to the cost of this processing relative to the bandwidth cost. One could argue that processing power has become very cheap, however, history indicates that on-board processing power is limited, and the priority should always be given to more time-sensitive processes. Consequently, some cost must be associated with the extra amount of information delivered to the aircraft.

In our analysis we determine the average total cost of bandwidth and processing in a spot-beam for a given traffic density. We consider a certain area to be transmitted over the broadcast channel to all aircraft in the spot-beam. This broadcast area (BA) is a square with its center coinciding with the center of the spot-beam (Figure 1). As the BA increases, the amount of information transferred over the uni-cast channel decreases. However, beyond a certain BA size, the processing cost starts increasing, since unnecessary information has to be filtered out by each aircraft. Thus, there is an optimal BA size that minimizes the sum of bandwidth and processing costs. We assume that the bandwidth and the processing costs are directly related to the size of the area that is broadcast, where the bandwidth per unit area is derived from the analysis given in [2]. We consider that each aircraft can be at any location in the spot-beam at a given time, so we determine the total bandwidth and processing cost of an aircraft with respect to its location. The bandwidth cost of each aircraft is the bandwidth of its uni-cast channel. Then, since the aircraft are uniformly distributed over the spot-beam, we average these quantities. This gives us the average total bandwidth and processing requirement per aircraft in a spot-beam. We then multiple this quantity by the number of aircraft in the spot-beam at any given time and add the total bandwidth cost of the broadcast channel to determine the average total bandwidth and processing costs in the spot-beam.

4 Bandwidth and Processing Cost Analysis

Figure 2 depicts the set-up for our analysis. Consider a single spot-beam. Let the origin be placed at the lower left corner of this spot-beam. The length of a side of the spot-beam is 2 units. The length of a side of the BA is $2d$, while the length of a side of the ROI is $2K$. In Figure 2, $A1$ and $A2$ corresponds to the locations of two aircraft in the spot-beam. The ROIs for A1 and A2 are also shown in the figure. Let C_p and C_b denote the cost of processing and cost of bandwidth for unit area of weather information. Clearly, the average bandwidth cost of broadcast channel is $C_b(2d)^2$. From Figure 2 it is easy to observe that for $K \geq d+1$, the complete area that is broadcast is required by all aircraft in the spot-beam. Thus, for $K \geq d+1$ the processing cost $p(x, y)$ for any aircraft at location (x, y) is zero. The additional bandwidth (over the uni-cast channel) $u(x, y)$ that

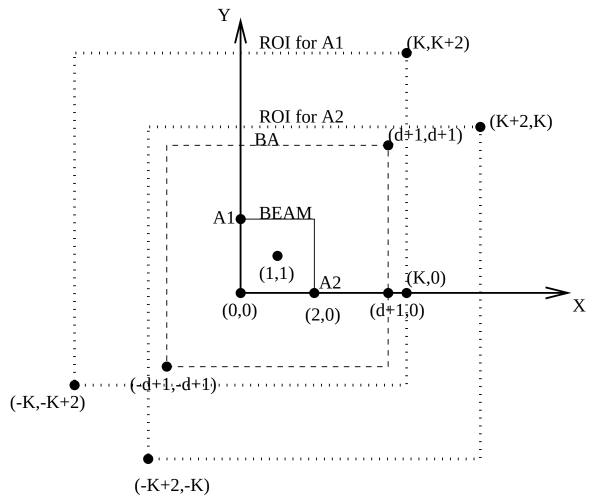

Figure 2: Set-up for the analysis.

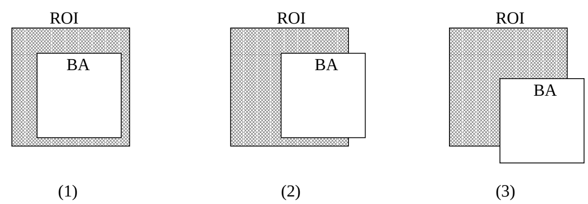

Figure 3: Three possible cases for the overlap of ROI and BA when $d \leq K < d+1$.

is required by an aircraft at location (x, y) is $u(x, y) = C_b((2K)^2 - (2d)^2)$. The average additional bandwidth cost is $\overline{u}(d) = C_b((2K)^2 - (2d)^2)$.

On the other extreme if $K < d-1$, then $u(x, y) = 0$, and the processing cost $p(x, y) = C_p((2d)^2 - (2K)^2)$.

For $d \leq K < d+1$, there is both bandwidth and processing cost for each aircraft. Notice that under the uniform distribution assumption, it is sufficient to focus on a single quadrant in the spot-beam. We can calculate the total requirements for the spot-beam from symmetry. Thus, we consider the aircraft to be located in the region $0 \leq x < 1$ and $0 \leq y < 1$. For the calculation of bandwidth and processing costs of an aircraft located at (x, y), we can identify three different cases which correspond to three cases shown in Figure 3:

1. $(K + x \geq d + 1, K + y \geq d + 1)$:

For this case, as illustrated in Figure 3, the ROI completely covers the BA. This is exactly the same situation as for the case $K \geq d+1$. $u_1(x, y) = C_b((2K)^2 - (2d)^2)$, while $p(x, y) = 0$.

2. $(K + x < d + 1, K + y \geq d + 1)$ OR $(K + x \geq d + 1, K + y < d + 1)$:

   The shaded area in Figure 3 corresponds to the area that needs to be transferred over the uni-cast channel, i.e. the source of the additional bandwidth cost. This area is given by $(2K)^2 - 2d(K + x + d - 1)$. The additional bandwidth cost for aircraft at location (x, y) is $u_2(x, y) = C_b((2K)^2 - 2d(K + x + d - 1))$. Right now, we focus on the calculation of the additional bandwidth costs. In the end we will show that processing costs can be derived from the bandwidth costs by symmetry.

3. $(K + x < d + 1, K + y < d + 1)$:

   The area of the corresponding shaded region in Figure 3 is $(2K)^2 - (K+x+d-1)(K+y+d-1)$. The additional bandwidth cost for aircraft at location (x, y) is $u_3(x, y) = C_b((2K)^2 - (K + x + d - 1)(K + y + d - 1))$.

The aircraft are uniformly distributed over the area of the spot-beam. The average bandwidth cost per aircraft, $\overline{u}(d)$, is calculated by taking expectation over the whole area of the spotbeam.

$$
\begin{aligned}
\overline{u}(d) &= \mathbf{E}\{u(d)\} \\
&= \mathbf{E}\{u(d) | K + x \geq d + 1, K + y \geq d + 1\} \mathbf{P}(K + x \geq d + 1, K + y \geq d + 1) + \\
&\quad + \mathbf{E}\{u(d) | (K + x < d + 1, K + y \geq d + 1) \text{ OR } (K + x \geq d + 1, K + y < d + 1)\} \\
&\quad \cdot \mathbf{P}((K + x < d + 1, K + y \geq d + 1) \text{ OR } (K + x \geq d + 1, K + y < d + 1)) \\
&\quad + \mathbf{E}\{u(d) | K + x < d + 1, K + y < d + 1\} \mathbf{P}(K + x < d + 1, K + y < d + 1) \\
&= (K - d)^2((2K)^2 - (2d)^2) + 2(d + 1 - K)(K - d) \int_0^{d+1-K} \int_{d+1-K}^{1} u_2(x, y)\, dy\, dx \\
&\quad + (d + 1 - K)^2 \int_0^{d+1-K} \int_0^{d+1-K} u_3(x, y)\, dy\, dx
\end{aligned}
$$

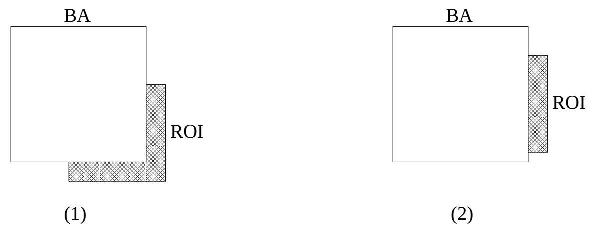

Figure 4: Two possible cases for the overlap of ROI and BA when $d-1 \leq K < d$.

When $d-1 \leq K < d$, for additional bandwidth cost we only need to consider the two cases depicted in Figure 4:

1. $(K+x < d+1, K+y < d+1)$:

   $u_1(x,y) = C_b((2K)^2 - (K+x+d-1)(K+y+d-1))$.

2. $(-K+y > -d+1, -K+x \leq -d+1)$ OR $(-K+y \leq -d+1, -K+x > -d+1)$:

   $u_2(x,y) = C_b(2K(K-x-d+1))$.

For $K+x > d+1, K+y > d+1$, BA completely covers ROI, so there is no information transfered over the uni-cast channel. The average bandwidth cost per aircraft, $\overline{u}(d)$, is calculated by averaging these quantities:

$$
\begin{aligned}
\overline{u}(d) &= \mathbf{E}\{u(d)|K+x<d+1, K+y<d+1\}\mathbf{P}(K+x<d+1, K+y<d+1) \\
&\quad +\mathbf{E}\{u(d)|(-K+y>-d+1, -K+x\leq -d+1) \text{ OR } (-K+y\leq -d+1, -K+x>-d+1)\} \\
&\quad \cdot\mathbf{P}((-K+y>-d+1, -K+x\leq -d+1) \text{ OR } (-K+y\leq -d+1, -K+x>-d+1)) \\
&= (d+1-K)^2 \int_0^{d+1-K}\int_0^{d+1-K} u_1(x,y)\,dy\,dx \\
&\quad +2(d+1-K)(K-d)\int_0^{d+1-K}\int_{d+1-K}^{1} u_2(x,y)\,dy\,dx
\end{aligned}
$$

The processing cost can be determined from the bandwidth cost by symmetry. Notice that while the shaded area in Figure 3 corresponds to the bandwidth cost for the case $d \leq K < d+1$, it also corresponds to the processing cost for the case $d-1 \leq K < d$. Similarly, the shaded areas in Figure 4 correspond to the bandwidth cost for $d-1 \leq K < d$, but also the processing cost of $d \leq K < d+1$. Consequently, the average processing per aircraft can be given as $\overline{p}(d) = \frac{C_p}{C_b}\overline{u}(2K - d + 2)$ for $d > K - 1$. As we have mentioned before, $\overline{p}(d) = 0$ for $d \leq K - 1$.

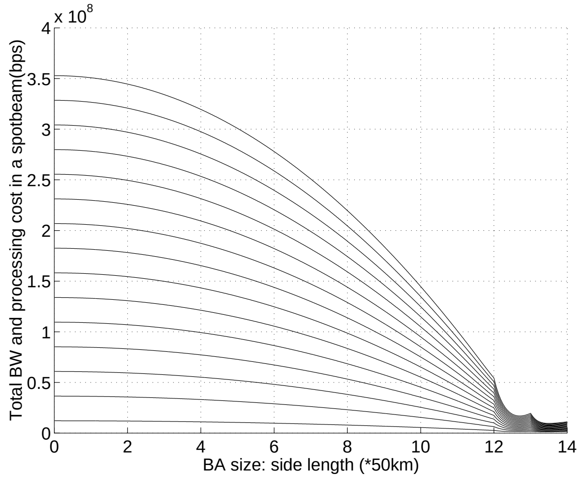

Figure 5: Total bandwidth and processing cost per spot-beam for Near-Term Strategic weather applications by LEO satellites vs. the size of the broadcast area for varying air traffic densities. Air traffic density changes between 0.5 and 15 aircraft per 100 km2.

5 Numerical Analysis

5.1 Weather Application Bandwidth Costs

A first-order analysis of the data size requirements to bring high quality weather information to the cockpit is performed in [2]. In the tactical domain weather information is assumed to be the resolution cells of the ground sensor. As discussed in more detail in [2] worst case scenario occurs when the aircraft flies near the ground sensor as the cell resolution of the ground sensor is highest. It is shown that using 30 degrees in elevation and 60 degrees of azimuth coverage provided by ground sensors spaced every degree requires 4.8 million bytes of information for a complete tactical region coverage. In the near-strategic domain weather information is assumed to be the resolution cells of the ground sensors available in the flight track. The desired range of weather information

Domain	**Total Weather Data Size (bytes)**	**Region size ($\mathbf{km^2}$)**	**Sampling rate (s)**
Tactical	4.8 E6	4.71 E4	60
Near Strategic	22 E6	4.24 E5	180
Far Strategic	4.0 E6	2.7 E6	600

Table 1: Communications requirements for a typical transport type aircraft cruising at 900 km/h. [2]

precludes the use of onboard sensors. A total of 28 million bytes of information will be required for a complete weather picture. In the analysis the authors have assumed the resolution of information to be the same as that of the tactical boundary. In the far-strategic domain weather information is assumed to be the resolution cells of the ground sensors available in the flight track with some loss in the quality of the image provided (5 pixels into 1).

Techniques to reduce communication bandwidth requirements are data compression techniques and a data validation and adaptive filtering algorithms to refresh weather cell elements that change from successive observations. It has been estimated that up to 25% of the weather information content could change between successive radar samples (using 60 second refresh rate) for a high-speed subsonic aircraft in the cruise mode. Anecdotal information from the NASA's Aviation Weather Information (AWIN) program [9] shows that tactical weather information savings are substantial using these two techniques. In one case the data filtering algorithms changed 41 kilobytes of a complete weather display (several Mbytes of information at 8 bit resolution).

The refresh rates of weather information are assumed to be consistent with the technology expected to be in place in the future. In [2] the authors assumed a technology multiplier that will provide faster sampling rate (down to one minute in 2020 for airport services). The tactical domain matters the most and has the fastest update cycle (60 seconds). It is argued that this level of detail over time would be sufficient to detect most of the harmful convective weather phenomena in the terminal area. Table 1 summarizes the communication requirements for a single aircraft.

Based on this analysis, we can determine the unit bandwidth costs for the three ROI options:

Domain	*Region Size (km^2)*	*Bandwidth (bps/km^2)*
Tactical	$4.71 \cdot 10^4$	13.58
Near Strategic	$4.24 \cdot 10^5$	2.31
Far Strategic	$2.7 \cdot 10^6$	0.02

Table 2: Unit Bandwidth costs.

Tactical, Near-Term Strategic and Far-Term Strategic. Table 2 summarizes these costs.

5.2 Simulation Results

For our base numerical studies we assumed that complete weather map (tactical, near-term strategic or far-term strategic) is delivered to the aircraft completely, periodically and continuously. That is, we do not consider differential information delivery solutions where only the data that has changed from the previous refresh period is delivered to the users. We also assume that the data transmitted is not compressed. An analysis that takes into account efficiencies derived from differential transmission, compression, etc. could easily be built on top of our basic analysis. In the next section, we present appropriate bandwidth reduction factors and discuss their implication.

The analysis we now present is driven by the ratio of processing cost to bandwidth cost. Given that we are projecting well into the future, it is difficult to determine a specific value for this ratio. We have chosen a nominal value of .1, which gives more weight to bandwidth, but leaves processing with still a significant impact. Both costs are measured in terms of bits per second (bps).

Figure 5 depicts the results of this analysis for delivering the Near-Term Strategic information using LEO satellites.The figure displays the variation of total cost versus the varying sizes of BA for different air traffic densities. A significant result of this analysis is that the optimal BA size is less than the size of the ROI by only a small fraction. For the specific case analyzed, the optimal diameter of the BA is 25 km less than the diameter of the ROI. Another important characteristic is tht optimal BA size is independent of the air traffic density. Although this result may seem counter-intuitive, it is reasonable due for the following reasons. First, the ROI of each aircraft is much larger than the area of the spot-beam. In the worst case, where all aircraft are collected at the opposite corners of the spot-beam, the ROI of these aircraft still overlap considerably. Consequently, it is better to broadcast a large area. Second, we assumed that the aircraft are uniformly distributed over the geographical area corresponding to the spot-beam. Thus, even though there may be a very small number (or very large number at the other extreme) of aircraft in the spot-beam, since any aircraft may be located at any location in the spot-beam with equal probability, on the average the optimal broadcast area will be the same for both low and high traffic density.

Figure 6 depicts the optimal BA size for delivering Near-Term Strategic weather information by GEO satellites. Similar arguments discussed for the LEO case apply here as well.

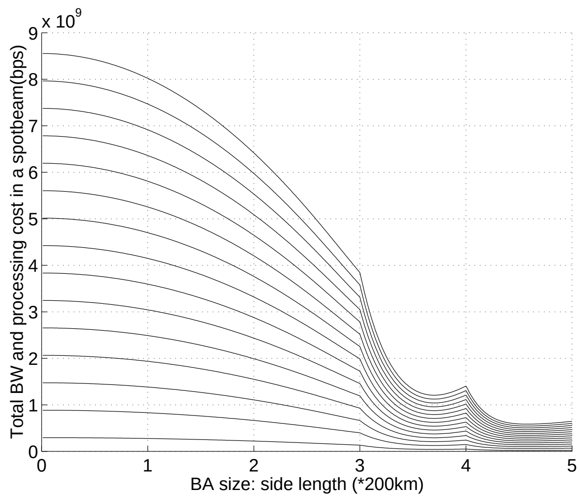

Figure 6: Total bandwidth and processing cost per for Near-Term Strategic weather applications by GEO satellites vs. the size of the broadcast area for varying air traffic densities. Air traffic density changes between 0.5 and 15 aircraft per 100 km2.

We also investigated the variation of the optimal BA size with respect to the processing cost. Figure 7 depicts the variation of total cost with respect to BA size for varying unit processing costs. We observe that as the processing cost increases the optimal BA size that minimizes the total cost decreases. Notice that when the unit processing cost is low, then the total cost mainly consists of bandwidth cost.

In Figure 8 we investigate the variation of optimal BA size with respect to the processing cost. It is interesting to observe that the optimal BA size decreases with a *jump* as the processing cost

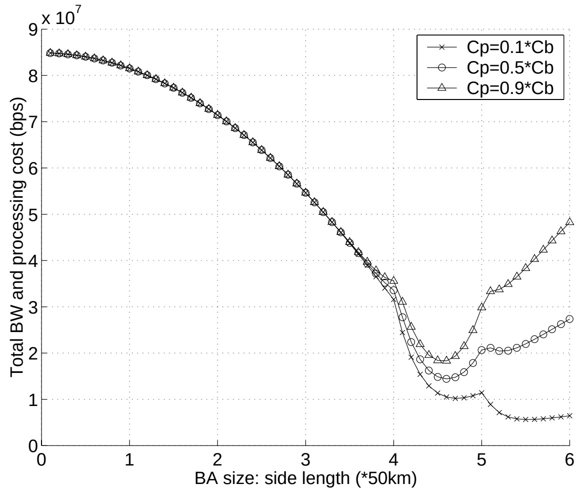

Figure 7: Total Bandwidth and processing cost compared for varying processing cost for Tactical weather application via LEO satellites. Air traffic density is 4 aircraft per 100 square km area.

increases. This jump arises from the nonlinearity of the total cost function as depicted in Figure 7.

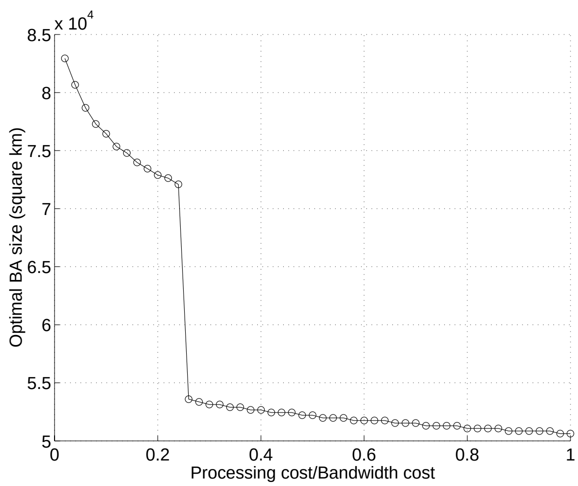

Figure 8: Optimal BA size for varying processing cost for Tactical weather application with LEO satellites. Air traffic density is 4 aircraft per 100 square km area.

In Figure 9 we observe the variation of optimal bandwidth cost with respect to the processing cost. The bandwidth cost increases as the unit processing cost increases. The optimal bandwidth cost also increases with a jump like the optimal BA size. This result is not as surprising as it first seems. Notice that our optimization objective is the minimization of total bandwidth and processing costs. As the processing cost is varied, the total cost changes continuously, but one of its components namely the bandwidth cost may not.

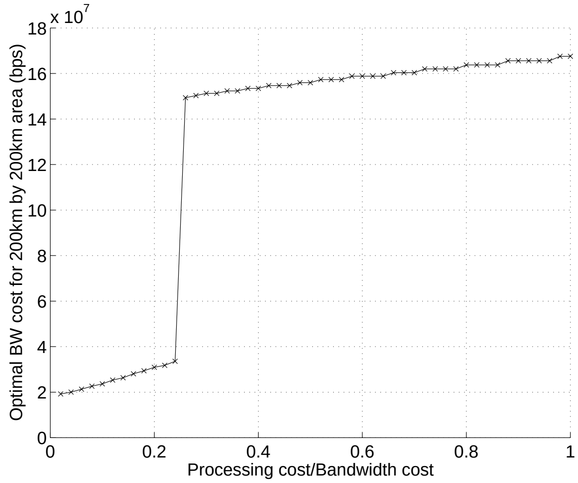

Figure 9: Optimal total Bandwidth cost per 200km by 200km area for Tactical weather application with LEO satellites. Air traffic density is 4 aircraft per 100 square km area.

In the following analysis the unit processing cost is set to one tenth of the unit bandwidth cost. In Figures 10 and 11 we compare the bandwidth requirements for each type of ROI with LEO and GEO satellites with respect to varying air traffic densities. For each curve we consider that the optimally sized BA is broadcast over the broadcast channel. Thus, the bandwidth requirement for each curve is the minimum for that type of application. In Figure 11, we focus on the variation in bandwidth requirements for the far-term strategic case served by LEO and GEO satellites.

We can observe that the derivative of the total bandwidth requirement for the LEO case is smaller than the GEO case. Notice that LEO satellites have smaller spot-beams. The ROI of each aircraft in a LEO spot-beam substantially overlap. The broadcast channel of a LEO satellite can, thus, deliver a more customized view where each aircraft requires less information to be transferred over the uni-cast channel. Since less information is transferred over the uni-cast channel, as a function of air traffic density, for the LEO case, the total bandwidth requirement does not increase as fast as in the GEO case. However, in order to cover the same area as the GEO satellite spot-beams we require multiple LEO spot-beams. Each LEO spot-beam has a broadcast channel which delivers the information that has a significant overlap with the information delivered over the broadcast channels of adjacent LEO spot-beams. Thus, in order to deliver comparable service to a same sized area, a LEO satellite solution consumes a larger amount of bandwidth over the broadcast channels compared to the GEO case. This leads to higher bandwidth requirements for LEO solution compared to the GEO case, when the air traffic density is low.

In Figure 10 we observe that, when the air traffic density is below 8 aircraft per 100 km^2, GEO satellites require less bandwidth for the delivery of Near-Term Strategic information. For Far-Term Strategic applications, however, we notice that (Figure 11) the GEO solution is always better than the LEO solution.

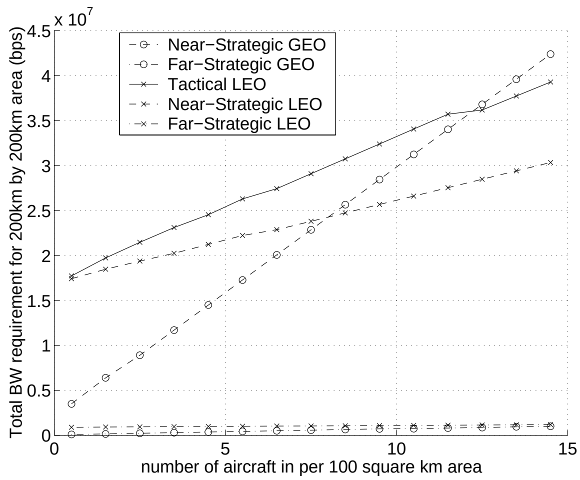

Figure 10: Total bandwidth requirements for different weather applications when served by LEO and GEO satellites for varying air traffic densities.

In Figures 12, 13 and 14 we compare the bandwidth requirements of uni-cast-only and broadcast-only solutions with the hybrid case. As depicted in these figures, the uni-cast-only solution is the worst. In the broadcast-only solution, the country is still divided into cells, however, in each cell there is a single channel, which broadcasts the required information for all aircraft. The broadcast-only solution appears to be better than the hybrid LEO case when the air traffic density is very low, since for the broadcast-only case we assumed larger cell sizes. For low air traffic density, the hybrid GEO solution appears to be the best. The hybrid GEO solution seems to combine the best of the two alternatives: broadcast and uni-cast. GEO satellites have larger spot-beams, which leads to

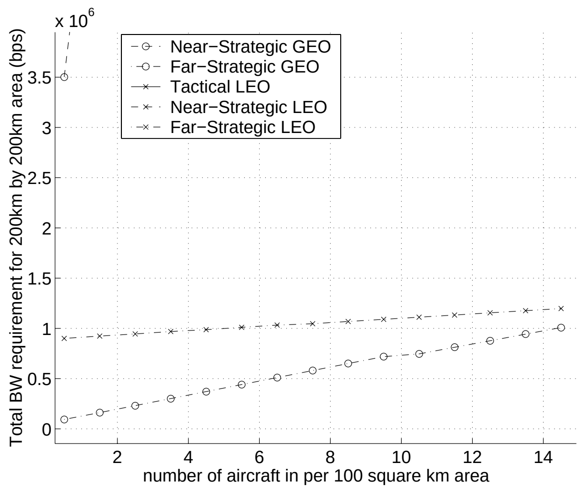

Figure 11: Total bandwidth requirements for different weather applications when served by LEO and GEO satellites for varying air traffic densities.

efficient use of the broadcast channel, and they have an additional uni-cast channel for delivering unique information for each aircraft. However as the air traffic density is higher we observe that hybrid LEO solution is better than the hybrid GEO solution. LEO satellites, due to their smaller spot-beams, can deliver a more customized view for each aircraft over the broadcast channel. Thus, each aircraft requires less information to be transferred over the uni-cast channel. However, the broadcast-only solution is the best solution for high air traffic densities. Notice that our optimal BA size is very close to the convex hull of the ROIs of all the aircraft in the spot-beam. In the broadcast-only solution we broadcast this convex hull of all ROIs, so that, as the aircraft density becomes higher, the total cost of the uni-cast channels becomes larger than sending the additional area of the convex hull over the broadcast channel.

6 Discussions and Remarks on the System

A number of interesting conclusions can be derived from the preceding analysis. Our first conclusion is that the BA size that leads to the minimum total bandwidth and processing costs is relatively independent of the air traffic density. This result enables a single static solution that can be applied throughout the country. Although the optimal broadcast area does not change with respect to the

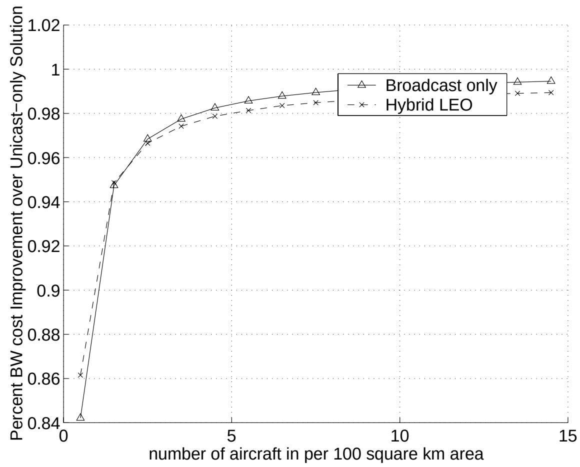

Figure 12: Total bandwidth requirements for Tactical Weather Application under different delivery options. Total bandwidth requirement for broadcast-only solution is 20.214 Mbps.

air traffic density, for low air traffic densities the hybrid-GEO solution can provide better bandwidth efficiency. Furthermore, when the air traffic density is high, the broadcast-only solution appears to be the best considering bandwidth efficiency. For TRACONs and within the terminal area, broadcasting can provide the lowest bandwidth requirements. However, for the delivery of far-strategic information in the en-route environment, use of a hybrid-GEO solution can provide the best bandwidth utilization.

We also demonstrated that future applications will require high bandwidth communication links. This supports the use of next generation satellite systems as an alternative to the current terrestrial systems. Table 3 summarizes the bandwidth requirements for different weather applications under different delivery options. The first row gives the bandwidth requirements for the three application categories assuming only uni-cast channels. The second row gives these same requirements under the assumption that the data transferred per refresh cycle can be reduced to 30% of its nominal value to account for differential delivery schemes and possible compression [2]. The third row gives the uni-cast bandwidth requirements for the advanced weather products that are derived using information derived from weather sensors placed on aircraft. Again the 30% reduction factor is assumed. The final three rows give bandwidth reduction factors associated with broadcast or hybrid

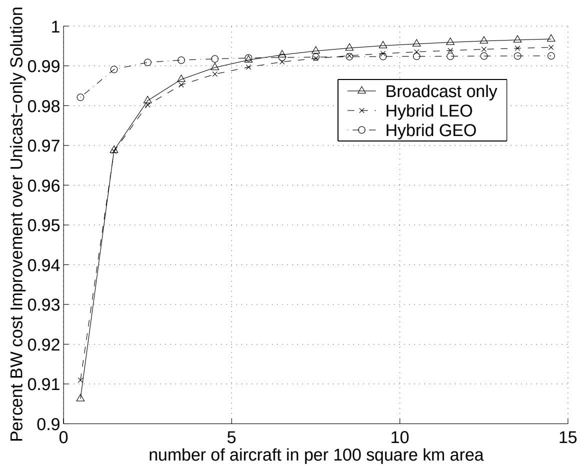

Figure 13: Total bandwidth requirements for Near-Term Strategic Weather Application under different delivery options.

architectures. The values in the rows assume nominal aircraft densities. These densities, which are derived in [2], are 2 aircraft per 1000 km^2 for enroute (far-strategic), 5 aircraft per 1000 km^2 for terminal area (near-strategic) and 9 aircraft per 1000 km^2 for tower area (tactical).

An issue that arises in a broadcast cellular system with mobile nodes is the timing of information broadcasts in adjacent cells. Like any other broadcast information delivery system, the information is broadcast according to a schedule. Assume for the sake of discussion, the same information is broadcast in two adjacent cells. A mobile user traversing different cells may encounter a different portion of the schedule in the new cell it is entering than the portion of the schedule in the cell it has just left, if the schedules are not perfectly synchronized. In the worst case, the mobile user may have to wait for the entire duration of a broadcast schedule to receive the part of information that it requires. In our case, the information that is broadcast, is not exactly the same though a large portion is common in adjacent cells. For this reason, synchronizing the schedules is not possible. To ensure all information in the ROI of the aircraft is updated according to refresh rate, we may increase the broadcast transmission rate, and the aircraft may request certain information that is *late* according to the schedule via the uni-cast channel. This type of information request will only occur once every time an aircraft changes spot-beams. Thus, the effect of this transient behavior

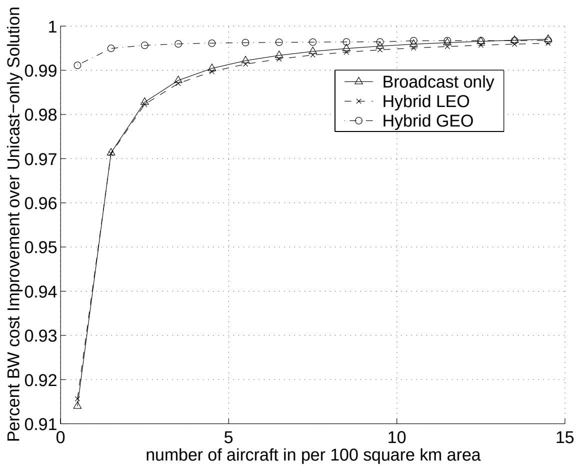

Figure 14: Total bandwidth requirements for Far-Term Strategic Weather Application under different delivery options.

should be be low compared to the overall uni-cast channel bandwidth requirements.

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	Tactical	*Near-Strategic*	*Far-Strategic*
Unicast BW requirement per aircraft	640 kbps	977 kbps	53 kbps
Unicast BW requirement per aircraft with differential transmission (30% updated)	192 kbps	293.1 kbps	15.9 kbps
Unicast BW requirement per aircraft when aircraft acts as a sensor with differential transmission	577 kbps	1.42 Mbps	49.63 kbps
Reduction factor in BW requirement by broadcast GEO at nominal air-traffic density	0.86	0.905	0.91
Reduction factor in BW requirement by hybrid GEO at nominal air-traffic density		0.98	0.99
Reduction factor in BW requirement by hybrid LEO at nominal air-traffic density	0.88	0.91	0.91

Table 3: A summary of bandwidth requirements under different approaches at nominal air traffic densities.

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