UNIVERSITY OF CALIFORNIA
IRVINE

Dynamic Resource Management in Future Satellite Systems to Improve Resource Utilization

THESIS

submitted in partial satisfaction of the requirements
for the degree of

MASTER OF SCIENCE

in Electrical Engineering

by

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2016

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ACKNOWLEDGMENTS

I would like to express my gratitude to everyone who supported my graduate studies. My parents and family have been a source of inspiration. I am always grateful for their support. I would like to thank my thesis advisor Dr. Ahmed Eltawil for this guidance during my thesis courses. I am grateful to Dr. Ender Ayanoglu and Dr. Sayed Ali Jafar for serving in thesis committee member.

My gratitude extends to Mr. Todd Hill and Mr. Christopher McLain for their continuous support during my graduate studies. I was privileged to meet some of the greatest faculties during my college years. I benefited tremendously from their professional expertise. I would like to thank them all.

ABSTRACT OF THE THESIS

Dynamic Resource Management in Future Satellite Systems to Improve Resource Utilization

By

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Master of Science in Electrical Engineering

University of California, Irvine, 2016

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Satellite-based broadband communication has experienced increased growth in Communications on the Move (COTM) platforms such as maritime, commercial aviation, and government aviation. COTM antennas must address the challenge of offering a desired data rate to users using wide beam satellites which are disadvantaged with low gain and asymmetric gain patterns. The new High Throughput Satellite (HTS) designs have large numbers of small spot beams, reuse frequency across the beams, and offer higher EIRP and G/T to address the challenges encountered by COTM. Satellite resources, mainly power and bandwidth, need to be allocated to meet the peak capacity demand in each of the HTS beam rather than the sum of the capacity demand in all HTS beams. This typically results in a larger capacity requirement to satisfy.

The researcher proposes a ground-based solution to plan transmission in HTS beams and dynamically adapt parameters such as bandwidth and transmission power in an HTS equipped with Multi Port Amplifier (MPA) such that the demand for the capacity that changes with time can be met in real time. At any given time, the available power and

bandwidth can be assigned to a beam based on its demand by varying the input power levels. Since the conventional transmission in satellite service is fixed and based on the peak demand in each beam, this solution will reduce the satellite resources required to meet the capacity demand and significantly benefit COTM services.

CHAPTER 1: INTRODUCTION

Satellite Communication

Communication satellites have provided service for over half a century. In their early operation, the principal use was for television broadcasts - ranging from President Eisenhower broadcasting a Christmas message globally to sporting events such as the Olympics and World Cups [1].

The first satellite was Sputnik, launched by the Soviet Union in 1957, which started the space race between the Soviet Union and the United States. After the creation of the National Aeronautics and Space Administration (NASA) by the Kennedy administration, the United States launched several space-related projects, including numerous satellites. In 1958, the United States launched project SCORE (Signal Communications by Orbiting Relay Equipment) sending the first communication satellite into orbit [2]. In 1961, NASA launched the Synchronous Communication Satellite (Syncom), the first geosynchronous satellite. Due to the constant relative location between the satellite in orbit and the communication station on the ground, geosynchronous satellites became the dominant satellites used in communication applications. Geosynchronous communication was expanded to early internet research and applications. In 1970 the University of Hawaii developed ALOHAnet, the first packet radio network (i.e., computer combined with a modem and transceiver) connecting computers between islands [3].

Satellites act as relays in communication applications such as media broadcasting, two-way radio, or the Internet. Figure 1 provides a simple illustration of how a satellite receives the signal that is transmitted from the gateway (or transmitting) communication station on the ground, amplifies the signal, and transmits it back to the receiver on the ground. Although communication satellites are increasingly more complex, the majority of communication satellites presently use the “bend the pipe” technique to receive, amplify and retransmit the signal as illustrated in Figure 1.

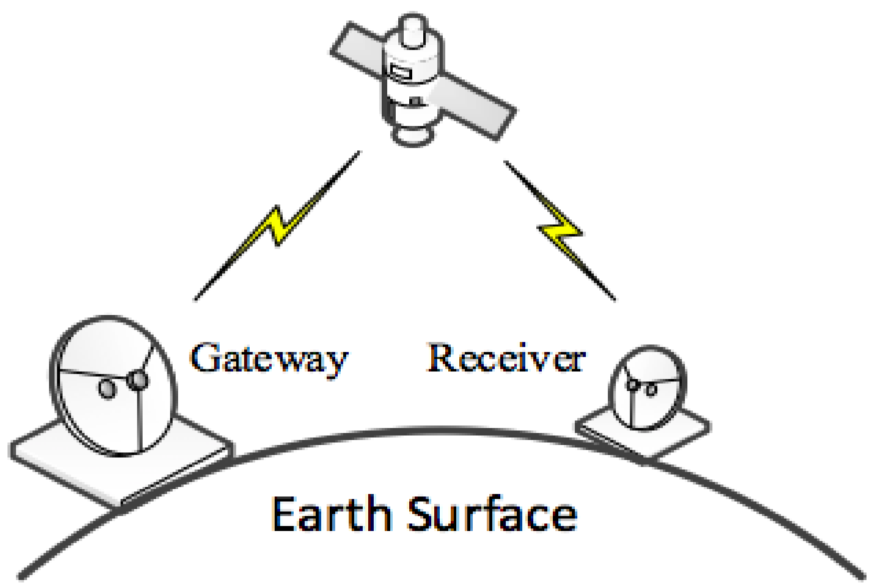

Figure 1: Satellite communication model

Satellite Beams and Transponders

Satellite payloads are designed to provide services in specific coverage regions. The illuminated beam shape and size varies and is based on the desired service area, international coordination, and international political boundaries. Satellite beams can be categorized into two types: wide beams and spot beams.

Wide Beams: Wide beams are typically created to maximize the coverage area. A wide beam can cover as much as 42% of the earth's surface from a single orbital location in the geostationary arc. With the help of three geostationary satellites, earth's surface can be almost completely covered; only the areas north and south of 81° latitude are omitted. This offers flexibility to deliver communication services in most parts of the world.

The antenna's physical properties and its directionality determines the area a beam can cover. The cross-sectional area, A_a, with respect to the half-power beamwidth, θ, of a circular satellite antenna is given by:

$$A_a = \pi \frac{\theta^2}{4} \tag{1}$$

In order to cover the continental United States, a cross-sectional area of 11.8 deg^2 is needed, which can be achieved with an antenna of gain around 32 dBi [5]. Figure 2 shows an example of a wide beam covering the North Pacific Ocean by Eutelsat 172B [4].

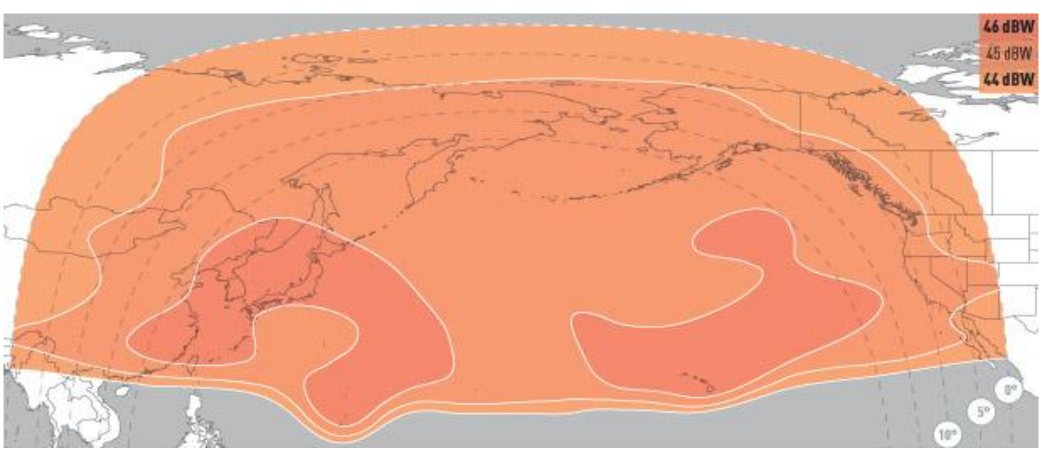

Figure 2: Wide beam satellite covering North Pacific region

Spot Beams: Spot beams are generally smaller than wide beams. Satellites that are equipped with a large number of spot beams are categorized as a High Throughput Satellites (HTS) because of the added capacity of the satellite in delivering throughput. Depending on frequency band, desired coverage, and desired capacity, the size of a spot beams varies but are generally around 2° for a high frequency band such as Ku and Ka-band. Spot beams are created to concentrate energy into a small area, reuse frequency, increase overall capacity of the satellite, and improve service in high user density areas. Spot beams offer benefits that wide beams cannot. Frequency re-use is one of the biggest benefits for a region where spectrum is limited and demand is high. Figure 3 shows the spot beams covering the North Pacific region by the Eutelsat 172B satellite [4].

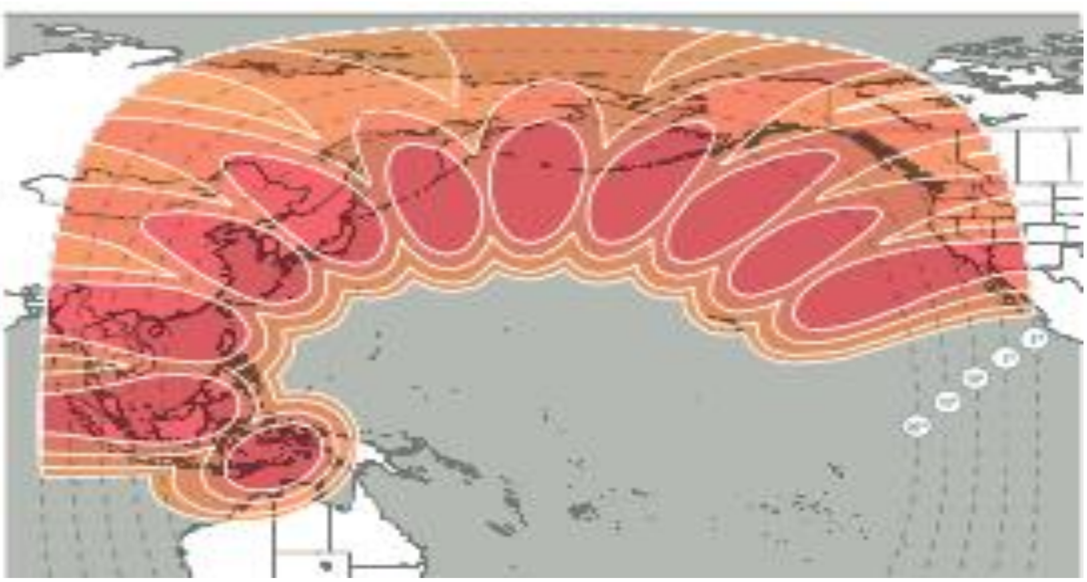

Figure 3: Spot beams satellite covering North Pacific region

Because of the energy distribution in a small area, a spot beam offers higher spectral efficiency in a communication link. It allows a small terminal to be mounted on a vessel and offer a broadband communication link which otherwise would not have been possible or would offer a very modest data rate.

Broadband Connection

Countries with an advanced economy generally offer high-speed data links to both urban and suburban areas via fiber optics, coaxial, twisted cable, and microwave relays. Places such as Alaska, Northern Canada, parts of Russia, Northern Australia, and Africa, rely on alternate means for their data connection – satellite based communication. Although satellite services have their own challenges, it is the only available means of broadband connection in such communities. It is possible that satellite-based broadband services will be migrated to fiber or microwave services in the future, but communication on the move (COTM) broadband service as is used in commercial aviation, military aviation, and maritime *will continue* to rely on satellite communication for the foreseeable future.

Geostationary satellites are commonly used for broadband service for both Fixed Satellite Service (FSS) and Mobile Satellite Service (MSS). Use of satellite in both FSS and MSS for such service have many advantages.

1) Large Coverage: Satellites cover a large geographic area with a wide beam. This can easily expand not only to cover a large country but also an entire continent. A geostationary satellite can cover up to 42% of earth's surface. That means that three such satellites can cover the entire visible earth from the geostationary arc.

Satellites are the only available service for COTM over oceans and large, sparsely populated expanses of land.

2) Higher Mobility: Satellites allows the user to move anywhere with a small antenna (earth station) and receive communication service. This often becomes the first choice for researchers, military, and explorers. It can reach where no other communication options are viable.
3) Small Infrastructure Footprint: With a minimum of two antennas, service can be established. The gateway earth station antenna is located at an accessible location and connected to the backbone network. This gateway is stationary and is able to keep its antenna pointed in one location without much adjustment due to the satellite's geostationary orbit. The second remote earth station antenna can operate anywhere within the footprint of a satellite.
4) Disaster and Rescue: Higher mobility and small infrastructure footprint enables satellites service to be the first source of connectivity during natural disasters.
5) Video Broadcast: Because of the large coverage of subscriber satellites, this is an ideal method for a broadcast services like television. Often the wide beams are created for a targeted viewer considering broadcast applications.

Figure 4 shows the typical hub to spoke satellite service.

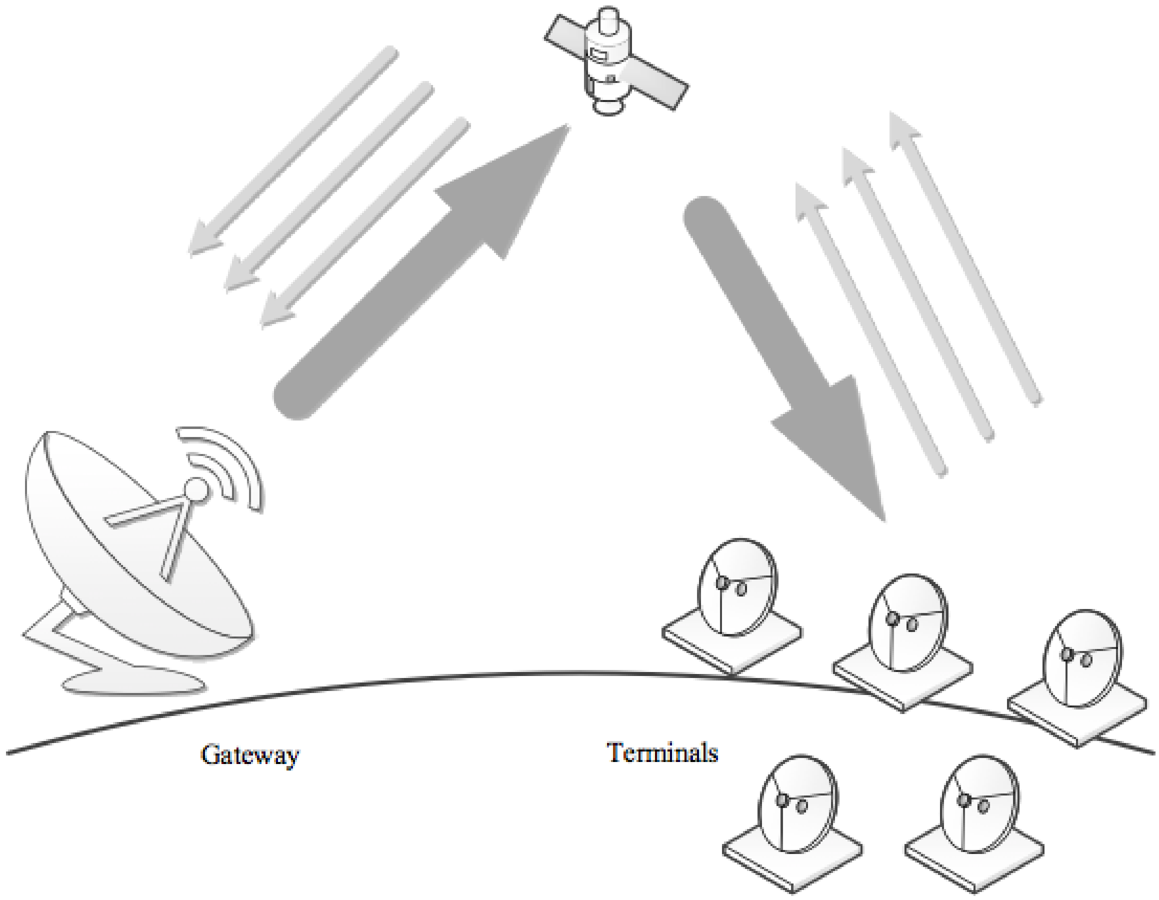

Figure 4: Typical broadband connectivity using the hub to spoke topology

CHAPTER 2: SATELLITE COMMUNICAITON ON THE MOVE (COTM)

Satellite-based broadband communication is a better solution for moving platforms such as buses, trains, planes, and ships. For aviation and maritime, satellite based broadband service is the only solution. It is impossible to have a physical connection such as fiber optics cable to an aircraft at 35,000 feet altitude. They operate outside of the terrestrial service areas and other radio range. Very High Frequency (VHF) radio is an option for kbps range of traffic for aeronautical and maritime services but it is lower in data rate than many of the modern communication applications and has a limited range of coverage. For safety purposes, maritime and commercial aviation have been using low data rate satellite-based service for a number of years now.

In 2003, the first vehicular communication using satellites was demonstrated by NBC when broadcasting a live video from Iraq. The retrofitted truck with a maritime auto-pointed antenna operating in Ku-band allowed the crew to broadcast live video from a war zone. Later, the US government adapted COTM on its inventory [10]. Today COTM is one of the fastest growing applications for satellite communication.

Maritime Communication

The history of maritime communication dates back to 1979 when a non-profit organization, the International Maritime Satellite Organization (Inmarsat) was formed by 54 member countries [6]. Communication capability was limited to safety, telemetry, and rudimentary communication needs. It was expanded to voice and email service using a C or L-band gateway earth station on land and a terminal earth station antenna on a vessel.

Internet surfing was available afterwards. The L-band based connectivity showed noticeable improvement from the prior data rate. Branded as *FleetBrodband* by Inmarsat, it had a rate of 432 Kbps with global coverage and was used for low data services [7]. The next generation broadband service *SEVSAT* used Ku-band satellites to offer service up to 2 Mbps with near-global coverage allowing applications such as high volume data and VPN. The limitation on the data rate has been improved over years in maritime applications and Inmarsat is now offering up to 50 Mbps with global coverage using spot beam satellite in Ka-band. As part of the newest satellite constellations, Inmarsat-4 provides broadband service in maritime, up to 50 Mbps. An Inmarsat-4 series satellite not only delivers higher capacity to the maritime traffic, it also employs a frequency re-use technique by using spot beams to improve the total capacity by several orders of magnitude. Figure 5 shows the Inmarsat-4 satellite covering global traffic that includes maritime and aeronautical services [8].

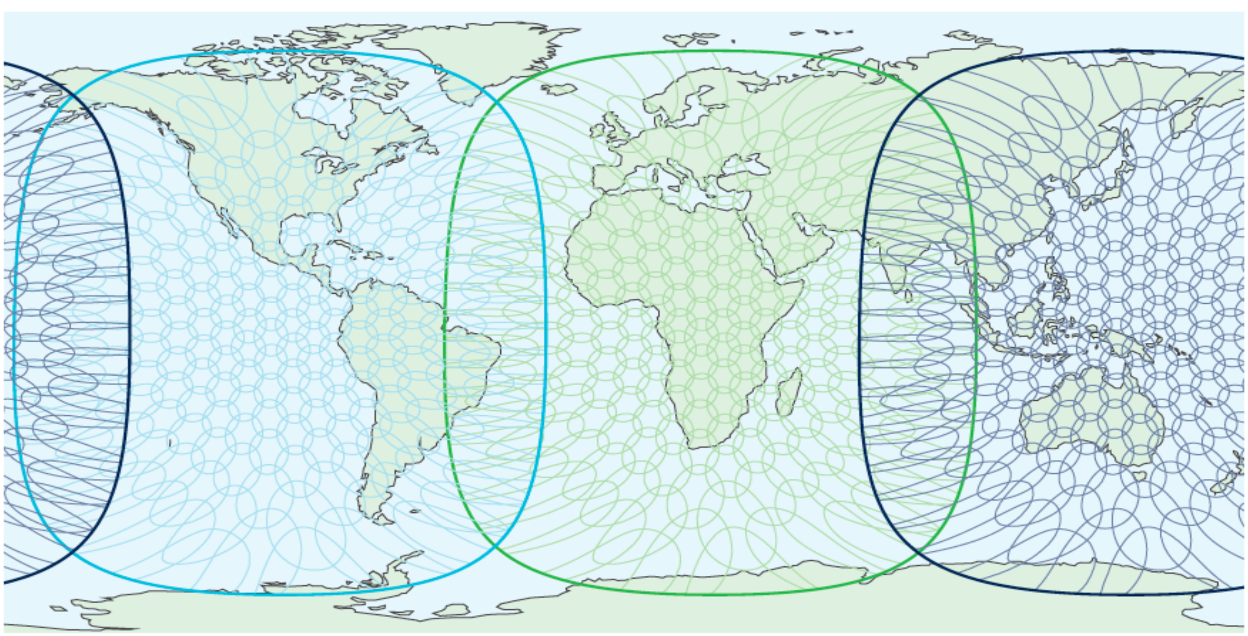

Figure 5: Global coverage for the Inmarsat-4 satellite constellation

Similar to other broadband services, commercial maritime applications for internet service use a hub to spoke topology with a large outbound link shared amongst a number of ships with smaller return link – commonly time division multiplexed. Maritime vessels can be in various sizes and can have different capacity demands. Large cruise ships with high numbers of passengers require a high data rate in the range of several hundred Mbps. In order to deliver such data rates, a vessel would require a large, stabilized parabolic antenna with a diameter of 2.4 meters and require a full transponder worth of capacity on a satellite. Conversely, a small yacht will have less space for large antenna and is either unable to receive satellite service or limited to modest data rate using a much smaller antenna.

Aeronautical Communication

The aeronautical market adopted satellite based communication for broadband service much later than maritime. VHF and L-band communication solutions are primarily used for critical communication but are far less capable and limited in range for broadband services. Inmarsat has been providing critical communication option globally but this option is limited to low data throughput and voice channels. NASA demonstrated the first aeronautical broadband communication in mid-nineties under the Advanced Technology Communications Satellite (ACTS) program [10]. The *Connexion by Boeing (CBB)* program became the first commercial broadband satellite service for aeronautical applications targeted at airline passengers and crew. *CBB* offered 20 – 40 Mbps data rates to the aircraft and up to 1 Mbps from the aircraft using continental-scale wide beam FSS satellites [11]. The program began in 2002 in the US and was expanded to trans Atlantic routes in 2003 and the Asian and European regions in 2004 [11]. Although Boeing continued this service for government customers, the commercial service was discontinued in 2006. The discontinued service highlighted the many hurdles in technological development and economic viability of satellite-based broadband service for the commercial aviation market.

Recently, other operators have started offering similar service by picking up where Boeing left off in the commercial aviation market using similar methods and technology as *CBB*. Panasonic Avionics, Global Eagle, Viasat, and Gogo are some of the leading operators offering broadband connectivity to commercial aviation today. Figure 6 shows a map illustrating the satellites, satellite beams, and gateway locations of the global aeronautical broadband service offered by Panasonic Avionics Corporation [12].

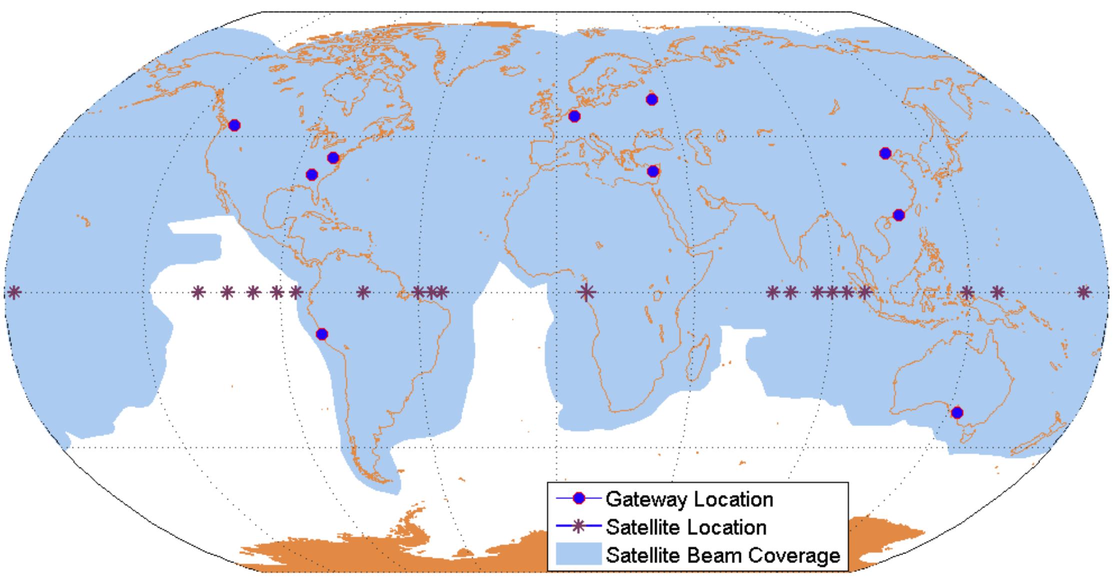

Figure 6: Global satellite coverage built for aeronautical broadband communication

Challenges in COTM

Satellite communication is a challenging medium for any communication applications. The service expansion to COTM adds more challenges – one need only to observe the discontinuation of *CBB* program in the commercial aviation space by one of the largest US companies to understand these challenges. Some of the most difficult challenges associated with broadband service in COTM are described below.

Cost: Building a satellite, launching it into orbit, and retiring it after 15 years adds a tremendous cost burden to a mission. On top of the massive cost of construction, satellite launches also have a large failure rate - about 5%. The manufacturing, launching, and operating of a satellite is more expensive than other communication infrastructure. Such cost is passed from the satellite operator, who commissions and launches the satellite and maintains its orbit and service, to the broadband service operator. The operator leases the transponder bandwidth and power on the satellite. Satellite communication requires more parties to be involved in delivering the end service, making it more expensive than other alternative communication techniques.

Low Gain Antenna: Antennas built for COTM are heavily constrained in size because they must be mounted on a moving platform. Such limitation is due to both the real estate available and aerodynamic requirements, which lead to a smaller-size antenna. A smaller antenna delivers lower gain both in transmit and receive because of its linear dependency with the surface area, which impacts the data rate. The gain of the antenna with aperture area A, efficiency k, and wavelength of operation λ is:

$$G = \frac{4\pi kA}{\lambda^2} \tag{2}$$

Wide Satellite Beams: Most satellite beams that are available today are built for television broadcast and land-based satellite broadband communication using Very Small Aperture Terminals (VSATs). Large wide beams have low EIRP and G/T create another challenge to maintaining a link and delivering broadband data rates with low gain COTM antennas. Most satellites offering service today are wide beams with traditional satellite transponders.

Asymmetric Antenna: Antennas mounted on COTM platforms are not necessarily uniform and circular. Aerodynamic consideration limits aeronautical antenna to be either rectangular plate or flat panel mounted on the fuselage. In such antennas, the gain pattern changes with the plane of view between aeronautical antenna and satellite throughout the flight. An antenna that is rectangular and is steered mechanically to a satellite, has a beamwidth and gain pattern that changes significantly with skew angle; the antenna picks up of interference from adjacent satellites – commonly known as Adjacent Satellite Interference (ASI). A skew angle of 0° is the result of the terminal antenna, which is at same longitude as the satellite longitude and increases to 90° at the equator.

Figure 7 shows the antenna gain pattern for a typical aeronautical antennal with a rectangular shape [12]. A second antenna type, electronically scanned phased arrays, can be mounted on a platform with a gain change with elevation angle in addition to skew angle to improve performance.

Figure 8 shows the gain of electronically steered antennas roll off as a function of elevation angle [12]. Such variation in antenna performance, which in large part varies with the geo-location where terminals are operating affects the date rate, spectral efficiency, and creates an interference environment.

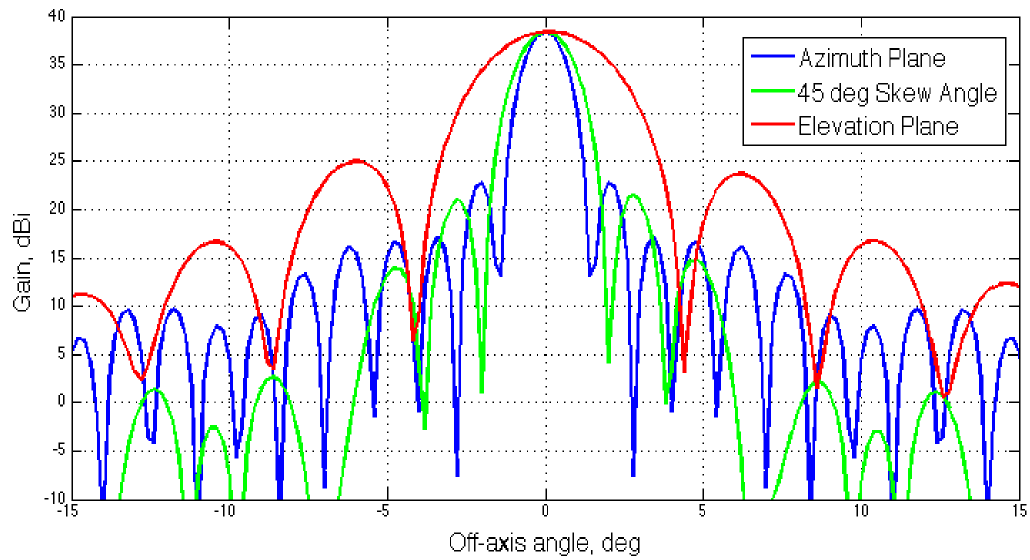

Figure 7: Gain pattern variation of a mechanically steered flat panel antenna

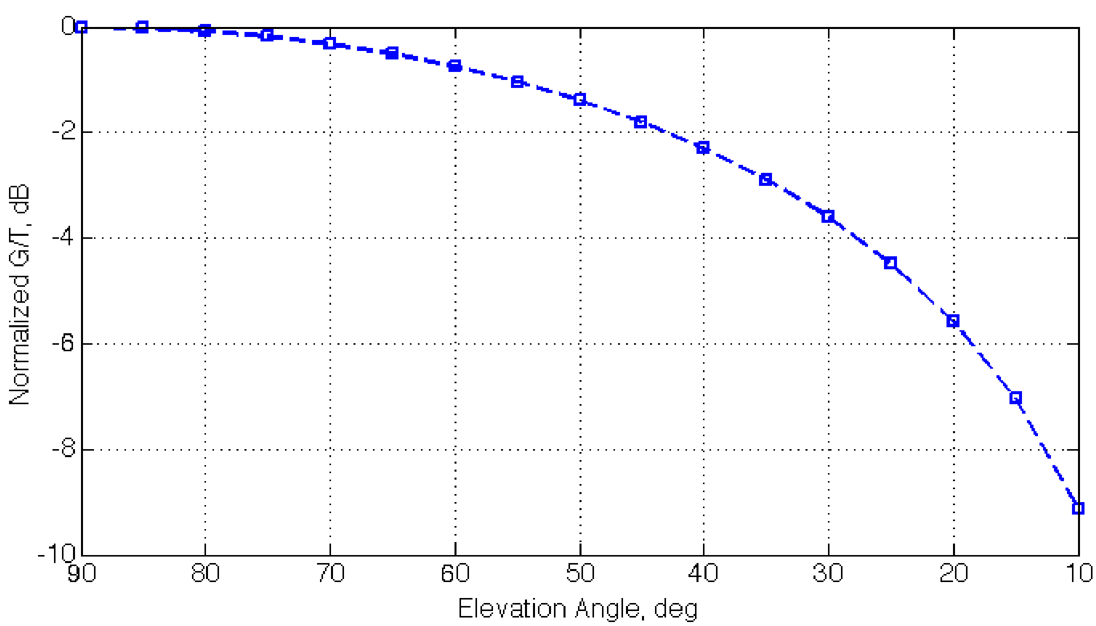

Figure 8: Relative loss in antenna gain as function of elevation angle

Low gain and an asymmetric antenna operating in wide beam satellite with low EIRP and G/T lowers the spectral efficiency of the broadband service for COTM applications.

Capacity Planning for Peak Demand: Maritime and aeronautical traffic are highly mobile and their traffic is growing and will continue to grow. Commercial aviation has long non-stop flight ranging up to 18 hours. Their peak traffic in a beam can occur for a short time window. The capacity must be planned for the peak demand, thus it is underutilized for a majority of the time. Figure 9 shows an example where the number of aircrafts in a beam peaks at a small time window – at UTC 24:00:00 in this example. The example highlights the typical traffic and corresponding demand in a beam for COTM service.

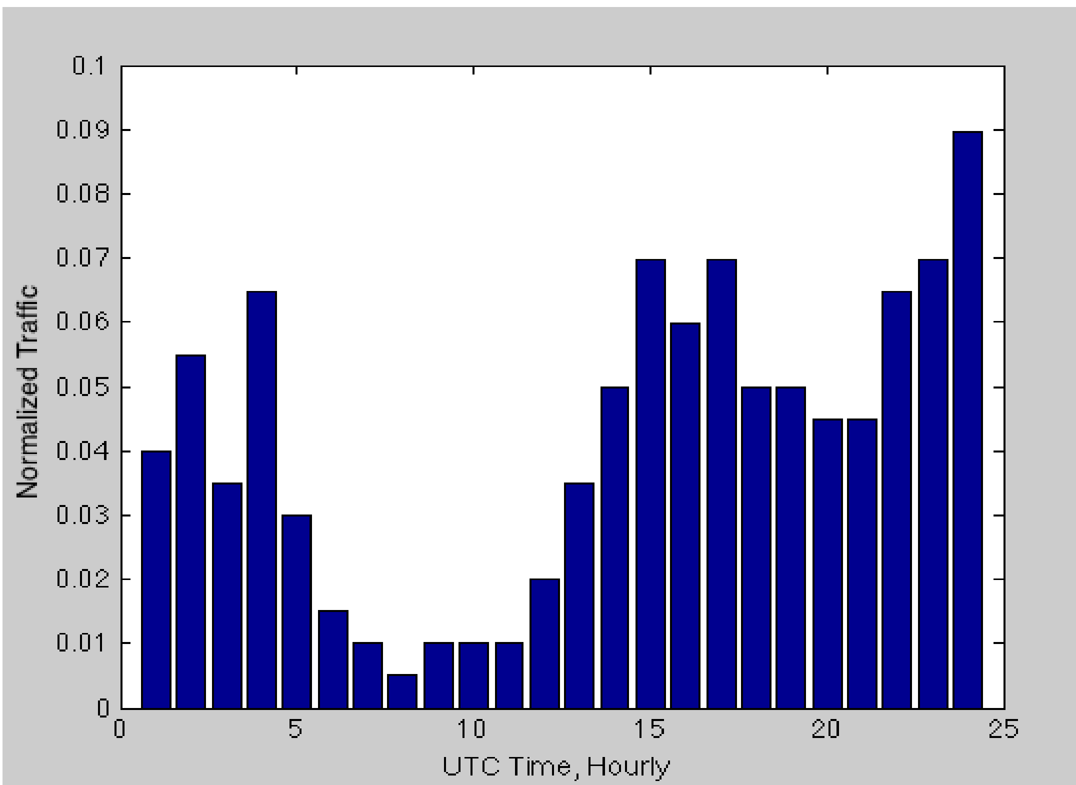

Figure 9: Commercial airlines traffic near hub airport in North America

Dynamic Capacity Demand: Unlike a fixed terminal, COTM terminals move from one satellite beam to another, have hours out of operation, and have usage activity that changes throughout the day. For example, flights from Europe to North America can fly through 4 different satellites and beams. However, aircraft are active for a short amount of time in a beam during long haul flights and activity moves to different beams as the flight progresses. A large number of aircrafts depart during a small window of time, peaking demand over this short period. For long haul flights, there are multiple such peaks of demand distributed among the satellite beams and changes with the time.

High Density Routes: Commercial aviation and maritime traffic have uneven distributions of traffic density relative to the earth's surface. A large part of the commercial aeronautical traffic density is concentrated in North America, the North Atlantic, Europe, and North-East Asia as shown in Figure 10 [13]. Furthermore, 50% of the aeronautical traffic is concentrated in 4% of earth's surface area and 80% of the traffic is concentrated in 15% of earth's surface area as shown in Figure 11 [13].

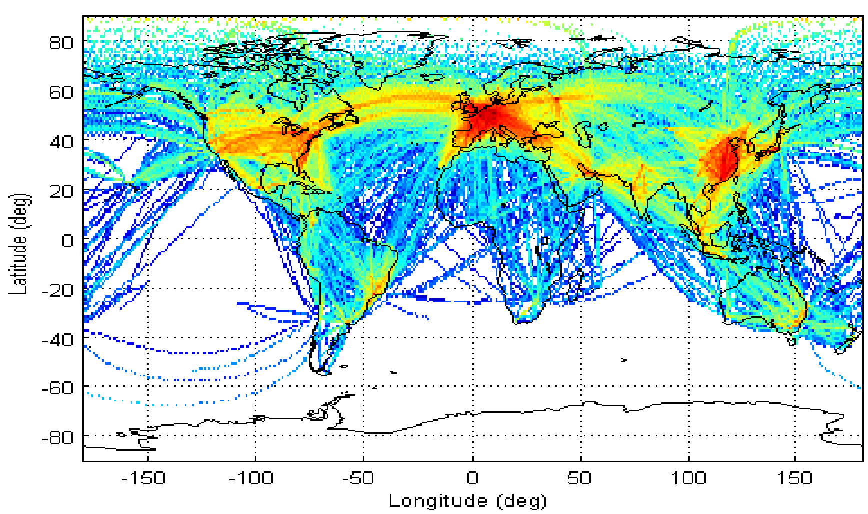

Figure 10: Global commercial aviation route density

Maritime traffic has similar density distribution as commercial aeronautical traffic and is shown in Figure 12 [9]. The Gulf of Mexico to northern Latin America, Brazil to Europe, South Africa to the Bay of Bengal, and the Sea of Japan are all heavy traffic areas for ships. Current wide beam satellites do not take into account route-specific traffic. Planning a satellite transmission to support aeronautical and maritime services with uneven traffic using current wide beam satellites is very inefficient and costly.

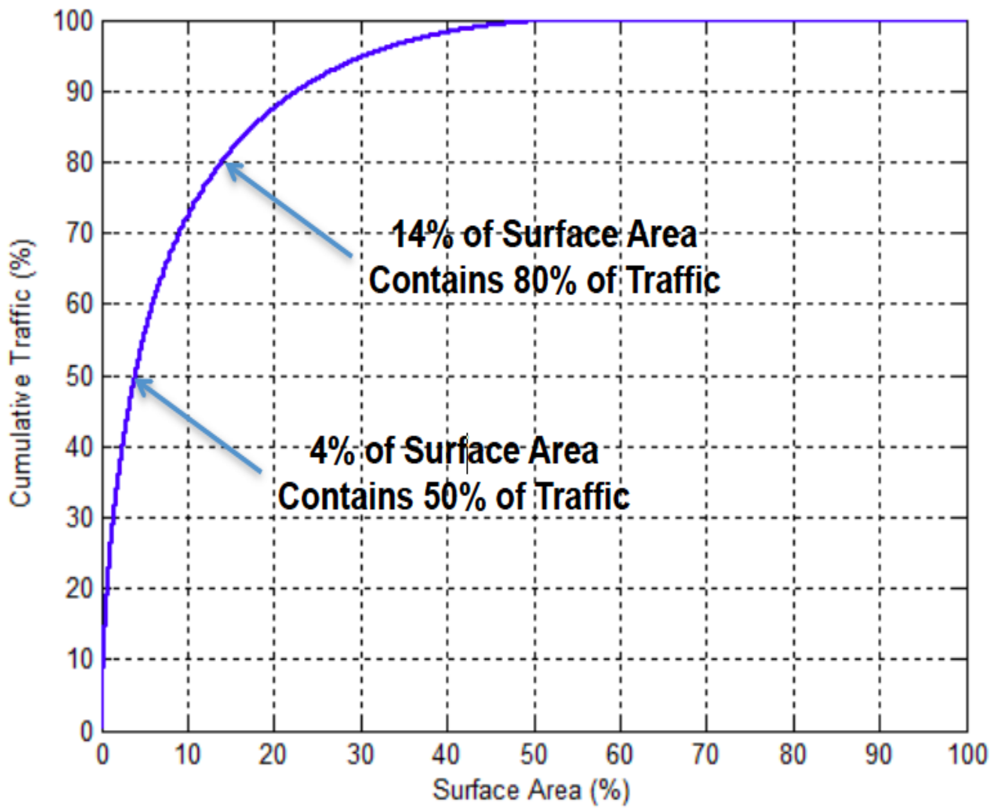

Figure 11: Global aeronautical traffic distribution as function of earth surface

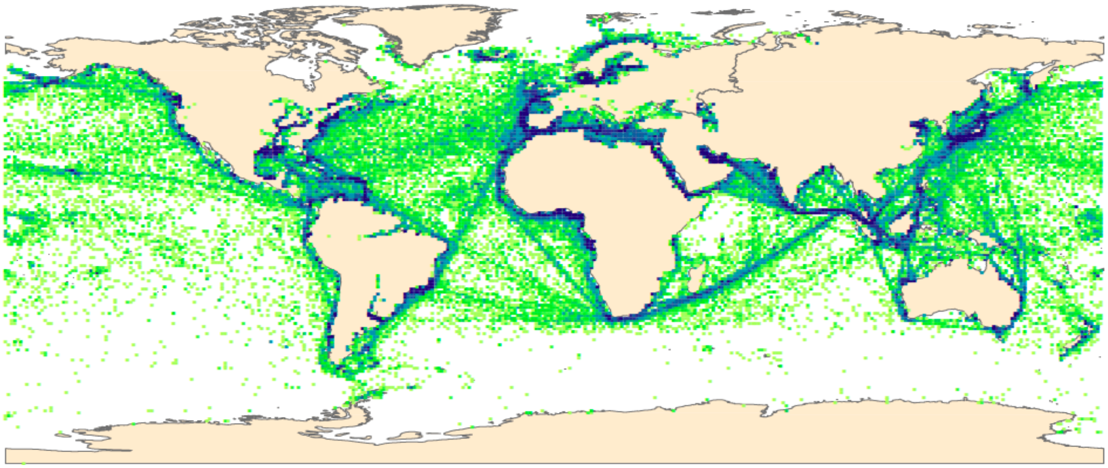

Figure 12: Global maritime vessel traffic

Spectral Density Limit: The International Telecommunication Union (ITU) has placed limitations and conditions on operation levels of power flux density towards the earth. Generally, such levels are coordinated and mutually agreed upon with the satellite operators and the ITU member states. Levels are often derived into EIRP spectral density (ESD) for space to earth. In order to compensate for low gain antennas in a COTM, the satellite link must operate at a high ESD but lower than the limit. A satellite that has a strict limit may not be usable for COTM service.

Similarly, for the earth to space portion of the link, ESD limits are given in beam peak and at off-axis angles. Maximum permissible levels of off-axis ESD are shown in Table 1. Smaller and asymmetric aeronautical antennas that change their ESD during flight must operate with low spectral efficiency to comply with these strict limitations.

Table 1: Maximum permissible level of off-axis ESD limit (ITU-R S.728-1)

Off-axis angle	Maximum EIRP in 40 kHz band
$2° \leq \phi \leq 7°$	$33 - 25 \log(\phi)$ dBW
$7° < \phi \leq 9.2°$	12 dBW
$9.2° < \phi \leq 48°$	$36 - 25 \log(\phi)$ dBW
$\phi > 48°$	-6 dBW

Current and Previous Work

The broadband service on COTM is a relatively new service using geostationary satellites. Although Boeing is truly the first operator to offer a broadband service for aeronautical application, service discontinued after 2006 for commercial aviation. However, it was an engineering success and paved the way for new operators to enter the market. Because Boeing used wide beam satellites including Telstar 6 [21], Telstar-14 [15], and GE-23 (currently called Eutelsat 172A), it is understood that the service had limitations associated with small antennas operating on wide beam satellites and no flexibility in transmission design to deliver capacity as demanded.

In the maritime environment, HTS did not provide coverage for vast ocean areas until recently. Since maritime services have some flexibility of mounting larger antennas on a large vessel, up to around 2.4 m, the demand for capacity can be met. Inmarsat *Global Express* became the first HTS that provides global coverage with an Inmarsat-4 series satellite and is expected to be completed in 2015-2016. Inmarsat-4 series satellite can operate up to 72 beams at any given time, but are designed with a maximum of 89 nested spot beams. Some of the beams can be enabled or disabled to meet the demand. With the introduction of digital beam forming and onboard signal processing, Inmarsat added an extra degree of flexibility into the service [22]. With the help of enabling and disabling beams, the capacity that satellites can offer can be moved to different beams. However, it fell short of the full potential of HTS because of the lack of Ka-band Multi Port Amplifier (MPA) availability for those satellites that are already in orbit. Despite improvements in service for small antenna terminals, this solution lacks the full capability to dynamically adapt transmission parameters to meet the demanded capacity.

Although MPAs have been implemented in satellites in orbit for a while, their use has been mainly on the lower frequency and narrower bands. L and S-band MPAs are already operating. Mitsubishi has developed an 8 x 8 L-band MPA for the MTSAT satellite. MTSAT delivered an aggregate power of 80 Watts and operated at a narrow band, which is not enough for the broadband service [20]. Eutelsat has been operating an S-band MPA on the Eutelast 10A satellite [17]. MPAs that are available on lower frequency do not contribute to any service improvement in COTM for broadband service because this service operates in higher frequency bands such as Ku or Ka-band.

The non-linear behavior of Traveling Wave Tube Amplifier (TWTA) creates a spurious intermodulation product on the adjacent channels in high frequency [25]. This is one of the factors contributing to slow adoption of MPAs on higher frequency bands such as Ku and Ka. The Wideband InterNetworking engineering test and Demonstration Satellite (WINDS) became the first program to use an 8x8 MPA with an 80-Watt amplifier output power in Ka-band [26]. This program proved the potential of the MPA in high frequency.

Leading manufacturers are in different stages of development and integration of MPAs that offer flexibility in HTS. Airbus Defense and Space and Thales Alenia Space are two notable manufacturers leading wideband Ku-band MPA development and integration on new HTS platforms. Airbus Defense and Space has extended its prior experience in building L-band MPAs to wide band Ku-band MPAs and will be integrating it into their new satellite Eutelsat 172B in 2017 [23]. Eutelsat 172B will be the first HTS mission with an MPA in Ku-band, offering flexibility in power distribution in COTM broadband service.

Eutelsat, in partnership of Airbus Defense and Space and backing from the European Space Agency (ESA) and UK Space Agency, is planning a next generation satellite that will offer beam size, beam steering, bandwidth, and spectrum flexibility. Although the first mission is yet to be launched, development of this new platform known as Eutelsat Quantum is the first of its kind, with full flexibility onboard the satellite payload [17]. Quantum satellites will add significant strength to COTM broadband service and expand the capability of the satellite even beyond MPAs.

Some of the existing missions in satellite building and past research have paved the way for a new type of transmission design philosophy in COTM broadband service. Because flexible satellite development is still in its infancy, the proposed design method will be the first of its kind using the flexibility of the satellite payload to improve the broadband services in COTM.

Thesis Statement

Broadband service in COTM is offered globally with a modest data rate, but lacks the flexibility and efficiency to improve the performance. Earth station antenna terminals mounted on such platforms and available satellites are two primary limiting factors. The introduction of HTS platforms aids in overcoming the limitations on COTM broadband services that are directly associated with the low gain wide beam satellite and constrained earth station antenna. An HTS still lacks the flexibility of moving resources from one beam to another if demand for such resources changes with time. An MPA introduced in an HTS takes its capability to the next level by allowing resources to be allocated dynamically.

The researcher proposes a new satellite network transmission design technique that takes into account highly-mobile COTM terminals and delivers capacity as demanded with the help of an MPA-equipped HTS. The proposed solution can further be expanded to any spot beam satellites with common power-shared beams if the traffic among such beams has time correlation. Applications with demand dependency in the time and/or space dimensions such as maritime, aeronautical, and fixed terminals can benefit from the new technique.

Satellite network transmission design principles for broadband communication traditionally have been based on the peak demand on each beam on both wide and spot beams. The proposed solution will allow capacity requirements to be planned based on the peak sum of the demand requirements across all beams rather than sum of the peaks in each HTS beam. By implementing this new design architecture, the satellite resource requirement for capacity will be significantly lower than traditional methods. This leads to both lower satellite bandwidth and power required to meet the same demand for capacity.

CHAPTER 3: NEW GENERATION SATELLITES FOR COTM

Satellite broadband services have three major components: a gateway station with a large earth station antenna, a satellite transponder, and a user earth station antenna. Gateway stations have large diameter parabolic antennas, around six meters or larger and amplifiers with output power around 750 Watts. Gateway resources are optimally designed and considered to be an abundant resource in satellite communication, especially when compared to satellite and COTM terminal resources. The user terminals targeted for broadband service are smaller, ranging from 0.4 to 2.4 meters in diameter. Such antenna terminals and their amplifier power are adjusted to match the desired link availability and data rate. Additionally, wide beam satellite transponders are sized with a downlink peak EIRP of 42 to 50 dBW at saturation with bandwidths of 27 MHz to 72 MHz in Ku-band. These satellites are expected to cover a large region, resulting in lower satellite EIRP and G/T. In a traditional satellite design, resources are fixed for the lifetime of the satellite once launched.

In summary, satellite broadband service has an optimized gateway, fixed satellite resources, and variable terminal resources to meet the service demand. Newer satellite broadband applications such as COTM have fewer degrees of freedom to meet service demand by changing both the terminal antenna and amplifier capability. Unlike in VSAT service, COTM antennas are forced to have a small form factor. For example, aerodynamic consideration, certification, and regulatory approval limits size, shape, and design change of an antenna onboard an aircraft.

Optimized gateway resources and disadvantaged terminal resources leave the satellite, as the last element that can be optimized to increase the efficiency of broadband service to COTM.

Recently satellite operators have acknowledged the growth in COTM and are adapting by tailoring satellite coverage and design to address the COTM market. HTSs opens up more opportunity to improve COTM service.

High Throughput Satellite (HTS)

A satellite that delivers ten times the capacity of a traditional communication satellite is referred to as an HTS. As the demand for capacity grows and application of satellite services is expanded to COTM, HTS is an attractive choice. An HTS has following properties:

1) Several small spot beams
2) Frequency reuse
3) Wider band transponders
4) Higher EIRP and G/T
5) Several orders of magnitudes greater capacity

Anik F2 is one of the early generation HTS. It was launched in 2004 and delivered about 8 Gbps of capacity to the service area [14]. Numerous HTS have been built since then, including IPSat, WidlBlue-1, Spaceway-3, and ViaSat-2. An HTS operating in Ka-band is currently providing aeronautical connectivity service in both the continental United States and the North Atlantic. HTS such as Intelsat 29e, Intelsat 33e, and Eutelsat 172B are in various stages of manufacturing and launch. Frequency usage architecture, beam size, beam numbers, and transponder bandwidth in an HTS are designed to match the target applications and maximize the capacity. The size of HTS beams decreases as the frequency of operation increases for the same size satellite antenna. For an example, 2.0 meter antenna on a satellite can create 0.7° to 0.8° beams in Ku-band and 0.3° to 0.5° beams in Ka-band [15].

Frequency Reuse: One of the strengths of an HTS with a large number of small spot beams is frequency reuse. In order to avoid interference:

1. A beam must be spatially separated by another beam of a different frequency.
2. No co-frequency beam can be adjacent to another co-frequency beam.
3. Four-color reuse is a technique where the available frequency is divided into four assigned beams in such a way that every beam is separated by one beam of frequency.

The same technique applies for a two-color reuse scheme. An example of four-color frequency reuse is shown in Figure 13. An HTS with n beams and u-color reuse, and available bandwidth B in both polarizations can deliver capacity with an effective bandwidth F_ϵ of:

$$F_\epsilon = 2\,n\,\frac{B}{u} \tag{3}$$

An HTS satellite with 16 beams in a coverage area and four-color reuse pattern can increase the available bandwidth by four times. This increase is relative to a conventional wide beam satellite covering the same area and improving the available capacity, proportional to the increased bandwidth.

Lowering Peak Demand: An HTS with spot beams improves performance for broadband applications in COTM. There is even more potential in aeronautical communication because of the time-correlated behavior. A wide body aircraft such as Boeing 777 can fly a commercial route up to 16 hours moving from beam to beam.

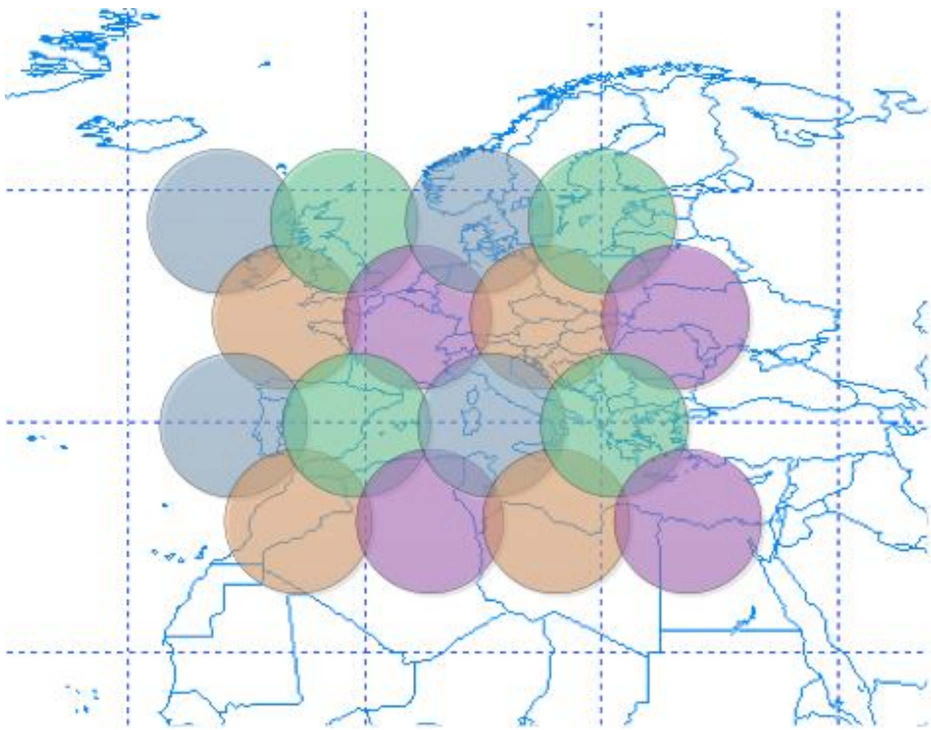

Figure 13: A satellite with spot beams using four-color frequency re-use

Many long haul commercial flights last around 8 hours from one continent to another. An HTS with multiple spot beams can lower the peak demand that can occur once in 24-hour cycle in a wide beam by dividing the peak over time into various spot beams. The capacity can be planned to lower individual peaks in various beams versus planning for one high peak in a wide beam. Meeting a peak demand in a wide beam with large coverage with low EIRP and G/T is challenging with limited bandwidth and a disadvantaged COTM antenna. Figure 14 and Figure 15 shows four different scenarios where the same coverage is divided from one to eight beams and correlated with the demand in the beams [15]. Note the drastic reduction in overall peak capacity demands per beam as the number of beams increases. This behavior is consistent with diurnal aeronautical traffic in the North Atlantic. In a traditional wide beam satellite, transponders of size 27 MHz to 72 MHz can deliver 40 Mbps traffic on the forward link (gateway to satellite and satellite to terminal) and 500 Kbps on the return link (terminal to satellite and satellite to gateway) [15].

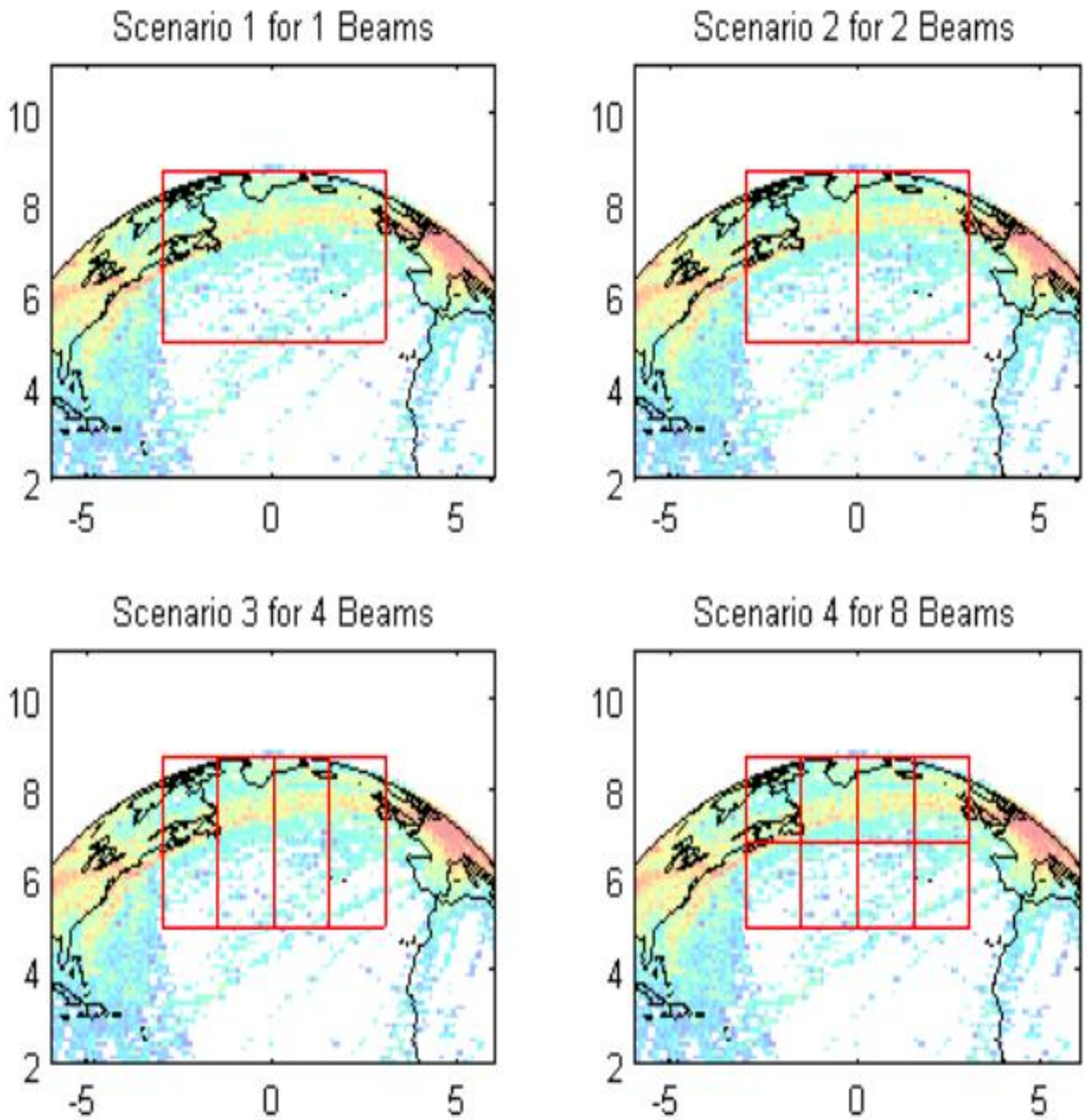

Figure 14: Scenario of covering north Atlantic corridor from wide to 8 beams

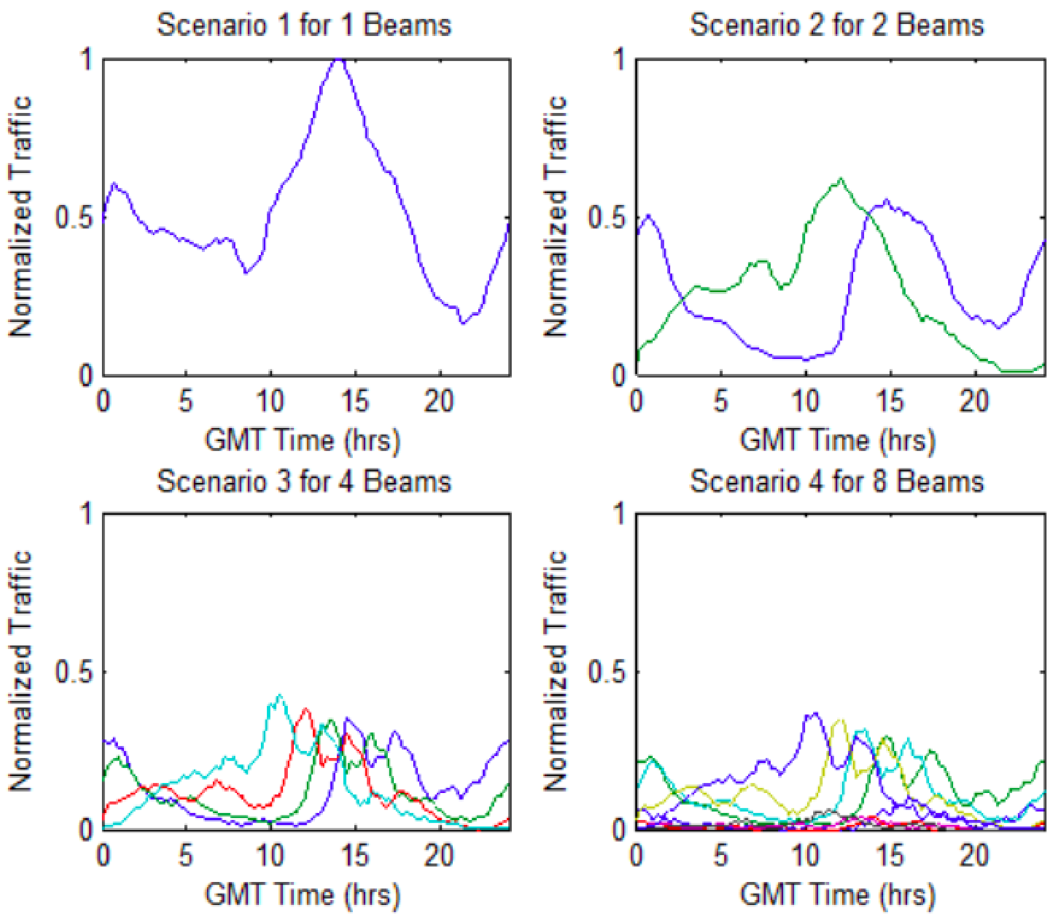

Figure 15: Beam traffic load as function of time

An HTS of size less than 2° in Ku-band can improve that to 160 Mbps per transponder on the forward link and up to 4 Mbps on the return link [15]. The improvement in data rate on the forward and return links is made possible by a higher EIRP and G/T achieved through smaller, more focused spot beams. By lowering the peak demand per beam and improving throughput per beam, one can improve the quality of broadband service in COTM.

Custom Transponder Design: A large single forward link of size 36 MHz with DVB-S2 link, shared amongst both several terminals and small TDMA links of less than 1 MSym is common when operating in a hub to spoke topology for COTM. Internet traffic has large downlink to upload asymmetry, about a 6:1 ratio. The forward link is governed by the satellite's power, EIRP, and uses the full transponder EIRP to close the link with a low gain COTM antenna. On the other hand, the return links are bandwidth deficient and use less transponder power but more transponder bandwidth. An HTS that is tailored to this new service, such as COTM can account for asymmetry in transponder power and bandwidth during the satellite payload design process. A transponder of size 100 MHz for 1.5° beams on the forward link and 500 MHz on the return is optimum for Ku-band [16]. When compared to a traditional wide beam satellite transponder, an HTS transponder increases the capacity for a small COTM terminal.

Further Improvement: Although the peak demand per beam is lowered and distributed more in time domain, and higher capacity is delivered per beam to a smaller number of COTM terminals, capacity cannot be moved from beam to beam when demand for such capacity is time dependent. More work is needed within the framework built by HTS architecture to be able to dynamically move satellite bandwidth and power based on the capacity demand.

Dynamic Resource Allocation

Terrestrial satellite services operating in fixed locations tend to have relatively flat demands for capacity in a beam. COTM, on the other hand, exhibits significant time and location dependence, which is challenging to accommodate.

For example, in aeronautical service, departure and arrival schedules are created so that the local time at departure and arrival is convenient for the passenger. Figure 16 shows the traffic activities of commercial aviation at two airports, both hubs for North Atlantic routes, the busiest commercial aeronautical corridor with heavy densities.

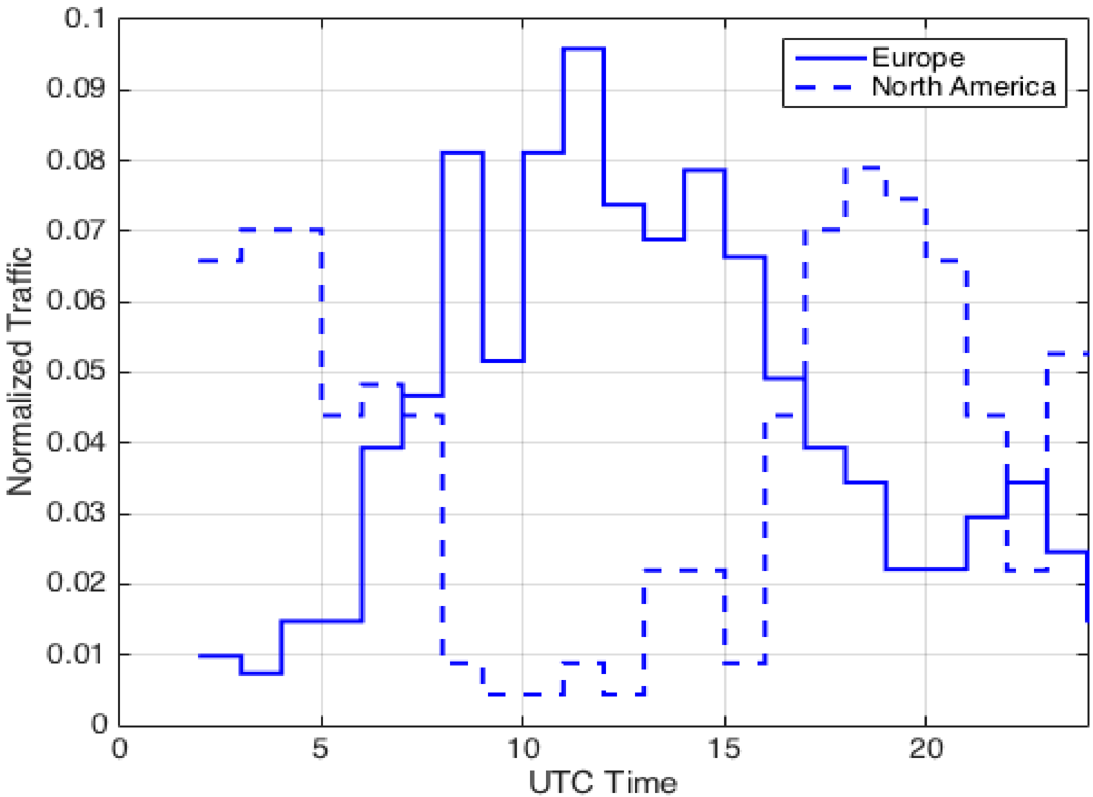

Figure 16: Airline flight near two hub airports across the Atlantic Ocean

Although HTS platforms help to overcome some of the challenges in COTM broadband service, they still lack flexibility in operation with regard to time dependent demand for capacity. In order to address such loss in efficiency, a step can be taken to tailor HTS for future satellite design [15]:

1) Designing beams with shared transponder, allowing power to be moved from one beam to another to match the flow of traffic.
2) Introduce multi-port amplifiers (MPA) to offer a pool of power and bandwidth amongst a number of beams with highly mobile traffic and distribute as necessary.
3) Build newer generation satellites with capability to: [17]
    a. Change the beam shape and size by using electronically steerable technology
    b. Change frequency plan using a programmable channelizer
    c. Allow amplifier power to be pooled

Multi Port Amplifier (MPA)

In a conventional communication satellite design with bent pipe architecture, amplifier power is delivered with Travelling Wave Tube Amplifiers (TWTA). Each transponder belongs to one wide band; around 36 MHz bandwidth and 150 Watt TWTA output power. A user can operate carriers to up to the saturation of the TWTA and up to the allocated bandwidth – 36 MHz in this example. The user can utilize up to the highest capability of the transponder to deliver the peak demanded capacity without any flexibility during demand changes.

With the introduction of an MPA, capacity in HTS satellite beams can be assigned dynamically. At any given time, the available power and bandwidth can be assigned to a beam based on its demand by varying the input power levels. Resources can be pulled from beams that have low demand at a given time and assigned to beams that have high demand. The total capacity required by the HTS can now be the peak at the sum of the beams over time; this will always be equal to or lower than the sum of the individual beam peaks.

MPAs overcome the challenges in COTM, mainly with time both correlated capacity demand and peak demand in a beam for a small time window. An MPA consists of an Input Butler Matrix (IBM), High Power Amplifiers (HPAs), and an Output Butler Matrix (OBM) [18]. The size of the MPA is determined by the number of active amplifier paths ranging from 2 x 2 to 32 x 32 [19]. Figure 17 shows a model of an 8 x 8 MPA [23]. The input signal is divided equally in the IBM, passing through all active amplifiers and recombined in the OBM. The total output power at each output port is proportional to the input power at the corresponding input port, when operated in the linear range. Each signal may operate in the same frequency band with relatively high isolation between the ports.

During high demand, all power of MPA can be directed to the one output port. The output powers across the ports may be allocated arbitrarily by controlling the input powers, drawing power from the aggregate power of all of the amplifiers in the MPA. This allows power and bandwidth to be flexibly allocated across the ports [28].

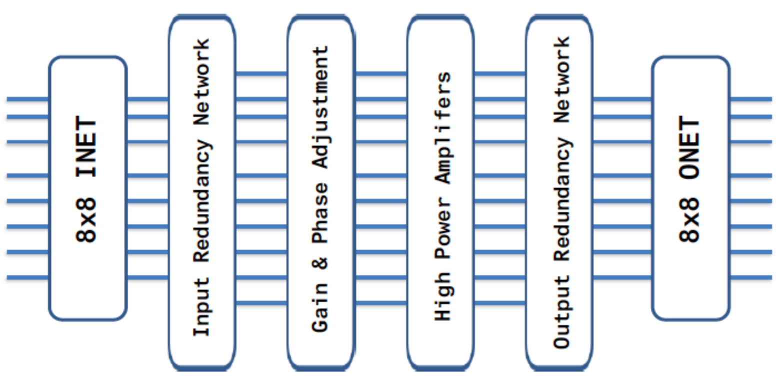

Figure 17: Block diagram of 8 x 8 MPA

CHAPTER 4: DAYNAMIC RESOURCE MANAGEMENT IN HTS WITH AN MPA

Prior chapters described the challenges COTM broadband service face. Several next generation satellites are in the design and manufacturing phase equipped with promising technology that can overcome the challenge of changing demand for capacity with time and space. Maritime, commercial aviation, satellite-based cellular backhaul, and disaster recovery services are applications that can benefit from the solutions proposed.

Satellite Network Transmission Design

Satellite network transmission plans account for all transmission related variables and find the most efficient transmission configuration to deliver the throughput. It ensures that the correct transmission configuration is generated and applied to the modem system to deliver the desired capacity, using both the bandwidth and the power of a satellite.

Transmission configuration largely varies with the terminal antenna and satellite properties. The transmission plan will have following key information.

1) Carrier center frequency
2) Modulation type
3) Available gateway EIRP
4) Forward error correction (FEC) type and rate
5) Downlink EIRP per carrier
6) MPA pool EIRP and bandwidth if applicable
7) Carrier symbol rate and spacing factor
8) Power spectral density limit

In a conventional wide beam satellite transmission, configuration stays fixed throughout the service and can only be changed manually. An HTS without power sharing capability among beams and the MPA will continue to use a similar methodology to plan for the transmission. Two constraints to consider are 1) The signal level such that the Carrier-to-noise ratio (C/N) must be higher than the lowest allowed C/N for a given modulation and coding, and 2) Power spectral density that must be lower than the highest allowed by regulations. It is important to plan transmission such that it stays within the desired range and resources during dynamic change.

In this research effort, transmission is planned for nominal level and automatically calculated from that level to meet the new requirement. An example of transmission configuration is shown Table 2. Transmission configuration is based on the link budget.

Table 2: An example of a satellite network transmission configuration

Beams	Carrier Notation	EIRP per Carrier (dBW)	Symbol Rate	Modulation	Uplink Frequency (Mhz)	Downlink Frequency (Mhz)	Forward Error Correction (FEC) Type	FEC Rate	Power Spectral Density (dBW/kHz)
Beam A	A	56	49	8PSK	14000	11700	LDPC-BCH	23/36	-20
Beam B	B	52	53	16APSK	14032	11372	LDPC-BCH	8/15	-20
Beam C	C	54	45	16APSK	14059	11759	LDPC-BCH	8/15	-20
Beam D	D	50	49	16APSK	14089	11789	LDPC-BCH	8/15	-20
Beam E	E	52	55	16APSK	14122	11822	LDPC-BCH	8/15	-20
Beam F	F	49	30	QPSK	14140	11840	LDPC-BCH	32/45	-20

Link Budget and Capacity

The goal is to establish the mathematical relationship between capacity, the satellite amplifier power, and the bandwidth. The next step is to apply this relationship to accomplish the goal of distributing capacity. Capacity, R with channel bandwidth, B and carrier to noise ratio, C/N according to Shannon is [28]:

$$R = B\ log_2\left(1 + \frac{C}{N}\right) \tag{4}$$

The carrier to noise ratio can be further defined using thermal noise, C/N_0 :

$$\frac{C}{N} = \frac{C}{N_0 B} \tag{5}$$

The forward link C/N_0 is dominated by satellite to terminal link C/N_{dl}. The C/N_{ul} and C/N_{dl} have a linear relationship with gateway uplink EIRP and satellite downlink EIRP respectively. Because of the dominant contribution from downlink C/N_{dl} and negligible contribution from the uplink, C/N_{dl}, the overall end-to-end C/N will be determined by the satellite downlink EIRP as shown below:

$$\frac{C}{N} \approx \frac{A\ (EIRP)}{\frac{\lambda^2}{4\pi}\ L_s\, L_a\ kT\ B} \tag{6}$$

Where A is the effective terminal area, k is Boltzmann's constant, L_s is the free space loss, L_a is the atmospheric loss, T is the noise temperature, and B is the channel bandwidth.

The capacity increases linearly with bandwidth but logarithmically with C/N as shown in equation (4) by Shannon's theorem.

However, if bandwidth is increased, the numerator, as shown in equation (6), EIRP must be increased to maintain the same C/N and the linear growth in capacity. Thus, satellite EIRP is the dominant variable in determining the capacity in this environment. The result affects the transmission configuration, which is the nominal configuration for the dynamic change. The next step is to define the demand of the capacity that changes with time and beam.

Define Capacity Demand

Pool – HTS Beams: It is crucial to find the number of HTS beams that have capacity demand variation. Less satellite resource will be required if the peak demand for the capacity does not occur at the same time across beams. Although users' demand for capacity cannot be controlled, grouping the HTS beam in a pool such that peak demand occurs at different time can be planned. HTS beam selection must be made considering the demand that occurs in the beam. Figure 18 shows an example six HTS beams with an ideal demand distribution of a normalized capacity in 24-hour cycle where peak demand does not occur at the same time. After the HTS beams with distributed demand are identified, the necessary pool bandwidth and power can be allocated.

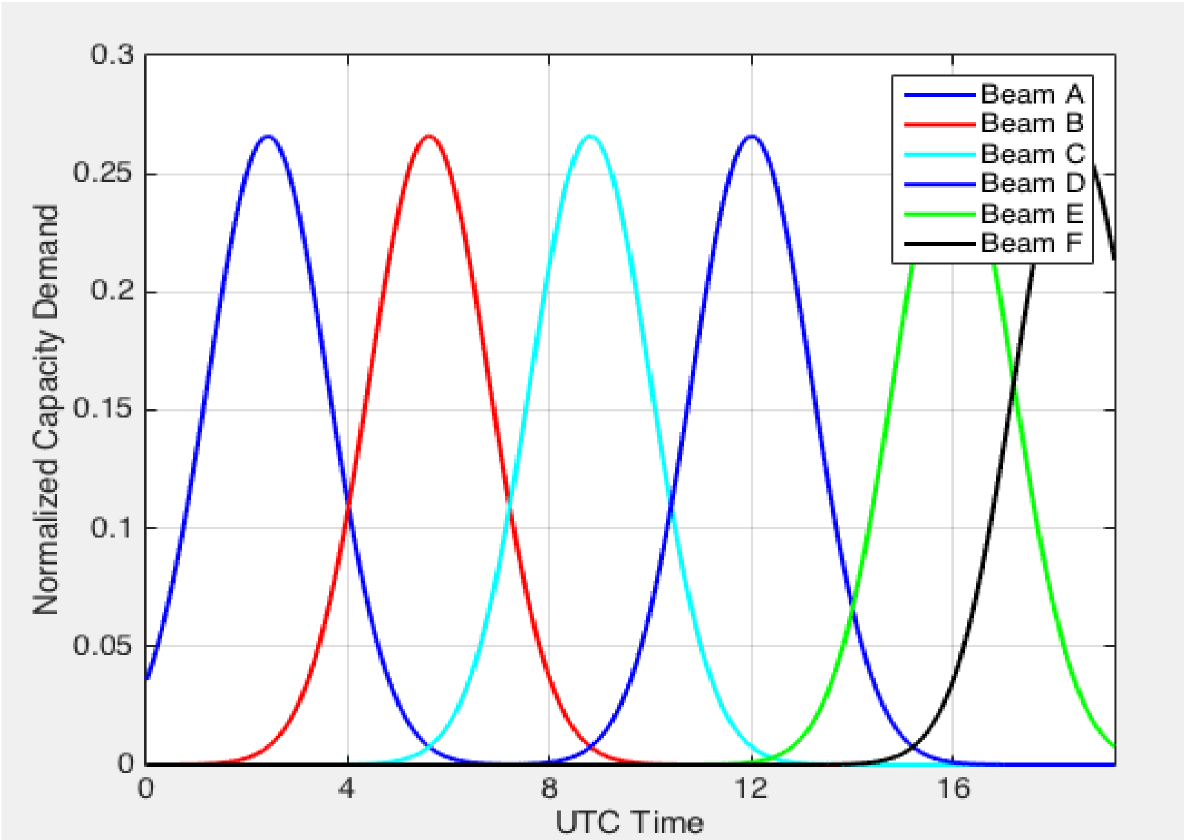

Figure 18: Desired capacity distribution during 24 hour cycle across HTS beams

Demand in a Single Beam: The second step in this process is to find the capacity demand as function of time within the beam and independent of the other beams sharing the same pool. The demand is shown as a fraction of the peak demand in the beam. However, such demand can be relative to a fixed reference number, which can be the peak demand for the capacity.

The relationship to define relative capacity demand C_{txb}, absolute demand at time t, $D_b(t)$, and peak demand in 24-hour cycle, $Max(D_b(t))$ is:

$$C_{txb} = \frac{D_b(t)}{\max(D_b(t))} \ x\ 100\% \qquad (7)$$
$$for\ t = 0, 1, 2, \ldots .24 \quad \text{and } b = A, B, C \ldots$$

Figure 19 shows the demand for a beam that varies with time using the relation shown in equation (7). It is important to find the peak demand for capacity. This will determine the data carrier's nominal configuration.

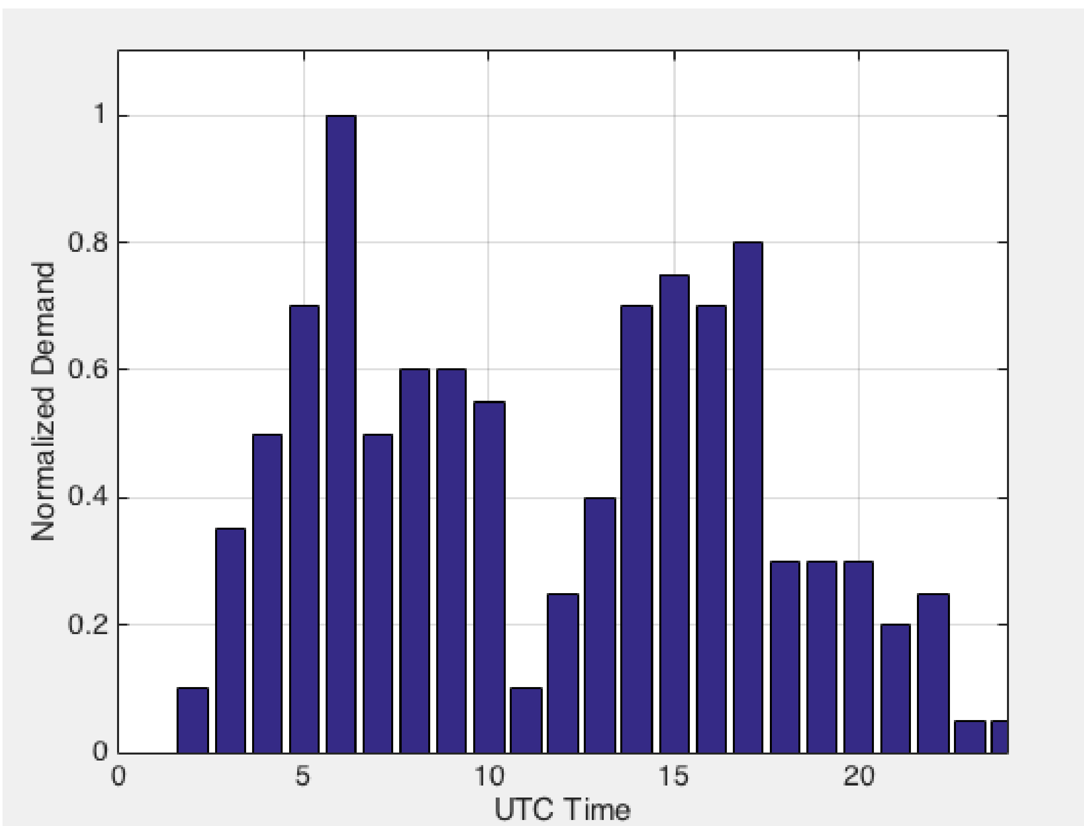

Figure 19: Demand in a single HTS beam in 24-hour cycle

Demand in all Beams: Once the peak demand and relative demand for capacity from each beam are defined, time relationship with such demand with all the beams need to be established. Since the relationship between the capacity and the MPA power is not linear, the MPA power for capacity demand need to be calculated. First, Shannon's theory from equation (5) is revised to reflect the realizable spectral efficiency. New waveforms such as DVB-S2 with 0.2 roll off factor operate near 60% of Shannon bound as shown below [27].

$$R = 0.6\, B\, log_2\left(1 + \frac{C}{N}\right) \tag{8}$$

The relationship shown in equation (6) and (8) can be derived to a new relationship with respect to the capacity and EIRP shown in equation (9).

$$EIRP \;= B\,(2^{\frac{R}{0.6B}} - 1)(\frac{\lambda^2 L_s\, L_a\, kT\, B}{4\pi\, A}) \tag{9}$$

The relationship shown in equation (9) can be further derived using known EIRP for the carrier and the associated capacity it can deliver. The method to measure EIRP in an HTS is shown in the Implementation section. With the known capacity and EIRP, new EIRP required to meet the new capacity demand with fixed bandwidth of B is:

$$EIRP' = \; EIRP\; \frac{(2^{\frac{R'}{0.6\,B}} - 1)}{(2^{\frac{R}{0.6\,B}} - 1)} \tag{10}$$

Where all the constant terms cancel each other

The new capacity requirement, R' can be defined with relative and a peak capacity as below:

$$R' = C_{txb}\ x\ \max(D_b(t)) \qquad (11)$$

The EIRP to capacity relationship with respect to the known EIRP derived in equation (10) can depicted in Figure 20.

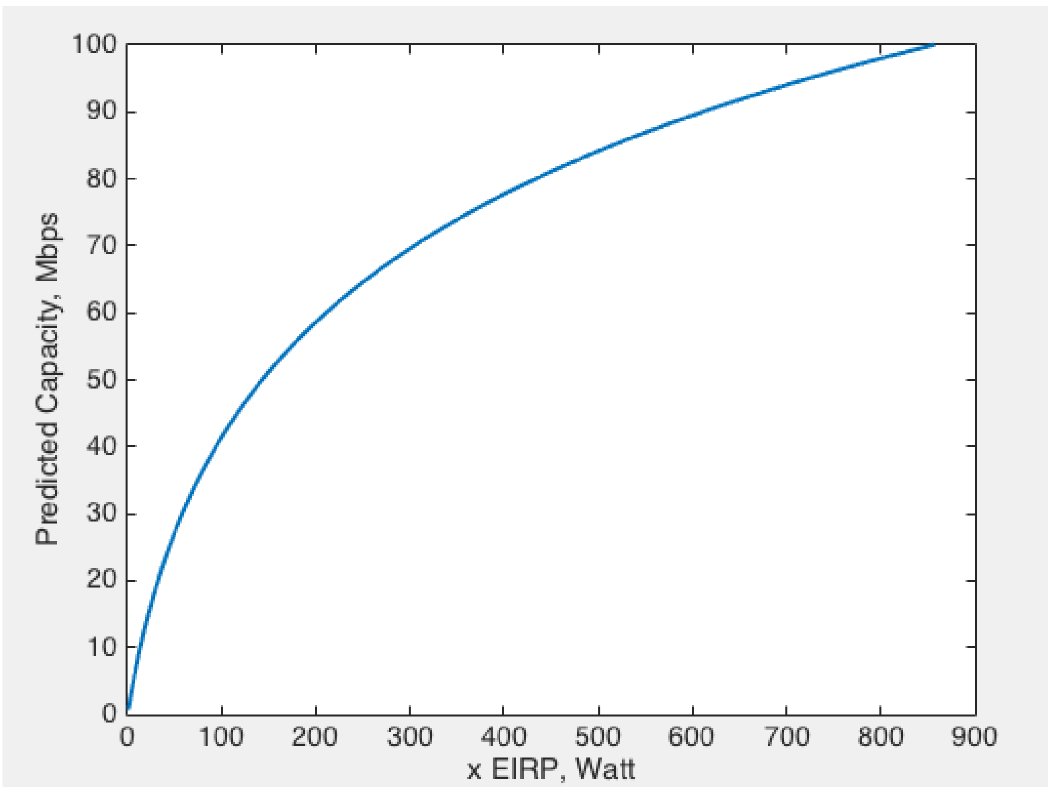

Figure 20: Relationship between capacity and EIRP as a factor of data carrier EIRP

Maximum Sum of All EIRP: After successfully calculating the EIRP required on each beam, the maximum sum of such EIRP is calculated. The result determines the MPA power from HTS satellite necessary to meet the peak demand for each beam group.

In this case the bandwidth allocated on each beam is fixed. The maximum sum of EIRP requirements across the beams is:

$$EIRP_t = \max(EIRP(t)_A + EIRP(t)_B + EIRP(t)_C + \cdots) \quad for\ t = 1, 2, 3 \ldots \tag{12}$$

$$EIRP_t = max(\sum_{b=A}^{b=F} EIRP_b(t)) \tag{13}$$

In a given time instant the required EIRP in all beams is shown in Figure 21. The power requirement to meet the demand in span of 24 hour among all six beams is shown in Figure 22. The sum of required EIRP to meet the demanded capacity is shown in Figure 23.

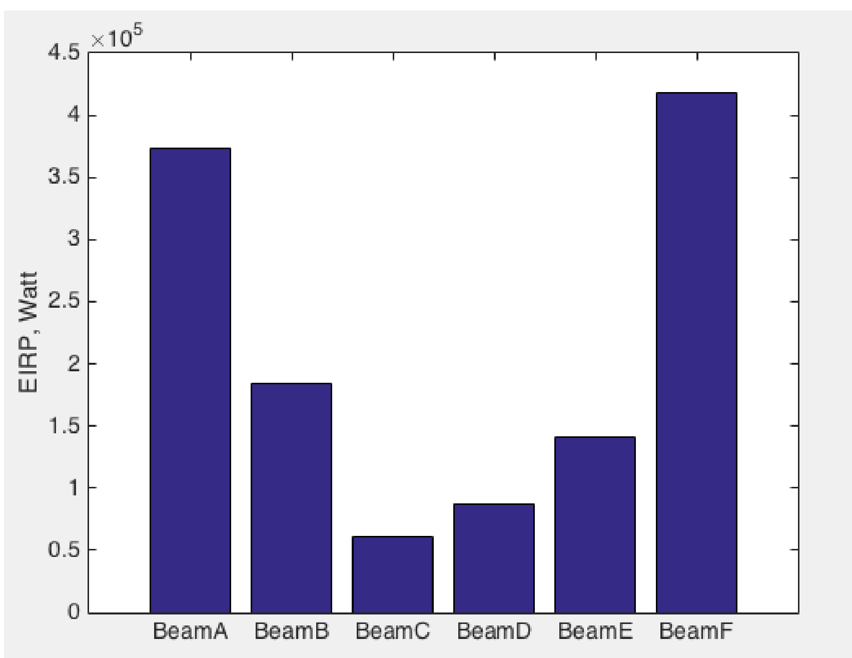

Figure 21: Required EIRP to deliver the demand in each beam in a given time instant

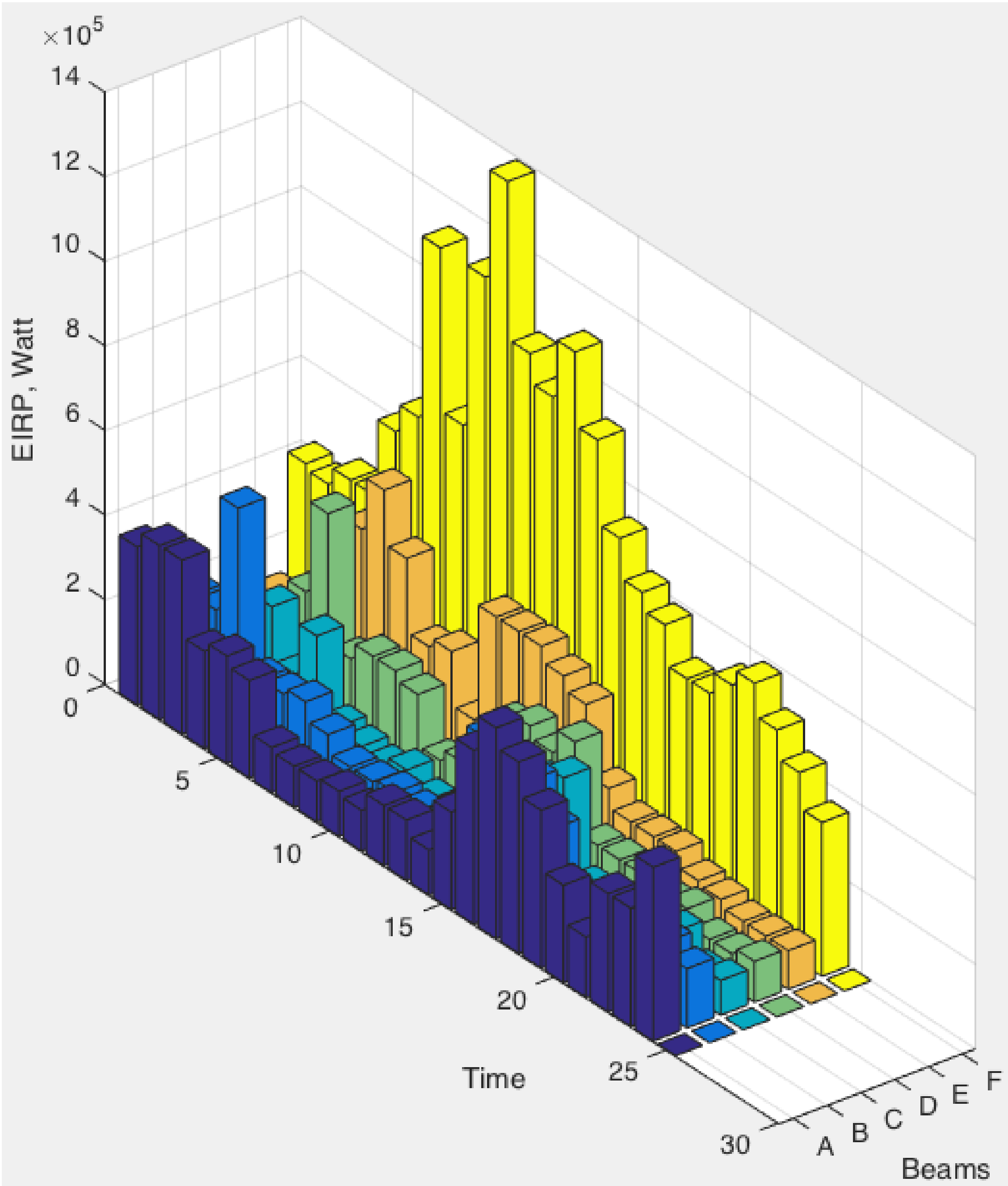

Figure 22: Required EIRP to meet the demand in 24 hour cycle across all beams

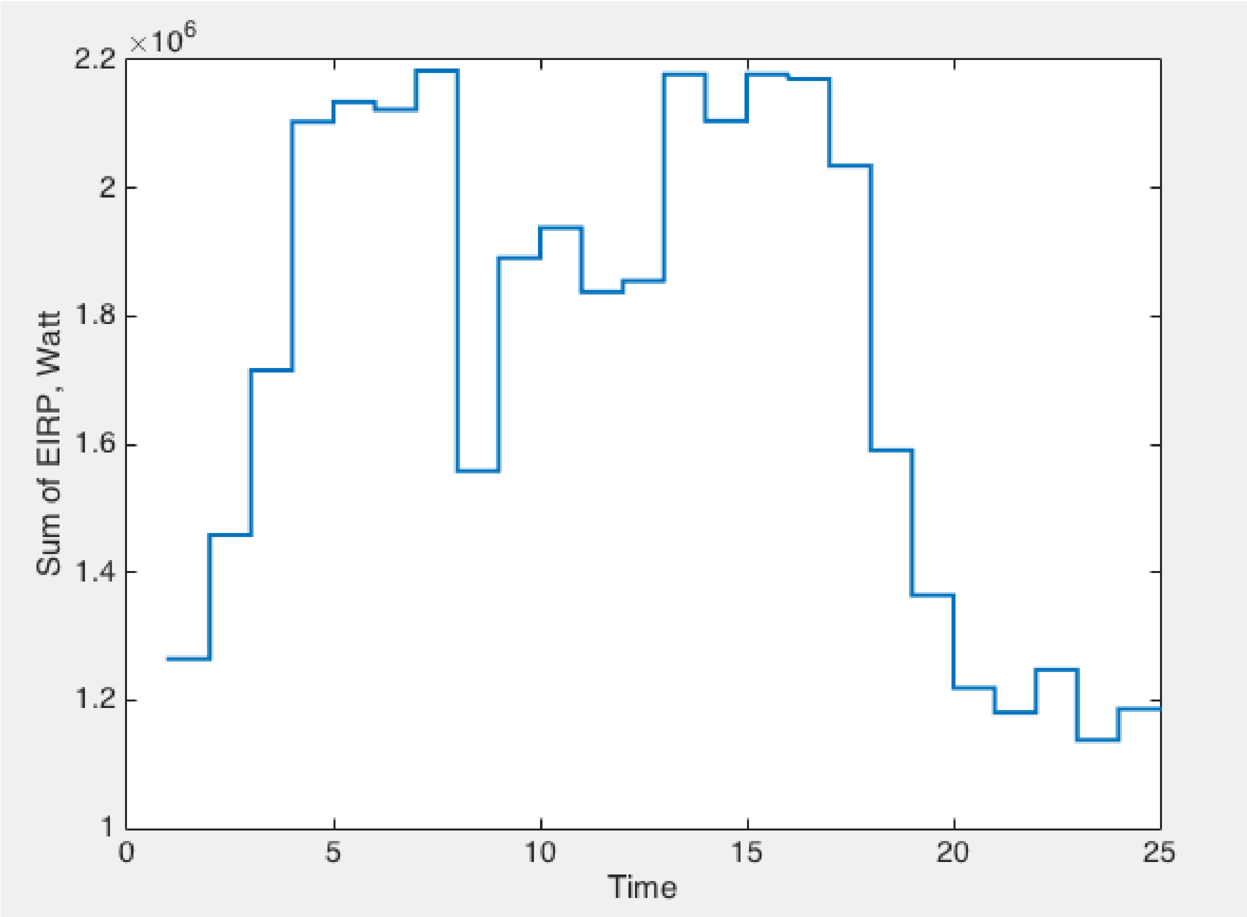

Figure 23: Sum of EIRP in a 24-hour capacity demand cycle

Proposed Implementation

The next step is to design the system level architecture to ensure demand can be met as a function of time. As shown in equation (6) the overall link budget on delivering the capacity is dominated by the satellite downlink EIRP. However, downlink EIRP can change in an MPA by varying input levels at the input port. The proposed ground-based architecture as shown in Figure 24 will ensure that the output of the MPA in terms of downlink EIRP can be varied by input port to achieve the desired result. The required ground-based components for this solution are the pilot carrier, data carrier, programmable attenuator, and management server. Defining the pilot carrier is the first step.

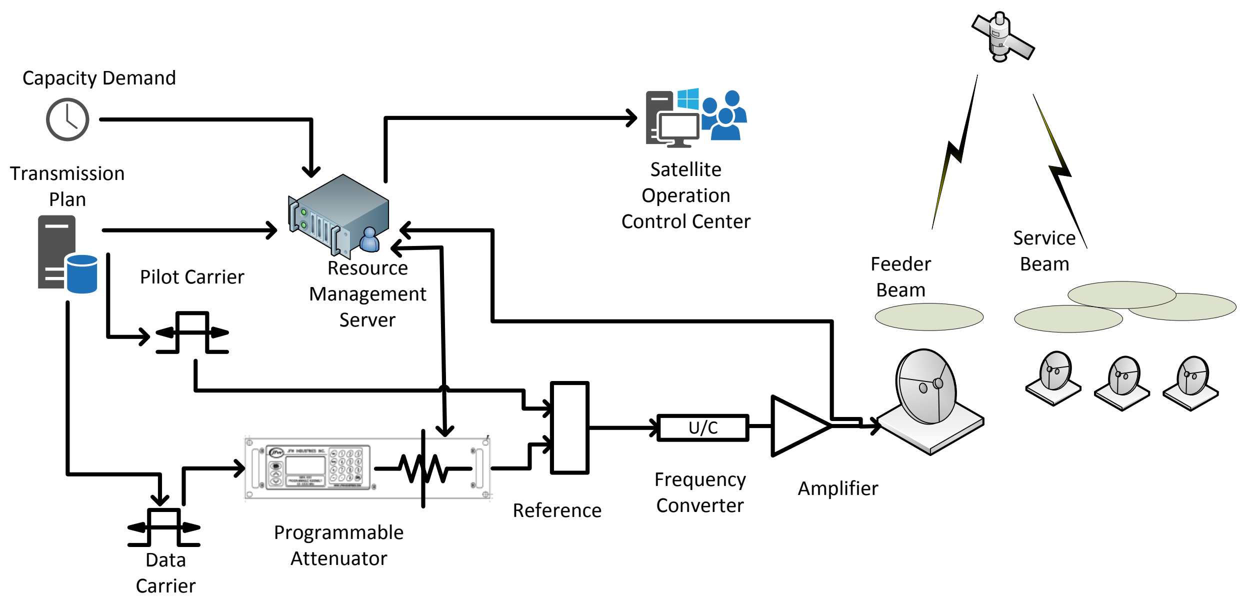

Figure 24: Block diagram of the implementation

Pilot Carrier: Making an accurate measurement of the downlink EIRP is important for satellite operators to comply with regulations and for monitoring the operational health of the system. A satellite operator and/or manufacturer uses ground-based monitoring terminals that are different than customers' terminals to measure the downlink EIRP of a carrier(s) in a beam. HTS satellites may have dozens of spot beams with uniquely channelized paths from feeder beams to service beams. A monitoring terminal in all of the beams will be impractical in a satellite with footprints on both land and ocean. In order to resolve this challenge, the concept of a pilot carrier is introduced.

A pilot carrier enables accurate measurements in an easily accessable service beam using a monitoring terminal. Such measurements help to accurately calculate the EIRP and C/N for data carriers in other beams. One pilot carrier will be valid for all the beams sharing the same feeder beam and gateway station. As shown in equation (4) - (6), capacity can be delivered based on demand by changing the satellite downlink EIRP that results in a change in C/N of a channel. Measurements required from a pilot carrier to accurately calculate the EIRP and C/N of data carriers, operating levels of the MPA, and capacity delivered by a carrier are:

1. Rx power at the reference (P)
2. Uplink frequency (f_{ul})
3. Downlink frequency (f_{dl})
4. Downlink EIRP
5. Carrier to Noise Ratio (C/N)
6. Coordinates of the monitoring terminals
7. Satellite coordinates

A spectrum analyzer or a modem can provide the EIRP and C/N of a pilot carrier. Figure 25 depicts carrier modulators, pilot and data carriers uplinked from the gateway-feeder link, carrier received in several HTS service beams, and pilot carrier received in a HTS beam.

Data Carriers: The data carrier operates in any service beams within the same gateway and feeder beam as the pilot carrier.

The nominal transmission configuration as shown in an Table 2 is applied to the data carriers. A large number of such carriers can follow one pilot carrier as long as they share the same feeder beam and gateway.

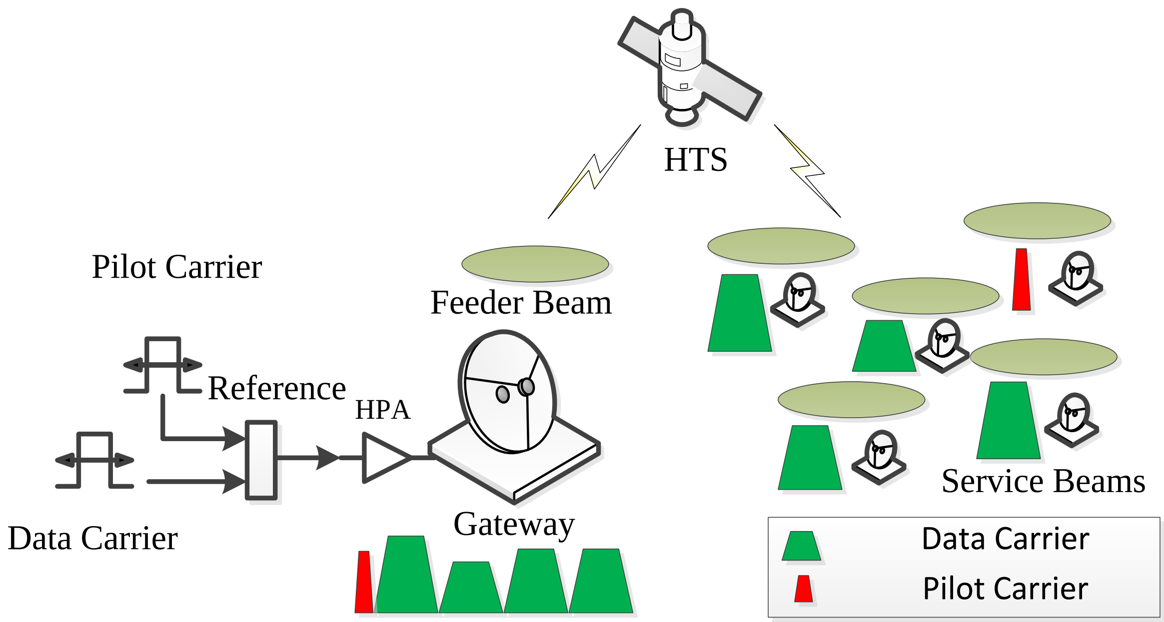

Figure 25: A model showing satellite communication with pilot carrier transmitter

It is not necessary that the data carrier and pilot carrier share the same service beam, though they may. Since monitoring terminals are not available for all data carriers, pilot carrier measurements are used to calculate key link parameters such as EIRP and C/N of a carrier. As the demand for capacity changes new transmission configuration is calculated and applied to the data carriers. The concept of a differential correction factor helps to accurately make the measurement in data carriers. A differential correction factor accounts for only the variables that are different and cancels common variables between the pilot carrier and the data carrier. The list of all correction factors that are relevant to this computation is shown in the next section.

Correction Factors: With the help of correction factors, key variables for the data carrier, and ultimately, the capacity, can be calculated. The correction factors can be differentiated between uplink and downlink. The correction factor in uplink (CF_{ul_1}) $EIRP_{cf\_ul}$ due to the difference in frequency between the pilot carrier, f_{pl_ul} and the data carrier, f_{rf_ul} is:

$$CF_{ul\_1} = EIRP_{cf\_ul} = -20\, log_{10}\left(\frac{f_{pl_{-ul}}}{f_{rf_{-ul}}} \right) \tag{14}$$

The second correction factor is for the two primary transmission losses: free space loss and atmospheric loss. The method to calculate the atmospheric loss is a statistical prediction, and the correction factor does not need to be changed with atmospheric condition. Gateway stations are equipped with uplink power control to mitigate the atmospheric loss. The atmospheric loss, due to the frequency difference, is not accounted for. The uplink chain includes the intermediate coaxial cables, waveguides, amplifier, an antenna, feed, gateway location, and satellite location between both pilot and data carrier is common and can be eliminated. The slant range between gateway earth station and the satellite is the same but the free space loss is different because of the frequency difference. The correction factor (CF_{ul_2}) due to the free space loss, L_s is:

$$CF_{ul\_2} = L_s = 20\, log_{10}\left(\frac{f_{pl\_ul}}{f_{rf\_ul}}\right) \tag{15}$$

On the downlink path, the location of the monitoring earth station terminal targeted for the pilot carrier and the operating earth station terminals is expected to be different. The difference in EIRP, slant range, and free space loss need to be accounted separately for the downlink path. The correction factor in downlink EIRP is same as equation (14), however the downlink frequency is different than the uplink frequency. The correction factor in downlink $EIRP_{cf\_dl}$ due to the downlink frequency is:

$$CF_{dl\_1} = EIRP_{cf\_dl} = -20\ log_{10}\left(\frac{f_{pl\_dl}}{f_{rf\_dl}}\right) \tag{16}$$

Calculating the slant range requires the coordinates of the satellite and a terminal. However it is possible that either no terminal or several terminals could be within the beam at the same time. The size of a HTS beam can vary, but they tend to be around 2° or less for Ku and Ka-band HTS satellites. Taking the coordinates at the center of the beam should give reasonable slant range. The correction factor in free space loss due to slant range between the monitoring station for the pilot carrier, S_{pl} and the center of the spot beam S_{rf} is:

$$CF_{dl\_2} = L_s = 20\ (log_{10}\frac{S_{pl}}{S_{rf}} + log_{10}\frac{f_{pl_{dl}}}{f_{rf_{dl}}}) \tag{17}$$

Slant range, S for a terminal pointing at elevation angle to the geostationary satellite, h radius of earth, R_e and distance between a satellite to a terminal, r is:

$$S = R_e \left[\sqrt{\frac{r^2}{R_e^2} - (\cos h)^2} - \sin h\right] \tag{18}$$

Elevation angle, h of a terminal operating at geostationary satellite can be calculated with the help of difference between satellite and terminal longitude, $\Delta\partial$ and latitude of the terminal $\emptyset$ and shown below:

$$h = \tan^{-1}\left[\frac{\cos\emptyset \cos\Delta\partial - 0.151}{\sqrt{1 - (\cos\emptyset\ \cos\Delta\partial)^2}}\right] \tag{19}$$

There is a common point from where the pilot carrier and data carriers share the same uplink chain. It is necessary to measure the difference in power between two carriers at the common reference point. Such correction factor for carrier power can be calculated by measuring the power difference at a reference point as shown on Figure 25 between the pilot carrier, P_{pl} and the data carrier, P_{rf}. This applies to the intermediate link within the uplink chain.

$$CF_{pwr} = P_{pl} - P_{rf} \tag{20}$$

Spot beams may have different gains depending on their location. The correction factor for pilot beam gain G_{pl} and data carrier beam gain, G_{rf} is:

$$CF_g = G_{pl} - G_{rf} \tag{21}$$

The precise calculation of the correction factor is important in determining the EIRP and C/N of the data carriers that directly relates to the capacity calculation.

Downlink EIRP and C/N: With the EIRP of the pilot carrier and the correction factors, the EIRP of the data carrier can be calculated. The $EIRP_{rf}$ of the data carrier with the help of the correction factor and $EIRP_{pl}$ is:

$$EIRP_{rf} = EIRP_{pl} + CF_{ul\_1} + CF_{ul\_2} + CF_{dl\_1} + CF_{dl\_2} - CF_{pwr} - CF_g \tag{22}$$

But the correction factor due to the EIRP and free space loss on the uplink cancel each other as shown in equation (14) and (15).

Similarly, the correction factor on the downlink has common terms that cancel each other. The relationship defined in equation (20) can be further simplified to:

$$EIRP_{rf} = EIRP_{pl} - CF_{pwr} - CF_g + 20\, log_{10} \frac{S_{pl}}{S_{rf}} \tag{23}$$

The final relation, equation (21) shows that the EIRP of a data carrier with in the same feeder beam can be calculated using four variables: slant range, receiver power at baseband, gain difference in the beam and EIRP of the pilot carrier. In order to dynamically change the satellite downlink EIRP of the carrier any or all of the four variable can be changed. Practically, for a HTS beam, change in correction factor at the reference CF_{pwr} is the most important variable. This is beause the EIRP of the pilot carier, beam gain of difference between beams, and slant range between pilot and data carrier beam are generally fixed for a given beam and a short time window.

After calculating the EIRP for the data carriers, C/N of such carriers can be calculated. The relationship below gives the C/N of the data carrier using the correction factor, C/N of the pilot carrier, and bandwidth of both carriers for similar receiving antenna properties.

$$\frac{C}{N_{rf}} = \frac{C}{N_{pl}} - 10\, log_{10}\left(\frac{B_{rf}}{B_{pl}}\right) + \left(EIRP_{rf} - EIRP_{pl}\right) \tag{24}$$

Two primary variables, EIRP and C/N, required to derive the capacity are derived.

The operation level of downlink EIRP has regulatory limitations to prevent harmful interference to terrestrial services using the same frequency. The key regulatory compliance on the downlink is based on the EIRP spectral density (ESD).

For a bandwidth B and carrier spacing factor α, ESD is:

$$ESD = EIRP - 10\ log_{10}\left(\frac{B}{\alpha}\right) \tag{25}$$

The ESD limit for a satellite gives the operational upper bound for a data carrier and the EIRP assigned to it during dynamic changes.

Resource Management Server: The resource management server performs the following roles:

1. Calculates correction factors, EIRP, and C/N
2. Calculates and enforces the ESD Limit
3. Tracks the aggregate EIRP usage from the MPA pool in real time
4. Maintains a database of demand
5. Maps between modulation coding and spectral efficiency for the given C/N
6. Maps between attenuator port and carrier
7. Has knowledge of the transmission parameters of all the data carriers

Dynamic Change in Capacity

As previously shown, capacity is related to the satellite downlink EIRP that can be changed by varying input levels to the satellite amplifier. The data carrier modulates and transmits at a certain transmit power. A programmable attenuator is inserted between the data carrier modulator and the uplink chain. Each data carrier modulator and attenuator port is mapped so that the input power to the satellite MPA port can be changed linearly. This changes the downlink EIRP.

A change in satellite downlink EIRP causes a nearly linear change in C/N of a carrier while operating within the linear amplifier region. The modem system implements Adaptive Coding and Modulation (ACM) based on the C/N at the receiver, which changes the spectral efficiency of a channel. The attenuator port are directed by a resource management server that will control the power going to the reference point and directly change the result shown in equation (18), (21), and (22). The reference is a point from where the data carrier and pilot carrier share the same uplink chain to the satellite. Figure 26 introduces the resources management server and programmable attenuator.

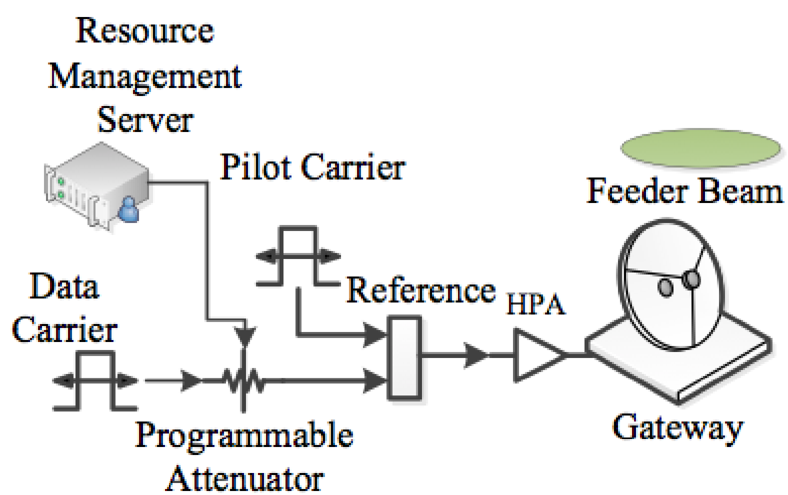

Figure 26: Uplink transmission chain with all necessary components

The dynamic change in capacity with an MPA can be shown with the following example. Assume the attenuation is set at an attenuator port in such a way that the calculated C/N of a data carrier due to the change in satellite downlink EIRP, with the aid of the pilot carrier and correction factor, is 4.5 dB. This corresponds to modulation 8PSK and coding rate 8/15 with a spectral efficiency of 1.52 bps/Hz in the DVB-S2X standard

[24]. At this operating point capacity can be calculated with spectral efficiency and channel bandwidth. If the size of the data carrier is 36 MHz, the information rate delivered at this modulation coding is:

$$1.52\ Bits/Hz \times 36\ MHz = 54.72\ Mbps$$

Next, when there is different demand for capacity, the new value of attenuation is calculated; the change in C/N will result in a new spectral efficiency and capacity requirement. This process will repeat each time there is a change in capacity demand.

Figure 27 shows an example of capacity delivered in two carriers operating in two beams as demanded by changing the attenuation, which ultimately results in change in C/N.

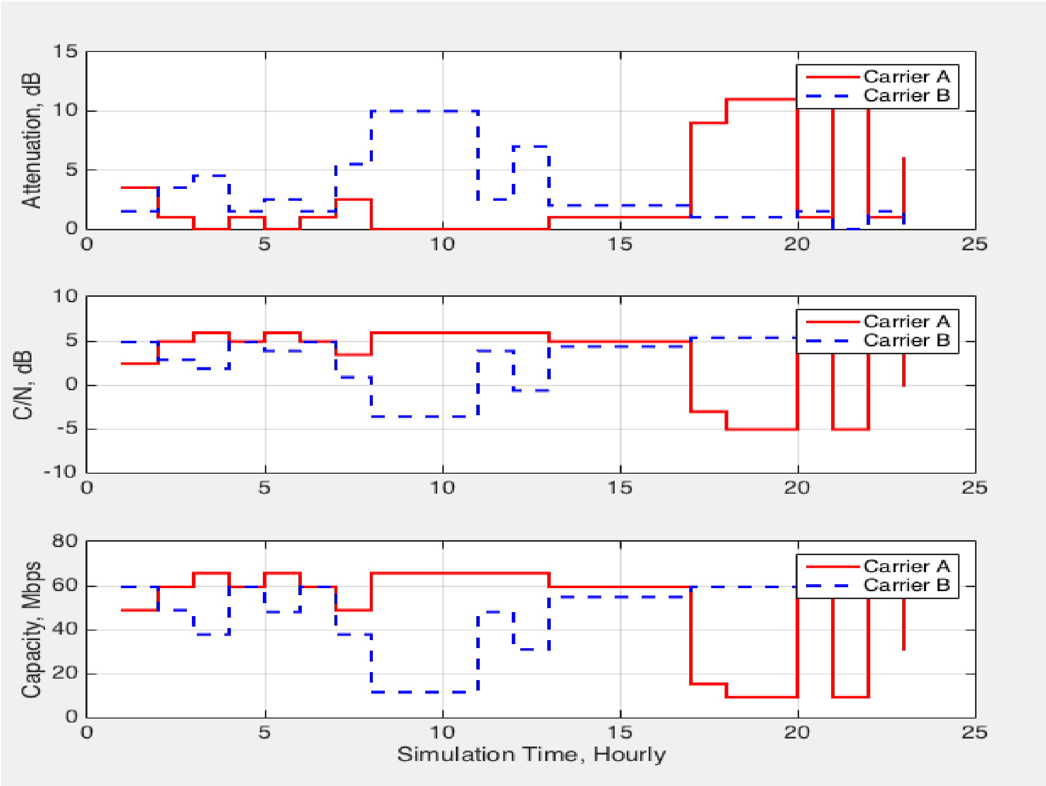

Figure 27: Simulation showing change in capacity hourly to meet the demand

In order to operate this process autonomously, two sets of inputs are necessary for initialization. The first step is to make a measurement with the pilot carrier. One measurement is necessary during a clear day and will continue to be valid if there is no change in location, frequency, beam, or receive antenna properties. When data carriers following the same pilot carriers are activated, a nominal transmission configuration, such as the modulation, coding type, and coding rate can be selected based on calculated C/N. The second input is the profile of the demand based on the time and beams. Such a demand profile can then be associated with the carriers in a given beam. Various demand formats can be used but a common format is to normalize demand based on the available pool resources: satellite bandwidth and power. Through the calculation of the link budget, a required EIRP can be found. The attenuator is then used to set this required EIRP which in turn changes the C/N of channel, therefore providing the necessary capacity to meet the demand.

Figure 28 shows the example of data carriers mapped to the attenuator port, which can change the attenuation to meet demanded capacity in a beam. Figure 29 illustrates the block and logical diagram of the operation. As expected, the operation begins with computing correction factors with the help of pilot carriers. EIRP, C/N, and offered capacity are calculated. As the demand for the capacity changes, a necessary attenuation change is made to meet the demanded capacity. The frequency of the operation is determined by the service provider to maximize the utilization and match the traffic type. With a minimum set of input variables at the beginning, the operation can continue without requiring any manual external inputs.

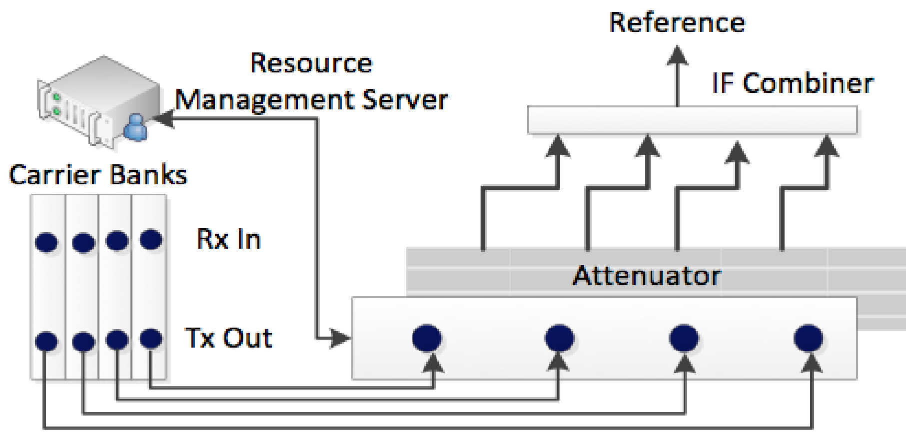

Figure 28: Diagram showing attenuator port mapping with data carriers

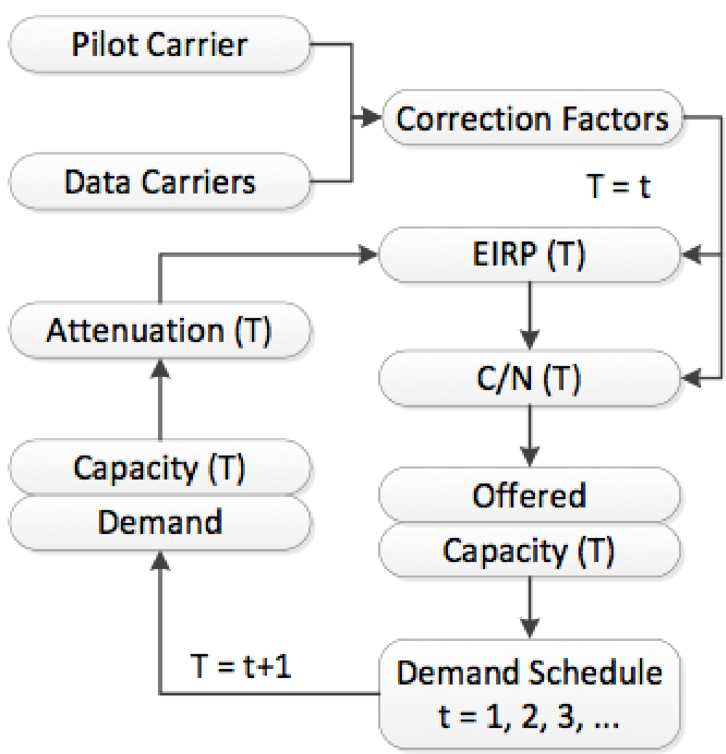

Figure 29: Block and logical diagram of operation

The aggregate amplifier power of an MPA is fixed. The flexibility comes from the ability to move MPA power between beams based on where the demand is located, while complying with power spectral density and aggregate limits. When the EIRP for a carrier in one beam increases, the EIRP in another carrier must decrease to maintain constant power within the MPA. A good illustration of beams, carriers, carrier properties and the change in such properties at different instants in time to match the new demand without exceeding the pool resource is shown on Figure 30. In this example, the available bandwidth and EIRP is 216 MHz and 51.6 dBW, respectively.

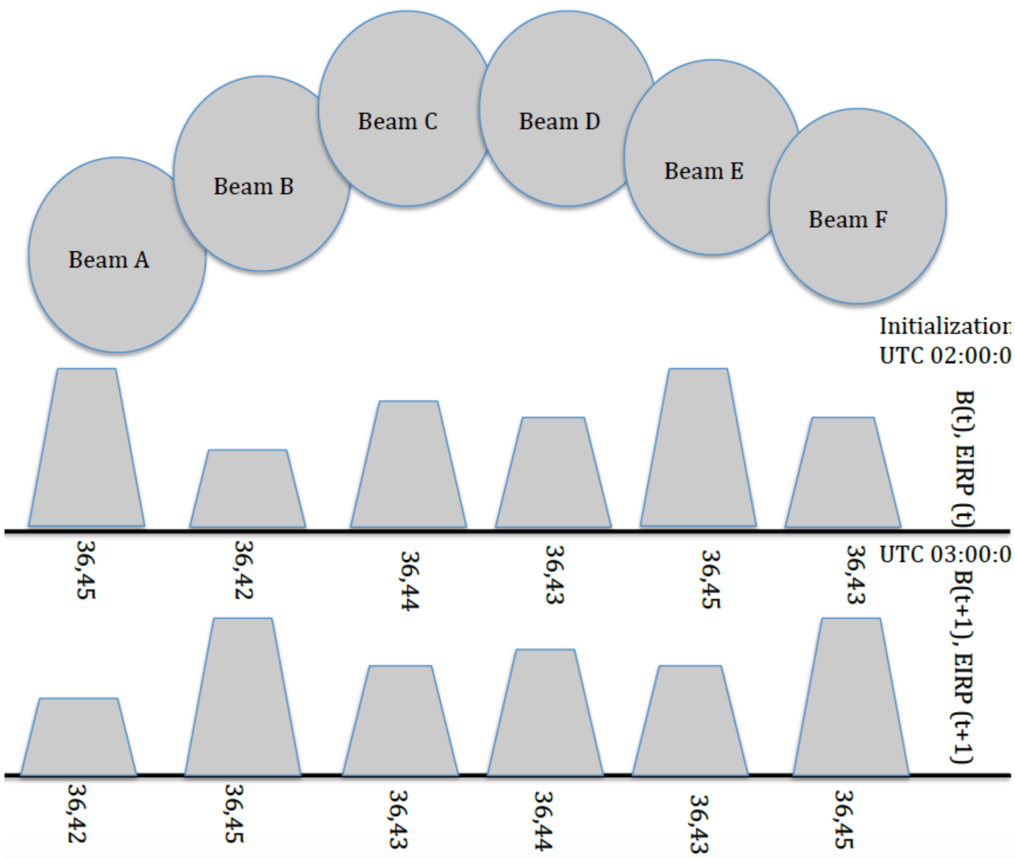

Figure 30: Relationship showing beams and the respective power assigned to carriers

At the first instant, the pooled resources are divided as demanded but will sum up to the total available resources – 216 MHz bandwidth and 51.6 dBW EIRP. At the second instant, carriers will experience a change in EIRP for the same bandwidth to meet the different demand without exceeding the pool resources. In a different demand profile the pool of MPA power and bandwidth will stay the same. EIRP per carrier, however, will change to match the new demand.

System Level Diagram

Figure 31 shows the detailed logical diagram of the operation and decision logic. First various input parameters, mainly for pilot carriers, needs to be entered. This data is used to calculate correction factors. Successful measurement and calculation of the correction factors leads to the EIRP and C/N of the data carriers. The capacity is calculated for initial data carrier and derived using EIRP, C/N and the capacity associated with the carrier. The system will look for a demand in capacity using the schedule. The required new EIRP, C/N, and corresponding attenuation are calculated to meet the new demand for the capacity. The final attenuation is applied to the port mapping of the attenuator to the data carrier. The change in attenuation manipulates EIRP and C/N that in turn changes the modulation and coding rate of the carrier and delivers the desired capacity in the channel. In this instance the new required EIRP is checked against the ESD limit, threshold C/N, and total available resources of the MPA. If any of the available resources are exceeded by the calculated inputs, the demand profile is adjusted at that instant, every active carrier gets equal resources.

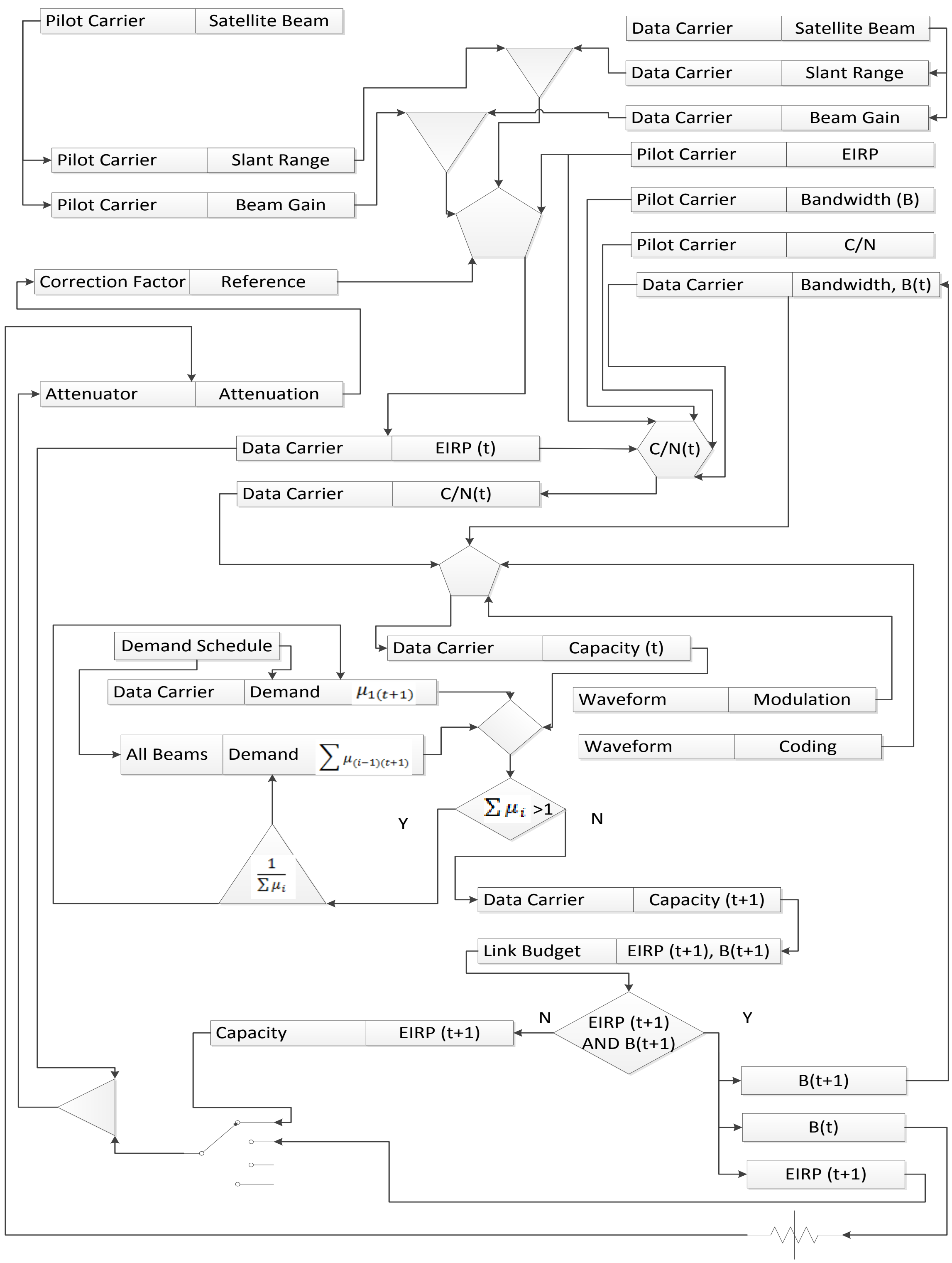

Figure 31: Detail logical diagram of the system architecture

Two methods can be used to deliver the desired capacity: either by changing the bandwidth and EIRP of a carrier proportional to demand or by changing only the EIRP of the carrier. If a change in EIRP is selected to meet the capacity demand, the attenuator is programmed to reflect the required change in EIRP. If the bandwidth option is selected, then the older bandwidth carrier is attenuated such that the carrier performs as turned down. The new carrier, proportional to new EIRP is un-attenuated to activate. At the same time, attenuation is lowered on the new carrier to meet the new EIRP demand. Over time, this operation is repeated to meet the demand as the demand profile evolves and runs autonomously.

CHAPTER 5: APPLICATION

An example case was created to demonstrate the proposed method utilizing the technique of a pilot carrier, and correction factors, the configuration of the data carrier is established. A data carrier is the nominal baseline carrier for further computation and automation. For this example, an MPA-equipped HTS with 6 service beams will be considered. Each beam has both different capacity demands and data carrier configurations. Table 3 shows the data carrier configuration that will be used for this example.

Table 3: Initialized data carrier parameter

Beams	Num. Carriers in Beam	Reference EIRP Allocation (dBW)	Reference Symbol Rate	Modulation	Coding Rate	Power Spectral Density Limit (dBW/kHz)	Nominal Attenuation Setting (dB)
Beam A	1	54	50	8PSK	23/36	-20	30
Beam B	1	55	56	16APSK	8/15	-20	30
Beam C	1	52	16	16APSK	8/15	-20	30
Beam D	1	54	25	16APSK	8/15	-20	30
Beam E	1	55	28	16APSK	8/15	-20	30
Beam F	1	58	70	QPSK	32/45	-20	30

The demand for the capacity changes hourly with a 24 – hour cycle in this example. There is no limit on how often the desired demand is changed. Figure 32 shows the demand for the capacity normalized to the beam peak demand as function of time.

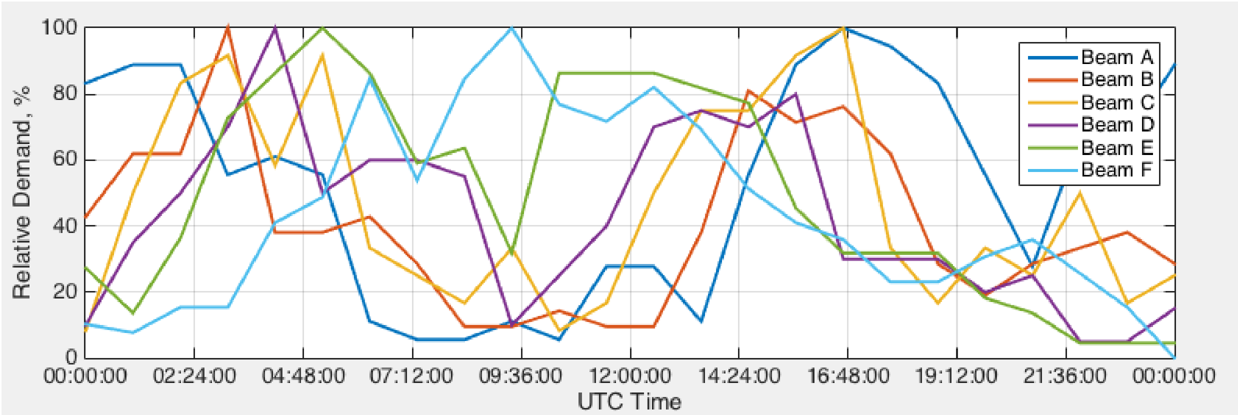

Figure 32: Relative demand for capacity in a 24-hour cycle

Three different cases of the satellite resource utilization scenario using the new method were compared against the traditional method of planning and allocating satellite resources. The traditional method uses satellite EIRP and bandwidth as resources and plans transmission to meet the peak capacity required in a given beam in any point in a time. Such configurations remain fixed until manually changed by the planner.

Method 1 - Change in Satellite EIRP: The first method uses the data carrier configuration, fixes the bandwidth, and changes the satellite EIRP, which changes the C/N of a carrier to meet the demanded capacity. In this case, attenuation of the programmable attenuator is adjusted to deliver the required satellite downlink EIRP of a carrier in a given beam. Figure 35 shows the result of satellite EIRP saving using Method 1 compared to the conventional method when attempting to meet the same demanded capacity. A lower amount of satellite EIRP is used, compared to the traditional method of planning. Since the EIRP must be allocated when the sum of all the demand is the highest, the overall savings using this method is 44% in satellite EIRP. However, it takes 75% less EIRP when the demand for the capacity is at the lowest.

Method 2 - Change in Satellite EIRP and Activate/Deactivate Carriers: In a second method, EIRP and predefined carriers are changed to meet the demanded capacity. A total of three data carriers with three different bandwidths are pre-defined per beam. After the demand for capacity reaches a threshold of 20% in this example, a new pre-determined carrier of a different bandwidth but same center frequency is activated. Activation and deactivation of different carriers can be accomplished by manipulating value of attenuation as shown in Figure 28.

If the value of attenuation is set very high at the output of the modulator, the receiver cannot detect the signal. Conversely, no attenuation or a low value of attenuation will allow the receiver to demodulate and decode the transmitted signal. At any given time, there is a one carrier detected and two undetected by demodulators, although all modulators operate at the same center frequency concurrently. Figure 33 shows an example using three beams and three carriers on each beam with small, medium, and large size bandwidth. The medium sized carrier is the same as the data carrier used in Method 1.

1. At beam A carrier of medium bandwidth is active and denoted by '0'
2. At beam B a carrier of small bandwidth is active and denoted by '-1'
3. At beam C a carrier of large bandwidth is active and denoted by '+1'

Figure 34 shows the carrier activation and deactivation decisions made by the resource management server and applied to the programmable attenuator to meet the requested capacity demand.

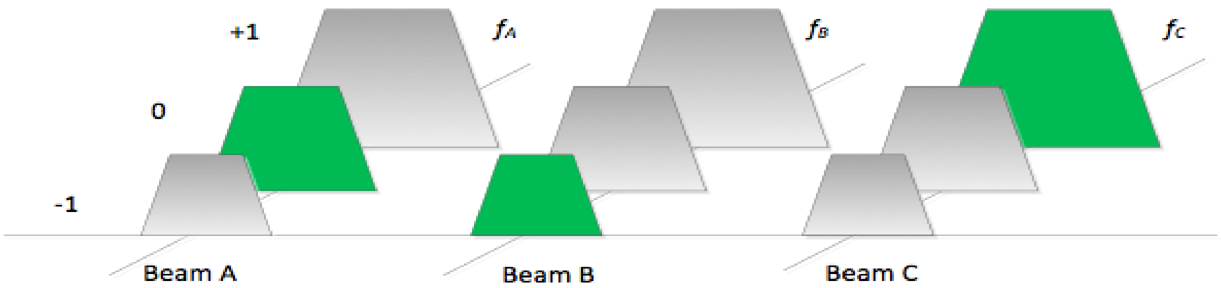

Figure 33: Model showing pre-defined carriers that are activated and deactivated

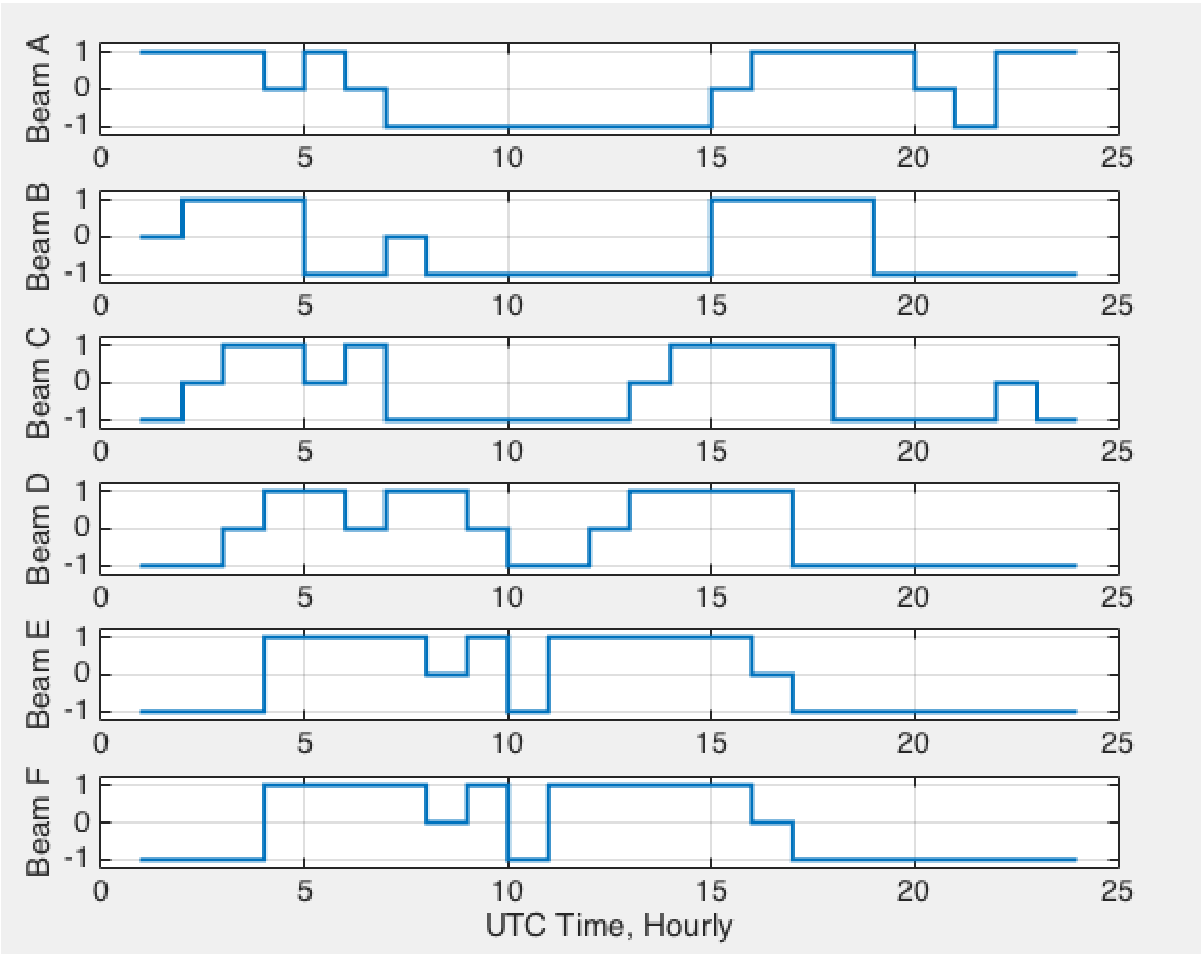

Figure 34: Activation and deactivation of predetermined carriers

The required EIRP to meet the same capacity demand is further lowered compared to the first method where only the EIRP is changed. At the peak, 49% less EIRP is required to meet the same demand, which is a 5% improvement over Method 1.

Similarly, at the lowest demand point, it takes 78% less EIRP to deliver the same capacity. Although the overall reduction in peak power is relatively small, the difference in the EIRP required when the overall demand for capacity is lowest is 12% lower than Method 1.

The penalty in Method 2 is that more bandwidth must be allocated. Bandwidth usage relative to the traditional method and Method 1 is shown in Figure 36. Although in many cases the bandwidth requirement is lower than Method 1, it must be allocated for peak requirement: 10% more bandwidth than traditional method and Method 1 must be allocated for this method.

Method 3 - Change in Carrier Bandwidth and EIRP: The third method changes both the EIRP and carrier bandwidth to meet the requested demand. At the peak demand the required EIRP to meet the demand is 51% lower than the traditional method. However, when the demand for capacity is the lowest, the EIRP requirement is 13% less than Method 1 and 8% less than Method 2. The penalty for this method, as was the case with Method 2, will be a higher bandwidth requirement. Although this method requires 59% less bandwidth at the lowest demand, it still requires 29% more bandwidth at the peak demand hour shown in Figure 36. Since bandwidth must be allocated for the peak demand, the overall penalty in bandwidth is 29% to gain the 51% saving in EIRP.

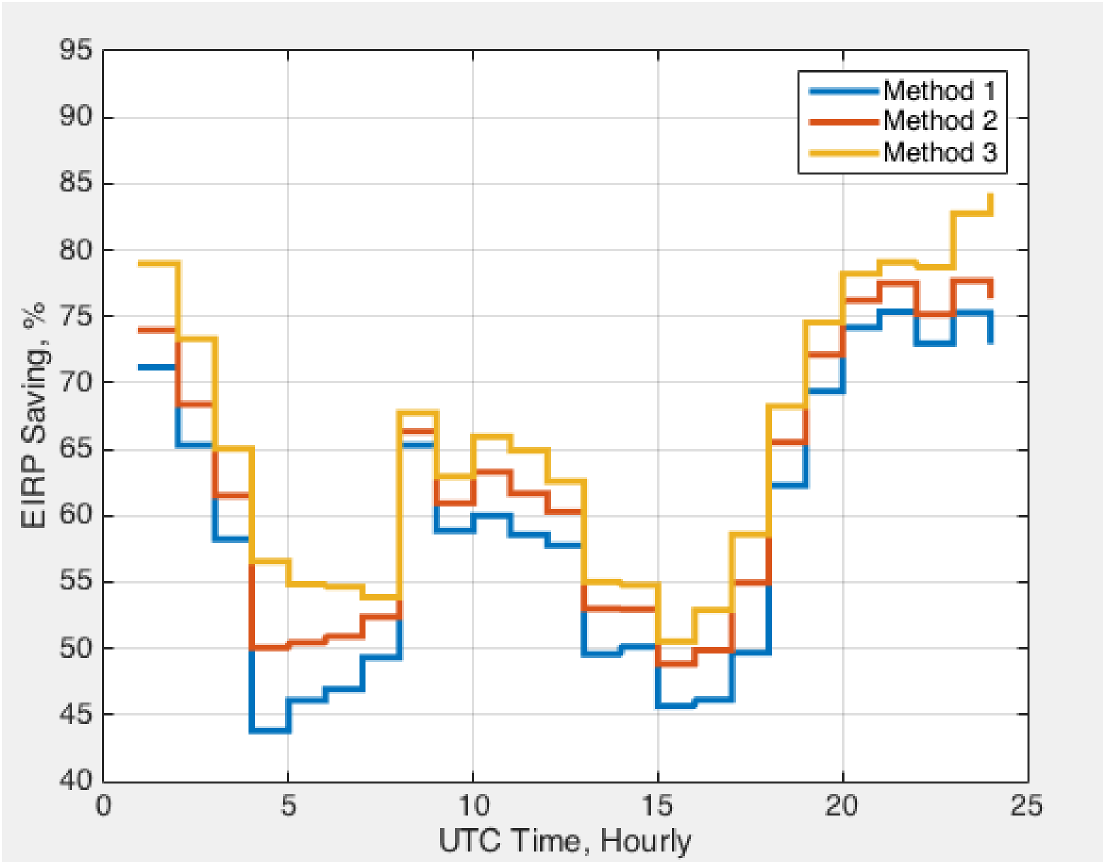

Figure 35: Satellite EIRP saving relative to traditional method

Generally, there is bandwidth penalty for the two cases to deliver the same capacity but satellite downlink service is more limited in EIRP than bandwidth. New HTS are tailored to have wide bandwidth transponders. It is preferable to save EIRP in an exchange for bandwidth for lower gain antenna such as COTM. The summary of satellite EIRP and bandwidth savings and penalties is shown in Table 4.

As long as an HTS has beams that can access a common pool of power and the peak demand on each beam is different, the methods in this research will contribute to a significant savings in satellite power while increasing the bandwidth requirement marginally.

The net result will be a positive savings in resources and overall cost to the operator and service provider; HTS solutions with the proposed power-sharing methods will be the most attractive technology for satellite platforms in the COTM market.

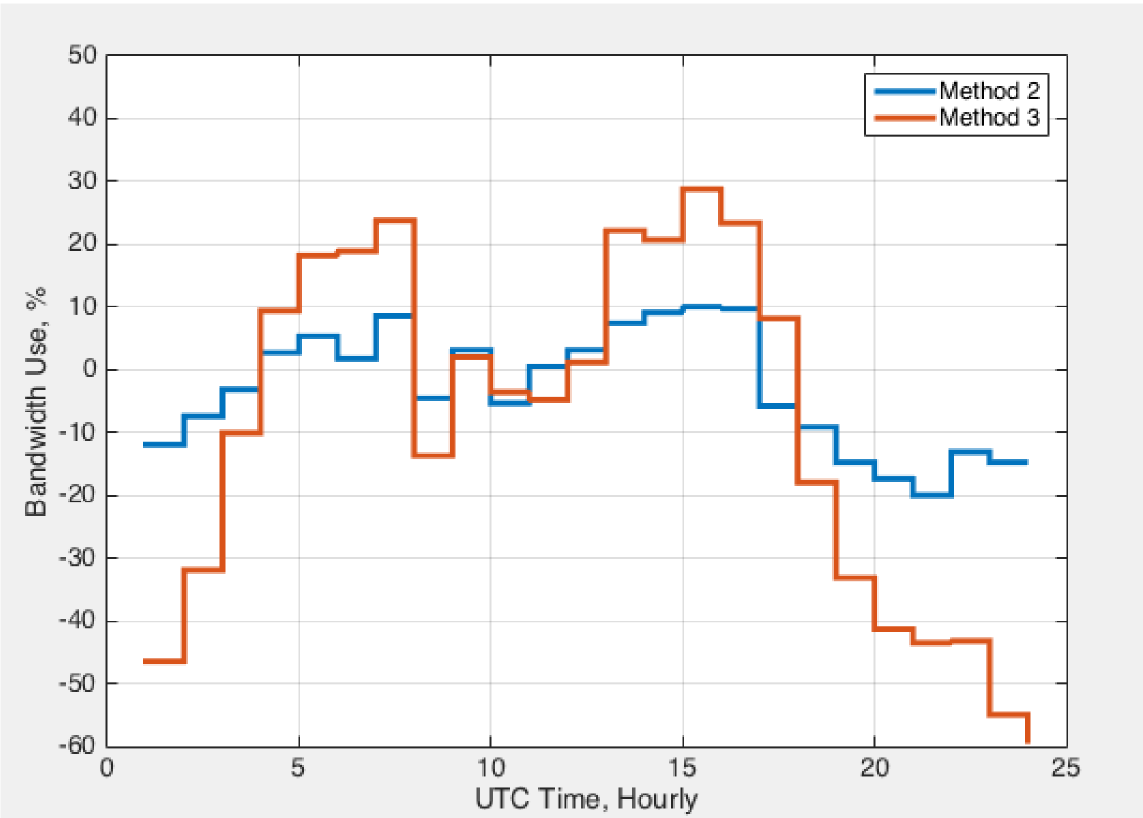

Figure 36: Bandwidth use relative to traditional method

Table 4: Satellite EIRP saving and bandwidth usage comparisons

	Satellite EIRP Saving		Satellite Bandwidth Usage	
	Peak Demand	Lowest Demand	Peak Demand	Lowest Demand
Method 1	44%	75%	NA	NA
Method 2	49%	78%	10%	-20%
Method 3	51%	84%	29%	-59%

CHAPTER 6: SUMMARY AND CONCLUSION

The primary goal of this research was to develop a new method to plan transmission to deliver the proper amount of requested capacity, while using less satellite resources. The traditional method in satellite communication has been to plan for the peak requirements. However, for applications such as COTM, peak capacity demand occurs for a small percentage of time, leaving the satellite resources underutilized for the majority of time.

This research introduced new methods to efficiently allocate satellite resources to serve the distinct needs of the COTM market, resulting in drastic reductions in cost for operators and service providers. The presented work covered the following aspects:

1. Overview of satellite communication in mobile platform.
2. Challenges faced in mobility broadband communication.
3. New generation satellite development and architecture.
4. Techniques to dynamically allocate resources with new satellites.
5. Mathematical model to calculate nominal transmission configuration.
6. Mathematical model to dynamically plan transmission.
7. System design to accommodate new type of transmission to deliver capacity that changes with the time.
8. Three applications using the proposed method.

Since the peak capacity demand across beams is always equal to or lower than the sum of all the peak capacity demands in each beam, this research has shown that the proposed methods will save precious satellite power compared to traditional transmission planning methods. Figure 37 shows that the differences between the peak demand across all beams of an HTS (left) versus the sum of the peak demand (right). The overall reduction in demand and consequential savings in satellite resources can vary but some primary factors are:

1. Selection of HTS beams for a desired COTM service.
2. Number of HTS beams in a pool.
3. Distribution of the capacity demands and its time relation.
4. Distribution of the peak demand and its time correlation.

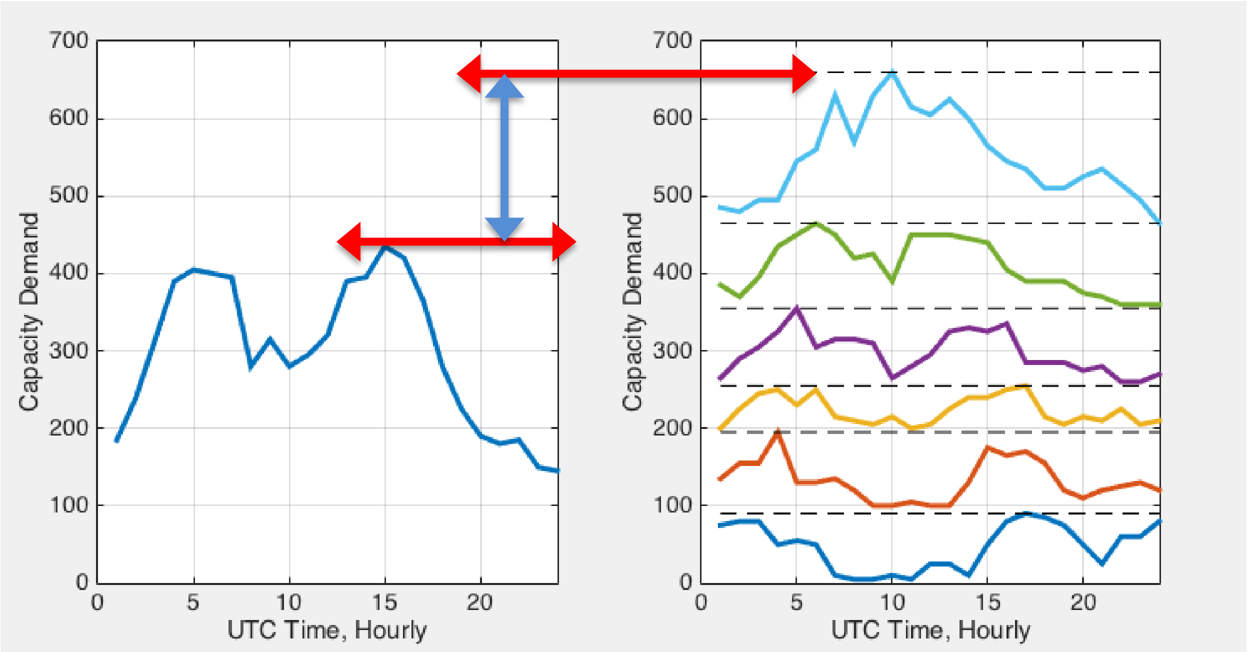

Figure 37: Example illustrating sum of demands and sum of peak demands

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