Coverage Extension via Side-Lobe Transmission in Multibeam Satellite System

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***Abstract*—In this paper, we study feasibility of coverage extension of a multibeam satellite network by providing low-rate communications to terminals located outside the coverage of main beams. Focusing on the MEO satellite network, and using realistic link budgets from O3b networks, we investigate the performance of both forward and return-links for terminals stationed in the side lobes of the main beams. Particularly, multi-carrier transmission for forward-link and single carrier transmission for return-link are examined and the resulting coverage and data rate for different setups are evaluated. Simulation results verifies that side-lobe transmission can extend the coverage area and provide considerable data rate, thereby providing a solution for enhancing capacity of existing networks.**

I. INTRODUCTION

We study possibility of providing low-rate communications to terminals located via the side lobes of multibeam satellite. In particular, we focus on a scenario where the user terminal is served by the MEO satellite network without steering a satellite beam directly to it. Instead, it is assumed that the geographical location of the user terminal is in between multiple spot beams originating from the same satellite. As none of the beams are pointing to the geographical location of the user terminal directly, useful power is received only through the side lobes of these beams, which renders signals received on each individual beam very weak. Channel dynamics with respect to the signal bandwidth and baud-rate are slowly varying.

O3b networks currently have 80 remote beams with their 12 satellite constellation [1]. Enhancing the coverage without increasing the number of beams warrants communication over side-lobes. The motivating factors for considering this scenario in MEO systems include:

- In typical MEO spacecrafts spacecraft, reflectors for the user beams (one reflector per beam) are very small and side-lobes are not as low as they would be with other bigger reflectors. Hence, it is possible to exploit transmissions received through side-lobes meaningfully.
- Since the spacecraft is closer to ground, the received power-flux density is high.
- Currently, there exists spare capacity which can be used for low rate communications over the side-lobes; thus service to the terminals in the main lobes are not affected.

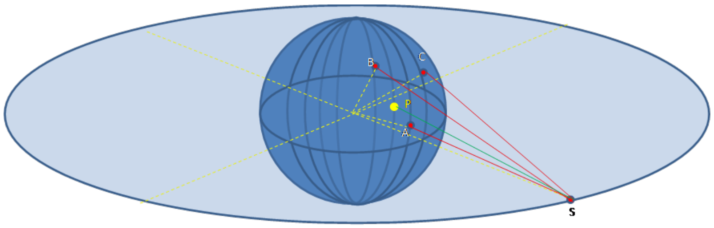

Fig. 1. Illustration of the scenario: 3 beams (with beam centers A, B and C) from a satellite are serving a parasite (P)

These motivating factors notwithstanding, it becomes essential to provide multiple links to the terminal to offset the loss in gain due to side-lobe transmissions. Multiple transmissions can be supported by using multiple satellites and/ or beams. However,

1) Typically each GW serves one satellite and hence using transmissions from multiple satellites is not attractive.
2) Multiple satellites need additional antennas for tracking

In view of these, multiple beams from a single satellite is considered. Further, since different beams use different frequencies, the use case involves transmissions over multiple carriers, one each from a beam. Due to the geographical spread of the parasite terminals (over half a continent sometimes), there is certain amount of immunity to rain fade.

A high level sketch of the scenario is presented in Figure 1 which indicates three beams centred at A, B and C being used to serve the terminal at location P, which lies outside of the coverage of these beams. The aim is to sustain low rate communications with terminals outside the normal coverage of a satellite beam by transmitting and receiving data on multiple beams in a region, and dynamically adjusting the proportion of data sent on a particular beam via ACM-type feedback.

The paper is organized as follows: Section II describes the multibeam MEO satellite system and corresponding satellite-earth Geometry. Return-Link and Forward-Link are introduced and studied in Section III and Section IV, respectively. Finally, Section V presents the simulation results and the relevant discussions.

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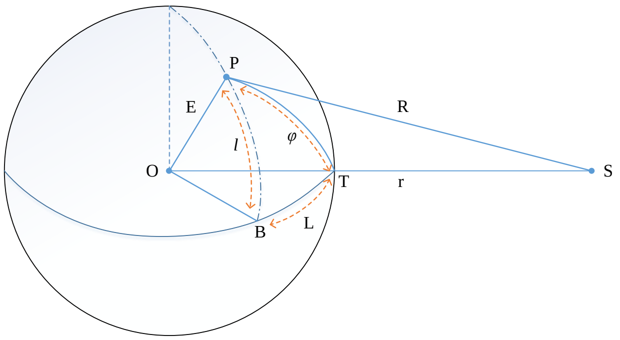

Fig. 2. MEO Satellite-Earth Geometry

II. MULTIBEAM MEO SATELLITE SYSTEM

Assuming the setting up of a connection with a terminal denoted by P in Figure 1, where there is no beam centered, one possibility is to send data on the beams centered over A, B and C. There is excess bandwidth in each one of these beams which can therefore be used for communicating to P through the side lobes of these beams.

As the satellite moves, the Space Craft (SC) antenna rotates to keep A, B and C in beam centers while the satellite S is moving with an angular velocity of 1 deg/minute. The signal strength in P from a particular beam is a function of the corresponding angles ASP, BSP and CSP and the spacecraft antenna pattern. These angles will change slightly as the SC moves. The changes may be in the order of a fraction of a degree through the pass but may be enough to vary the signal amplitude a lot. The evolution in time of the angles can be determined from the orbit geometry (assuming the satellite angular velocity of 1 deg/minute). The signal strength evolution in time can be subsequently determined based on the antenna pattern. Hence the time series for the received signal strength at the parasite will vary in a deterministic sense if we know the side-lobe performance of the SC antenna. The variability comes because each manufactured antenna could have slightly different side-lobe performance depending on manufacturing tolerances.

A. *MEO Satellite-Earth Geometry*

We consider that MEO satellites are on the equatorial plane with orbit radius of $r = 14440\ km$. During the pass coordinates of the MEO satellite changes, so do the angles between the parasite and beam centers with respect to satellite. These angles impact the effective gain of the satellite antenna. Therefore, in order to evaluate the system performance we need to calculate those angles over the entire pass. Figure 2 shows the satellite-earth geometry. Here P is an arbitrary point on the surface of earth and S denotes the MEO satellite. Let us denote the latitude and longitude of the point P by l and λ_P, respectively. The longitude of the satellite is denoted by λ_S. The point B is the projection of P on the equator, so both points have the same longitude, $\lambda_P = \lambda_B$.

We first find the distance between the satellite and point P on the earth (can be a parasite or beam center). Consider the triangle POS, law of cosines gives:

$$R^2 = E^2 + r^2 - 2rE\cos\varphi \tag{1}$$

where E is the earths radius and φ is the center angle POS. In the spherical triangle PBT, we can have [2]

$$\cos\varphi = \cos L \cos l \tag{2}$$

Where l is the latitude of point P and L is the difference in longitude of points P and T as $L = \lambda_T - \lambda_B = \lambda_S - \lambda_P$. Here, T is the sub-satellite point. Knowing the coordinates of MEO satellite and a point on earth, then distance between them can be calculated as,

$$R = \sqrt{E^2 + r^2 - 2rE\cos L \cos l} \tag{3}$$

We denote the distance between the satellite and a parasite by R_1 and the distance between the satellite and the beam center by R_2. Using above expression we can find R_1 and R_2 readily.

The Euclidean distance between a parasite and the beam center, denoted by d, can be calculated by transforming their coordinates in to Cartesian coordinate. Having three side of a triangle (R_1, R_2 and d) and using the cosine rule, the angle between parasite and beam center with respect to satellite can be found as,

$$\theta = \cos^{-1}\left(\frac{R_1^2 + R_2^2 - d^2}{2R_1R_2}\right) \tag{4}$$

After calculating θ for a parasite, we can find the corresponding antenna gain using beam cuts table provided by antenna manufacturer.

III. FORWARD-LINK STUDY: CLEAR SKY

For the forward-link, multiple beams from single satellite is used to provide low data rate communication over the side-lobes. Each small carrier in each beam is separated in frequency and independent DVB-S2X streams are transmitted over the side-lobes in different carriers. Therefore, there need to be multiple modulators at the gateway and multiple demodulators at the parasite receiver. There is no processing (i.e. signal combining, ...) needed and the forward traffic is delivered to the parasite via multiple paths in a load sharing scenario.

The bandwidth allocated to each side-lobe transmission is $10MHz$ out of $216MHz$ total bandwidth of transponder. The transmission power is assumed to be 20% of the total transponder's power. Based on the beam cuts considered in this study, antenna gain is $32.1dB$ at beam centers. We assume this value is the same for all beams and fixed over the satellite pass. From the considered link budget, we observed that average C/N (over the pass) at beam centers is $13.1dB$ at PEB (power equivalent bandwidth) level and in clear sky condition. For any other operating point, the average C/N can be calculated as,

$$\frac{C}{N}(\text{power}\%, \text{BW}\%) = \frac{C}{N}(\text{PEB}) + 10\log_{10}\left(\frac{\text{power}\%}{\text{BW}\%}\right) \tag{5}$$

TABLE I
RETURN-LINK PARAMETERS

Parameter	Description
u_0	Uplink Thermal Noise C/N
u_1	E/S HPA C/IM
u_2	Uplink Co-Channel Interference (CCI) C/I
u_3	Uplink Adjacent Satellite Interference (ASI) C/I
s_1	Transponder HPA Intermodulation C/IM
s_2	Adjacent Carrier Interference (ACI) C/I
d_1	Downlink Thermal Noise C/N
d_2	Downlink Co-Channel Interference C/I
d_3	Downlink Adjacent Satellite Interference C/I

Considering operating point of (20%, 4.6%), the average C/N at beam center is calculated as,

$$\frac{C}{N}(20\%, 4.6\%) = 13.1dB + 10\log_{10}\left(\frac{20\%}{4.6\%}\right) = 19.45dB. \tag{6}$$

We can observe that antenna gain of $32.1dB$ at beam center results in C/N of $19.45dB$, which mean $12.64dB$ gain offset. We can assume that this offest is same for all other points in the coverage area over the satellite pass. We are also ignoring the change in noise temperature of the antenna with elevation angle as more ground noise enters at low elevation angles.The only parameter that changes considerably with satellite move and coordinate of the parasite is the antenna gain which is function of θ and can be calculated using (4). So, for any parasite we first calculate the corresponding antenna gain from all 5 beams and then deduct the gain offset in order to find the achieved C/N from each beam.

IV. RETURN-LINK STUDY: CLEAR SKY

A. Multi-Carrier vs Single Carrier

Unlike forward-link where it is possible to communicate via multiple transmitters (beam antennas), on the return link there is only one transmitter. It is still possible to transmit over multiple carriers at different frequencies. However, we can show that in order to maximize the sum-rate (for a given transmit power), it is optimal to transmit over a single carrier whose channel gain is the best. Therefor, we consider a single-carrier return link.

B. Single Carrier Return-Link

The end-to-end return-link C/N can be calculated as,

$$\frac{1}{(C/N)_{RTN}} = \frac{1}{u_0} + \frac{1}{u_1} + \frac{1}{u_2} + \frac{1}{u_3} + \frac{1}{s_1} + \frac{1}{s_2} + \frac{1}{d_1} + \frac{1}{d_2} + \frac{1}{d_3}. \tag{7}$$

The parameters in (7) are defined in Table I. Except uplink Thermal Noise C/N (u_0), all other parameters in (7) don't change considerably with location of user terminal and coordinate of the satellite over the pass. Therefore, we can assume that they are fixed and represent them by f as,

$$\frac{1}{f} = \frac{1}{u_1} + \frac{1}{u_2} + \frac{1}{u_3} + \frac{1}{s_1} + \frac{1}{s_2} + \frac{1}{d_1} + \frac{1}{d_2} + \frac{1}{d_3}. \tag{8}$$

Let us denote the uplink thermal noise at beam center operating at PEB level by u_0'. Then at a parasite, u_0 can be calculated using similar argument behind the expression (5) as (in decimal),

$$u_0 = u_0' \, \frac{g_{ps}\, W'}{g'\, W_{ps}} \tag{9}$$

where g' and g_{ps} are the antenna gain at beam-center and parasite location respectively. W' and W_{ps} are bandwidth for main-lobe and side-lobe transmissions accordingly. By replacing (9) and (8) in (7), we can have,

$$\left(\frac{C}{N}\right)_{RTN} = \frac{1}{\frac{\alpha W_{ps}}{g_{ps}} + \beta}, \tag{10}$$

where $\alpha = g'/(u_0' W')$ and $\beta = 1/f$.

Remark 1. *Since user terminal can transmit with a limited power, we assume that it transmits at maximum available power in order to close the return-link. At forward-link only a portion of the available power is allocated to the side-lobe transmission as main-lobe transmission also needs power.*

C. Choice of Return-Link Bandwidth (W_{ps})

As can be seen from (10), return-link C/N depends on the bandwidth, W_{ps}, which is a design parameter. There are several aspects which need to be taken into consideration when choosing W_{ps} :

1) Closing the Return Link: In order to close the return-link, the total C/N should be greater than $-9.9dB$ that is minimum C/N required for successful signal reception. So,

$$\frac{1}{\frac{\alpha W_{ps}}{g_{ps}} + \beta} \geq -9.9dB. \tag{11}$$

or equivalently,

$$W_{ps} \leq \frac{g_{ps}}{\alpha}(10^{0.99} - \beta) = W_{ub}. \tag{12}$$

W_{ub} can be seen as an upper-bound for return-link bandwidth.

2) Maximum Permissible Levels of off-axis EIRP Density: In order to limit the interference in the network, the ITU-R S.524-9 Recommendation [3] provides a maximum off-axis EIRP levels which should not to be exceeded by earth stations. Based on this recommendation, the earth stations operating in the $27.5 - 30GHz$ frequency band should be designed in a way that at any angle, ϕ, which is 2° or more off the main-lobe axis of the earth station antenna, the EIRP density should not exceed the following values

$$\text{Maximum EIRP per } 40KHz = 19 - 25\log(\phi) \tag{13}$$

Following this recommendation, we could find a lower bound as $2MHz \leq W_{ps}$.

TABLE II
COORDINATES OF THE BEAM CENTERS

Beam	Longitude	Latitude
1	0.29	12.55
2	15	12
3	18.33	4.23
4	14	-4.3
5	28.21	8.43

3) Choice of W_{ps} to Maximize Rate: Having an upper-bound and a lower-bound for W_{ps}, the question is what W_{ps} should be chosen in order to maximize the communication rate. Using Shannon formula, we can calculate the rate as,

$$R = W_{ps} 10 \log_2 \left(1 + \frac{1}{\frac{\alpha W_{ps}}{g_{ps}} + \beta}\right) \qquad (14)$$

We can show that R is a concave function of W_{ps} and it is monotonically increasing with W_{ps}. Therefore, we can conclude that to maximize the rate, we should use the largest possible bandwidth.

V. SIMULATION RESULTS: COVERAGE AND RATE STUDY

This section presents the simulation results for the performance evaluation of the both forward-link and return-link. For this study, we have considered 5 beams pointed to central Africa. The coordinates of the beam centers are given in Table II. The considered coverage area spans from latitude -10 to 20 degrees and longitude 0 to 30 degrees including all 5 beams. We also considered that satellite moves from $4E$ towards $44E$ over the pass with angular speed of 1 deg/minute.

A. Forward-Link Results

Some of the forward-link parameters have already been introduced in Section III. We summarized considered parameters in Table III. As mentioned earlier, for the forward-link we use multi-carrier transmission. In this study, we assume that any parasite location may receives signal from up to 5 beams (Table II) and signals are then decoded independently. For evaluating the rate performance, we use DVB-S2X ModCod's spectral efficiency. Figure 3 shows the minimum sum-rate over the satellite pass received from 4 side-lobes of beams 1 to 4. The regions between the contour lines are filled with a color. The region with white color shows the area in outage with sum-rate less than $0.01 Mbps$.

Figure 4 depicts the minimum sum-rate achieved by transmission over all 5 beams. As expected by increasing the number of transmitting beams, both sum-rate and coverage area increased. In Figure 3 and Figure 4, the coverage area is 94.8% and 97.9% respectively. It can be seen that it is possible to provide a meaningful rate to the large part of coverage area using multiple side-lobe transmission.

TABLE III
FORWARD-LINK PARAMETERS

Parameter	Value
Transmission Power	20% of transponder power
Transmission Bandwidth	$10MHz$
Transponder Bandwidth	$216MHz$
Antenna gain at beam centers	$32.1dB$
Average C/N at beam centres (PEB level)	$13.1dB$
Receiver Antenna size	$1.2m$
Minimum C/N for Modem Lock	$9.9dB$
Antenna pattern	provided by O3b

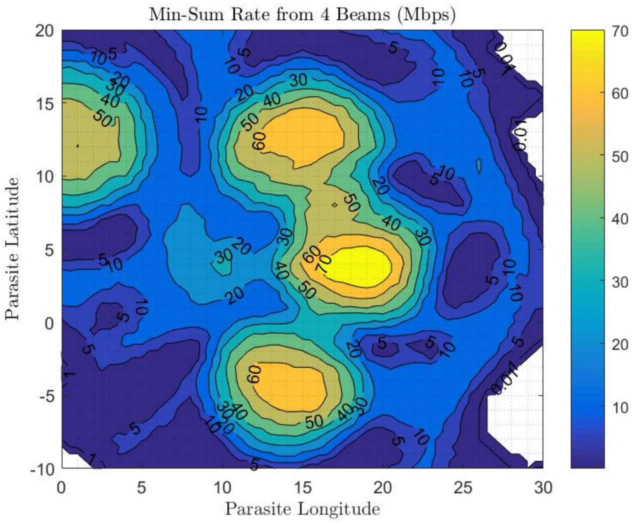

Fig. 3. Minimum Sum-Rate at Forward-Link over the satellite pass provided by 4 side-lobe transmissions, beams 1 to 4. Transmission power is 20% of transponder's power and the carrier bandwidth is 10 MHz.

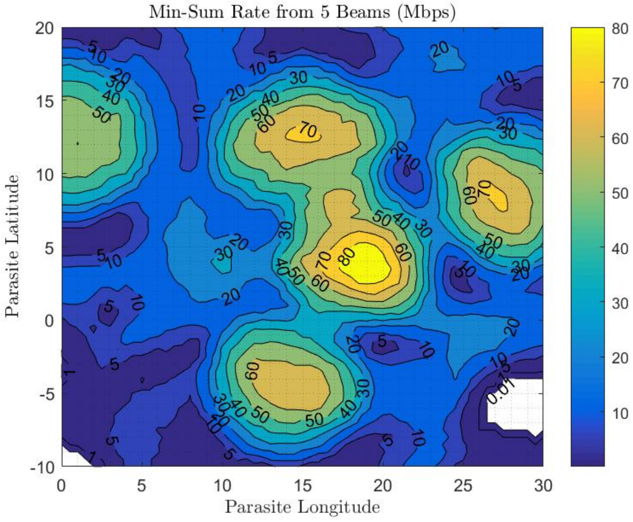

Fig. 4. Minimum Sum-Rate at Forward-Link over the satellite pass provided by 5 side-lobe transmissions. Transmission power is 20% of transponder's power and the carrier bandwidth is 10 MHz.

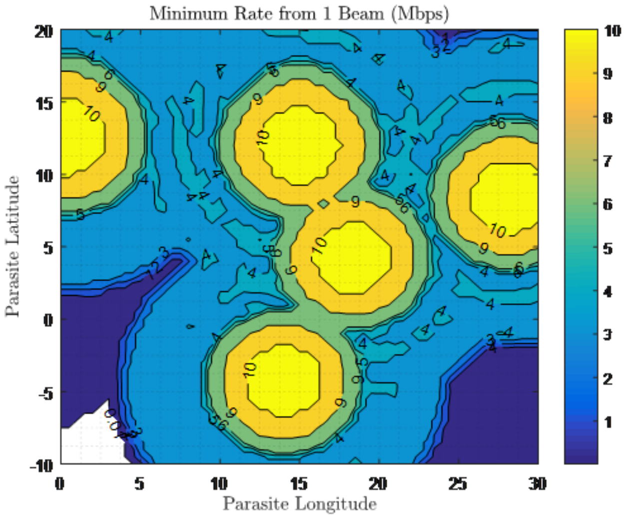

Fig. 5. Illustration of the outage area and the Minimum Rate (over the satellite pass) at Return-Link; the carrier bandwidth is 2 MHz.

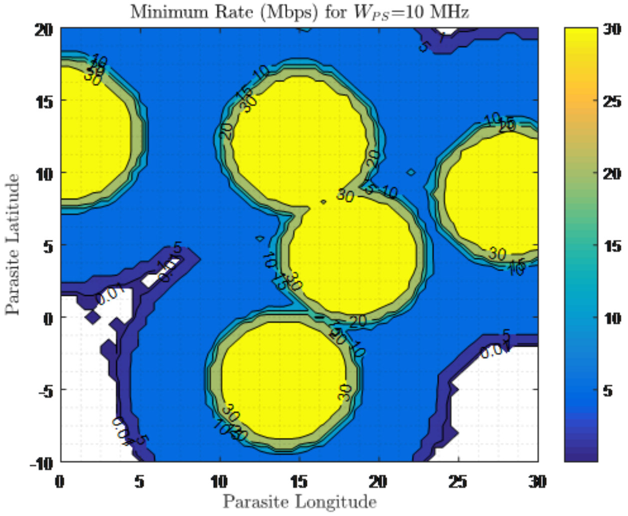

Fig. 6. Illustration of the outage area and the Minimum Rate (over the satellite pass) at Return-Link; the carrier bandwidth is 10 MHz.

B. Return-Link Results

As discussed in Section IV-A, we consider a single carrier return link and chose the best carrier for the transmission. Parameters of the Return-Link has already been introduced in Section IV-A. Based on the considered link budget parameters and expression (8), we find that $f = 17.78dB$. The antenna gain at beam center is $g' = 33.7dB$ and uplink thermal noise at beam center is $u'_0 = 11.6dB$.

Figure 5 shows the minimum rate (over the satellite path) at the return-link when $W_{ps} = 2MHz$. In Section IV-C, we discussed that in order to close the return-link, we should have $W_{ps} \leq W_{ub}$. Moreover, to satisfy the ITU-R recommendation, $2MHz \leq W_{ps}$. Therefore, when the minimum permissible W_{ps} is chosen ($W_{ps} = 2MHz$), we could expect to observe the minimal outage area indicated by the region in white, which is 1.77% in this case. Here, outage happens only when $W_{ub} < 2MHz$.

Figure 6 illustrates the minimum rate and outage area at return-link when $W_{ps} = 10MHz$. As expected, by increasing the bandwidth the coverage area reduces but rate increases at available area.

VI. CONCLUSION

We investigated the possibility of coverage extension using side-lobe transmission in multibeam systems in order to serve users located outside the main beam coverage. We considered O3b network as an example and studied the side-lobe transmission on forward as well as return-links using a link budget based approach. Simulation results confirmed the feasibility of this technique and showed that we could extend the coverage area and provide a meaningful rate to parasite users. While this work provides an avenue for better utilization of resources in existing networks, it comes at an increased cost for user terminals; since it requires user terminals to be equipped with multiple demodulators for the forward-link.

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