GROUND SEGMENT ARCHITECTURES FOR LARGE LEO CONSTELLATIONS WITH FEEDER LINKS IN EHF-BANDS

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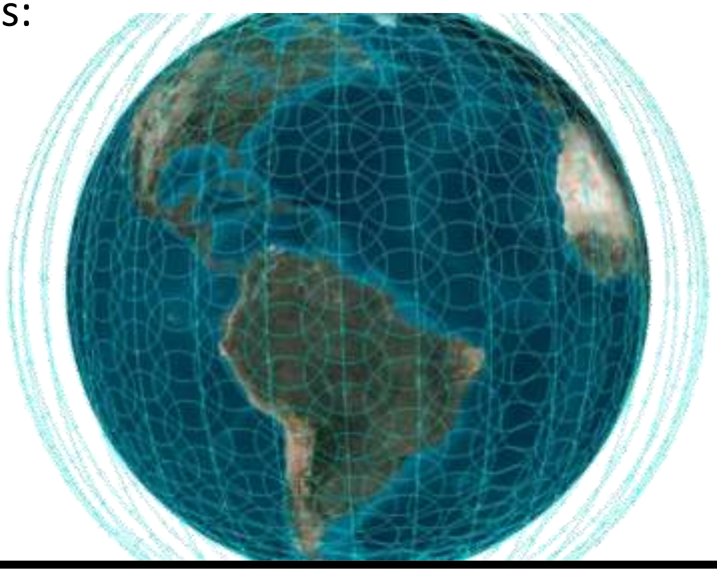
Introduction

- Several large constellations of LEO satellites have been proposed by different companies as a means to provide global broadband.
  - The first generation, uses Ka-band feeder links and Ka/Ku-band user links

- Increasing demand of satellite connectivity is driving the industry towards the development of systems with feeder links in EHF and optical bands.
  - Currently Q/V band and E-band systems are being considered for the second generation of these constellations

- Advantages of transitioning to higher freq. bands:
  - Increased bandwidth -> Higher data-rates
  - Reduced number of ground stations (?)
- Disadvantages of transitioning to higher freq. bands:
  - Higher atmospheric attenuation
  - Reduced availabilities



OneWeb's 720 satellite constellation

Research Objective

- Analyses for Q/V – band feeder link systems for GEO in the literature [1, 2]
  - Transition to EHF bands allows for higher capacities or lower number of ground stations.
- What happens for LEO constellations?
  - How many ground stations are required to provide service at a given availability?
  - What data-rates that can be achieved?

The objective of this paper is to assess the performance of ground segment architectures for large constellations of LEO satellites using feeder links in Q/V-band and E-band, and compare them against analogous architectures that use Ka-band (current architectures).

Performance drivers for comparison across architectures:

- **Number of ground stations:** Used as a proxy value for the cost of the ground segment
- **Coverage**: Measured as the percentage of the region of interest where service can be provided meeting a minimum QoS requirements
- **Data-rate:** Measured as the spatial average data-rate both in typical operation conditions as well as availability threshold conditions

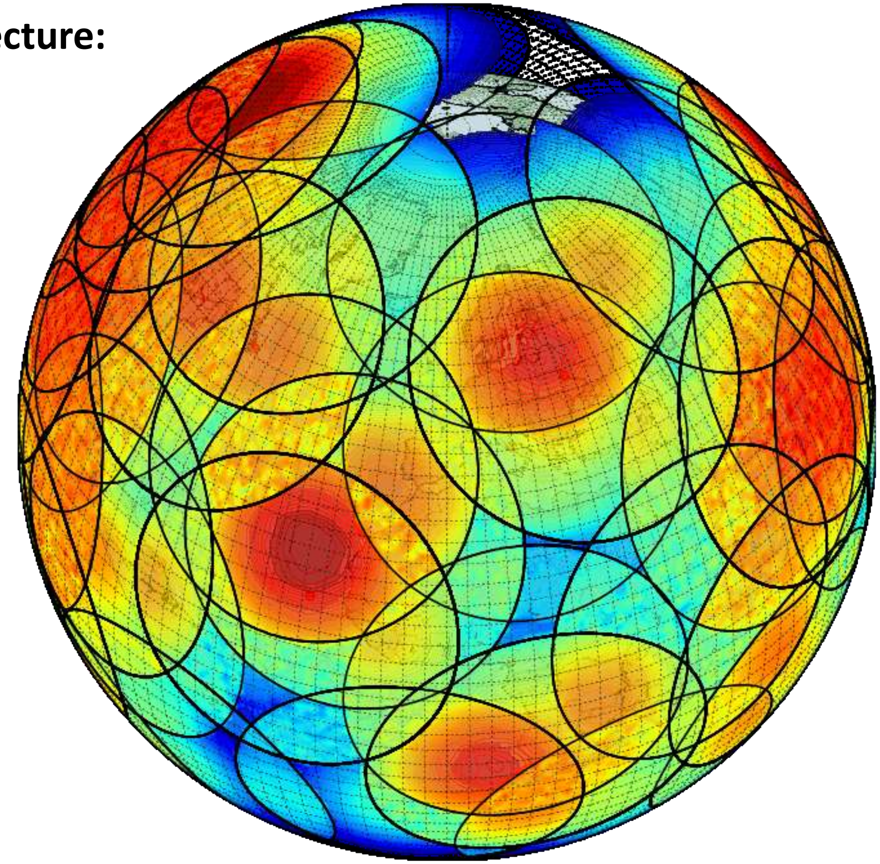
[1] T. Rossi 2014 **[2]** E. Cianca 2011

Our approach: Overview

Objective: Optimize the ground segment (minimize number of ground stations for maximum performance)

General overview – Analysis of a single architecture:

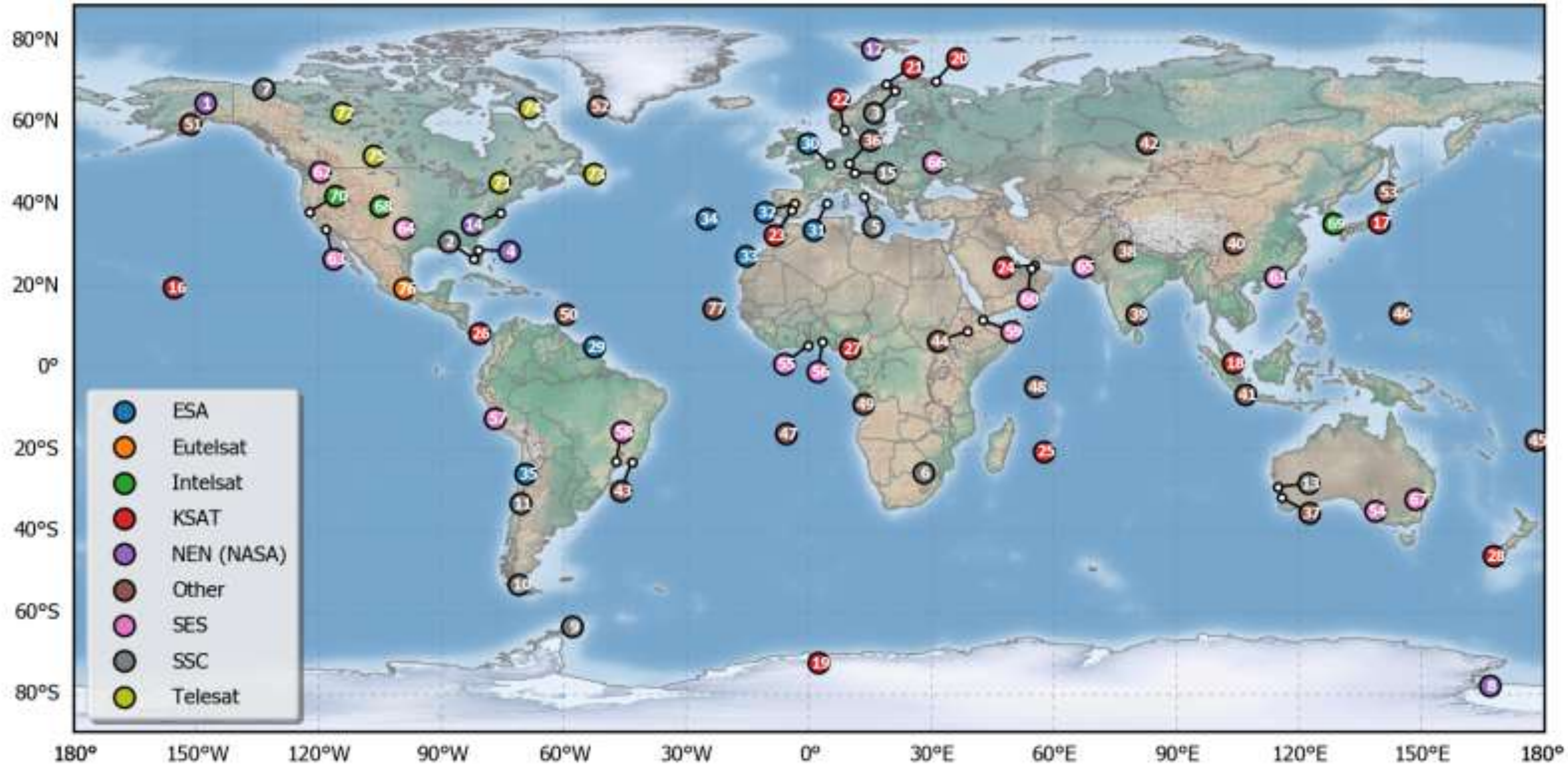
1. Define the ground segment architecture
2. Define the locus of the satellites and region of interest
3. Obtain coverage of each ground station and identify regions
4. For each point on each region, compute the CDF of the achievable data-rate.
5. Translate spatial results into aggregated metrics (coverage, average data-rate)



Step 1: Define ground segment architecture

We consider 77 candidate ground stations which:

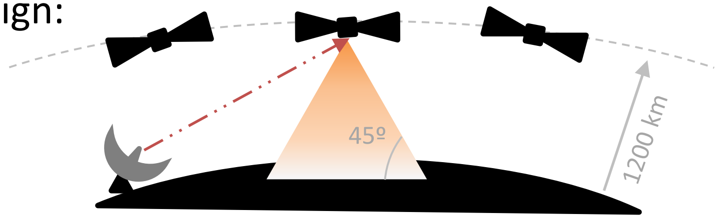
- **Guarantee global coverage**: evenly distributed across all continents
- **Do not present spatial correlated weather:** separated at least 1,000 km.
- **Are realistic ground stations sites**: Currently operative teleports of large satellite operators



Step 2: Reference constellation and demand model

Reference Constellation:

After analyzing the characteristics of 6 different proposed LEO constellations, we identify the following parameters for the reference constellation design:

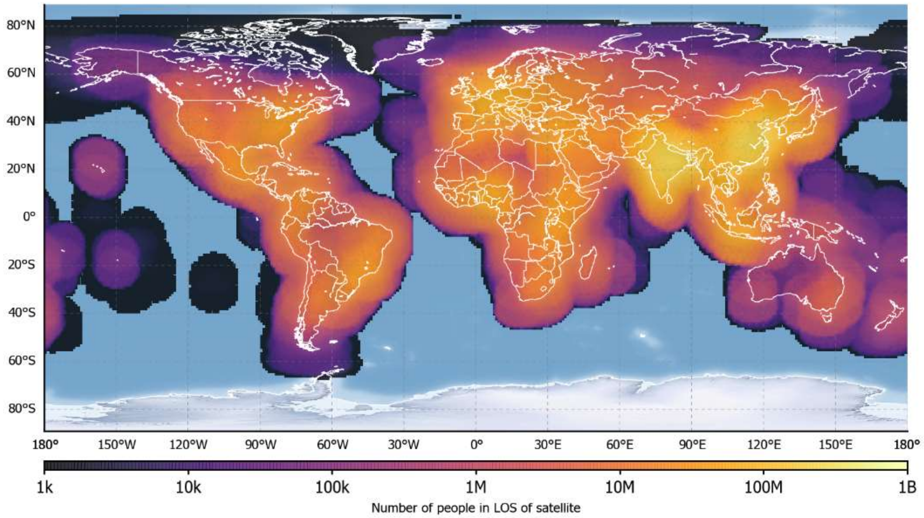


- Altitude of 1,200 km
- Combination of polar and non-polar orbital planes
- Satellites have 2 feeder antennas that can be used simultaneously
- Minimum elevation angle to a ground station 10 deg.
- Minimum elevation angle for a VSAT to communicate with a satellite is 45 degrees.
- There are no inter-satellite links.

Demand Model:

Used to define the region of interest and to weight which regions are more important to cover.

- Focus only on terrestrial services
- Assume higher data rates are required in high population density areas.



Step 4: Methodology to compute CDF of the uplink data-rate (single ground station)

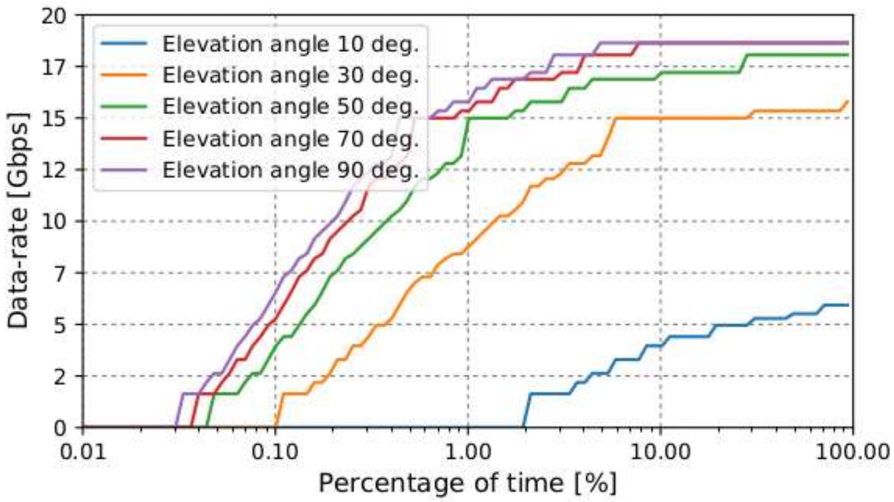
Link Budget

DVB-S2X recommendation MODCODs

ITU-R atmospheric models [1]:

- Rain: ITU-R P.838-5, ITU-R P.618-12
- Cloud: ITU-R P.840-6
- Gaseous: ITU-R P.676-10

For each location, we can derive the CDF of the total atmospheric attenuation…
and using it, the CDF of the data-rate.



	Uplink			
	E-band	V-band	Ka-band	Unit
Frequency parameters				
Frequency	83.5	50	29	[GHz]
Bandwidth	5	4	2.1	[GHz]
Transmitter parameters				
Tx Antenna D.	2.4	2.4	2.4	[m]
Tx Power (RF)	100	100	100	[W]
Receiver parameters				
Rx Antenna D.	0.50	0.50	0.50	[m]
LNB Noise Factor	4	3	2	[-]
Interference parameters				
C3IM	25.00	30.00	35.00	[dB]

[1] https://github.com/iportillo/ITU-Rpy

Step 4: Computing the CDF of the total uplink data-rate in a given orbital position (multiple ground stations)

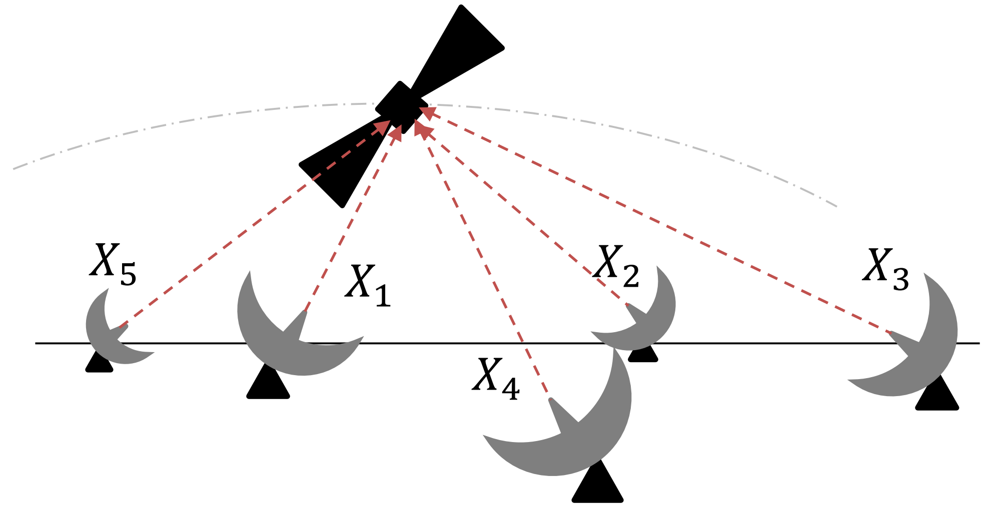
The data-rate to the *i*-th ground station is a random variable (X_i), with a known CDF.

If there are 5 ground stations in line of sight:

$$X = \{X_1, X_2, X_3, X_4, X_5\}$$

X = {21, 34, 0, 28, 0} Gbps

X = {18, 12, 32, 0, 0} Gbps



We define the order statistic random variables

$$Y_{(1)} < Y_{(2)} < Y_{(3)} < Y_{(4)} < Y_{(5)}$$

0 < 0 < 21 < 28 < 34 Gbps

0 < 0 < 12 < 18 < 32 Gbps

$$Y_{(1)} = \min(\{X_1, X_2, X_3, X_4, X_5\})$$
$$Y_{(5)} = \max(\{X_1, X_2, X_3, X_4, X_5\})$$

We assume that a satellite, will always connect to the N=2 ground stations with the highest data-rate. Therefore, the total uplink data-rate is: $Z = Y_{(4)} + Y_{(5)}$ Z = 28 + 34 = 62 Gbps / Z = 18 + 32 = 50 Gbps

How do compute the CDF of Z (total uplink data-rate for the satellite)?

- **Analytically**: Possible but computationally very expensive [1, 2]
- **Numerically**: Using Monte Carlo methods.

[1] R. Bapat and M. Beg 1989, **[2]** D. H. Glueck 2008

Step 5: Translate spatial results into aggregated metrics

Metrics

- Coverage: Percentage of orbital positions that serve the region of interest (demand map) with a data rate higher than 5 Gbps
- Average data rate: Weighted average of data-rate obtained at orbital positions that serve the region of interest
  - Weighted using the demand map

Consider both typical operation conditions and availability threshold conditions.

- Typical operation conditions are values obtained for at least 95% of the time.
- Availability threshold conditions are values obtained for at least 99.5% of the time.

Results in 4 metrics:

	Coverage	Data-rate
Typical Conditions	cov_{95}	Z_{95}
Availability Threshold	$cov_{99.5}$	$Z_{99.5}$

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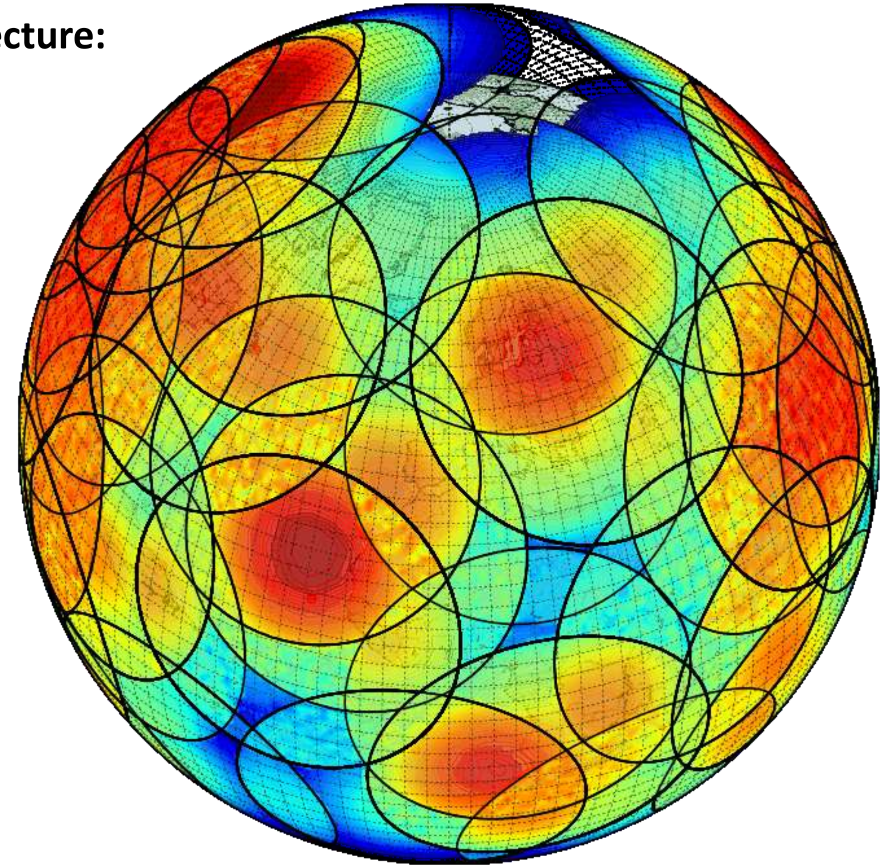
3. Obtain coverage of each ground station and identify regions
4. For each point on each region, compute the CDF of the achievable data-rate
5. Aggregate spatial results in simplified metrics (coverage, data-rate)



Optimization

Optimization formulation

Find the ground segment with the minimum ***number of ground stations*** while maximizing both the ***spatial average data-rate*** and the ***coverage***.

Optimization function:

$$O = \frac{1}{2} cov_{95} \sum_{p \in D} Z_{95}(p) \underbrace{\log_{10}\left(f_{pop(p)}\right)}_{\text{weight factor}} + \frac{1}{2} cov_{99.5} \sum_{p \in D} Z_{99.5}(p) \underbrace{\log_{10}\left(f_{pop(p)}\right)}_{\text{weight factor}}$$

- The optimization problem is well suited for using genetic algorithms.
- We can use a divide and conquer strategy, exploiting the spatial isolation across continents.
- We propose to use a two step genetic algorithm:
  - Step 1) Optimize at a continent level using a genetic algorithms (N_{pop} = 1,000, N_{gen} = 30)
  - Step 2) Optimize globally using good architectures from step 1) as the feed for new global candidate locations (N_{pop} = 500, N_{gen} = 15)

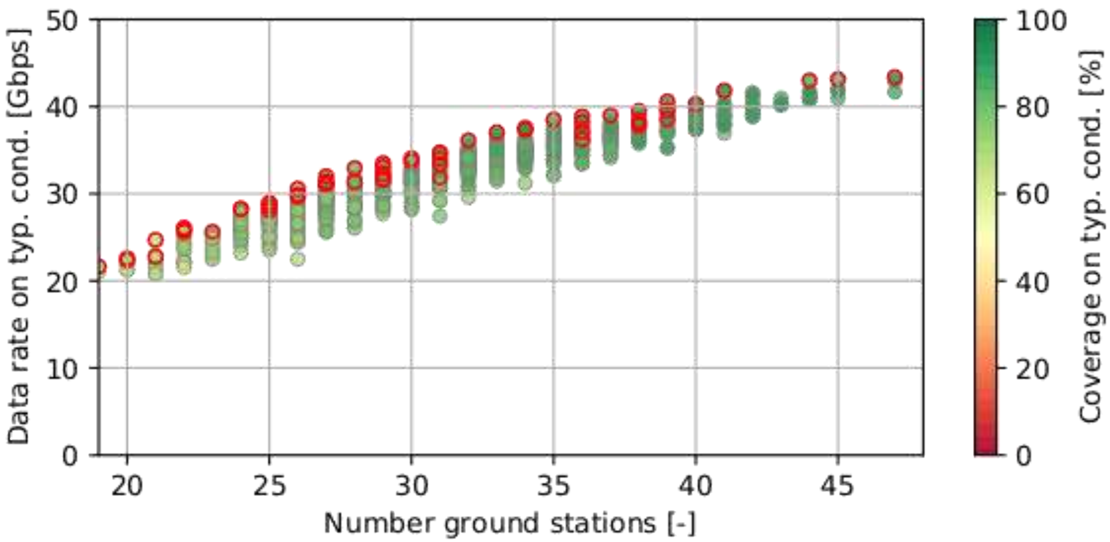
- It takes ~90 seconds to evaluate each architecture, we parallelize execution using a 44-core server. (< 24 hours of computation to generate the tradespace)

Results: Q-band

- For sufficiently large networks, high coverages can be obtained under typical conditions, but not enough coverage under availability threshold conditions.
- Average data-rates up to 45 Gbps per satellite can be obtained for large coverages when deploying large ground segments
- **Most popular locations**: Novosibirk, Svalbard, New Zealand, Fiji, Kumsan and Homer

Metric values for Q-band system

	Availability			
	95%		99.5%	
N	Data rate [Gbps]	Coverage [%]	Data Rate [Gbps]	Coverage [%]
20	22.58	69.13	17.09	35.14
25	28.91	76.06	23.78	49.05
30	34.06	77.69	30.93	57.47
35	38.50	86.93	35.25	67.80
40	40.29	92.11	36.28	70.84
45	43.13	92.19	40.36	74.79

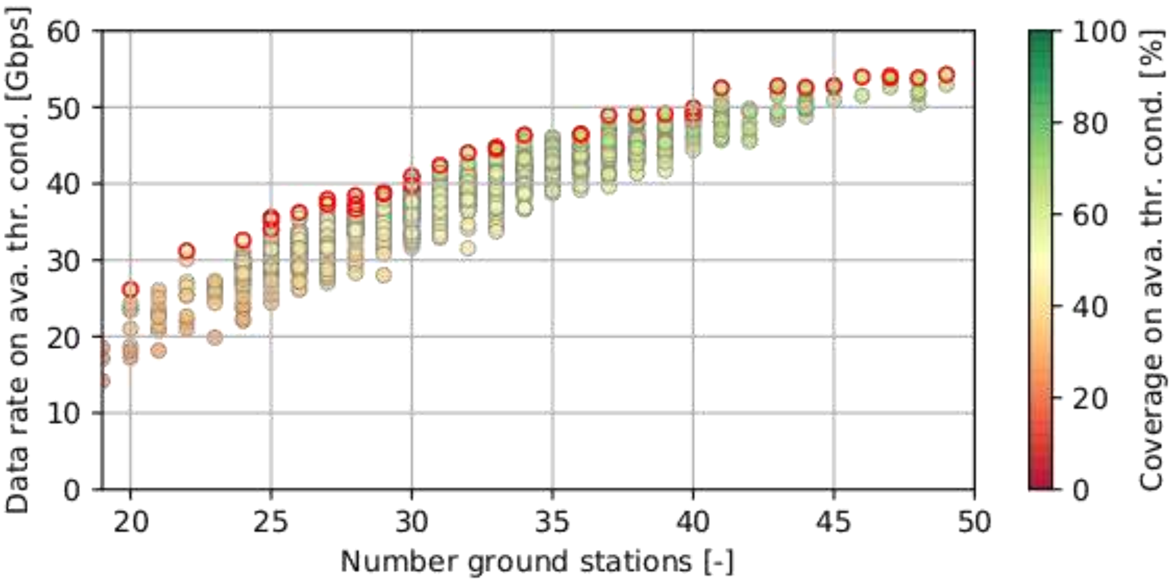


Results: E-band

- High coverages under typical conditions, not enough coverage under availability threshold conditions
- Average data-rates of up 55 Gbps per satellite can be obtained for large coverages, with regions that peak at 82 Gbps.
- **Most popular locations**: Novosibirk, Kumsan, Svalvard, New Zealand, Fiji and Lurin

Metric values for E-band system

	Availability			
	95%		99.5%	
N	Data rate [Gbps]	Coverage [%]	Data Rate [Gbps]	Coverage [%]
20	29.32	59.20	26.16	39.45
25	38.57	68.07	35.25	49.16
30	44.53	75.63	40.81	54.08
35	48.66	84.00	44.81	64.17
40	52.81	84.54	49.89	68.35
45	55.50	87.47	52.83	73.29



Comparison to Ka-band

Metric values for Ka-band system

	Availability			
	95%		99.5%	
N	**Data rate [Gbps]**	**Coverage [%]**	**Data Rate [Gbps]**	**Coverage [%]**
20	17.91	75.00	13.92	62.60
25	21.57	75.68	19.22	68.91
30	24.73	85.48	22.17	77.72
35	26.30	90.53	23.63	83.91
40	28.30	92.37	26.21	86.77
45	29.15	93.91	27.14	88.84

Metric values for Q-band system

	Availability			
	95%		99.5%	
N	**Data rate [Gbps]**	**Coverage [%]**	**Data Rate [Gbps]**	**Coverage [%]**
20	22.58	69.13	17.09	35.14
25	28.91	76.06	23.78	49.05
30	34.06	77.69	30.93	57.47
35	38.50	86.93	35.25	67.80
40	40.29	92.11	36.28	70.84
45	43.13	92.19	40.36	74.79

Metric values for E-band system

	Availability			
	95%		99.5%	
N	**Data rate [Gbps]**	**Coverage [%]**	**Data Rate [Gbps]**	**Coverage [%]**
20	29.32	59.20	26.16	39.45
25	38.57	68.07	35.25	49.16
30	44.53	75.63	40.81	54.08
35	48.66	84.00	44.81	64.17
40	52.81	84.54	49.89	68.35
45	55.50	87.47	52.83	73.29

Data-rate:

- Q/V-band 25-48% higher than comparable Ka-band systems,
- E-band 70 – 90 % higher than Ka-band.

Coverage:

- Even with large ground segments of 45 ground stations, an availability of 99.5% (threshold conditions) cannot be guaranteed in more than 25 % of the region of interest. (vs. only 12 % in Ka-band)

Conclusions and Future Work

- We presented a numerical method to compute the CDF of the achievable data-rate on any orbital position when multiple uncorrelated ground stations are in line-of-sight.
- We conducted optimization to determine the optimal ground segment architectures on Q- and E-band required to support a LEO constellation when no inter-satellite links are present, and we evaluated its performance in terms of data-rate and coverage.
- EHF bands have potential to greatly increase the average data-rates of these constellations (with respect to Ka-band).
    - Up to 50% higher for Q/V-band and 90% higher for E-band
- However, achieving acceptable coverage figures requires a very large of ground stations.

Future work

- Analyze systems with inter-satellite links: optical, RF
- Hybrid gateway links: combination of Ka- and EHF-bands.

THANK YOU

Q&A

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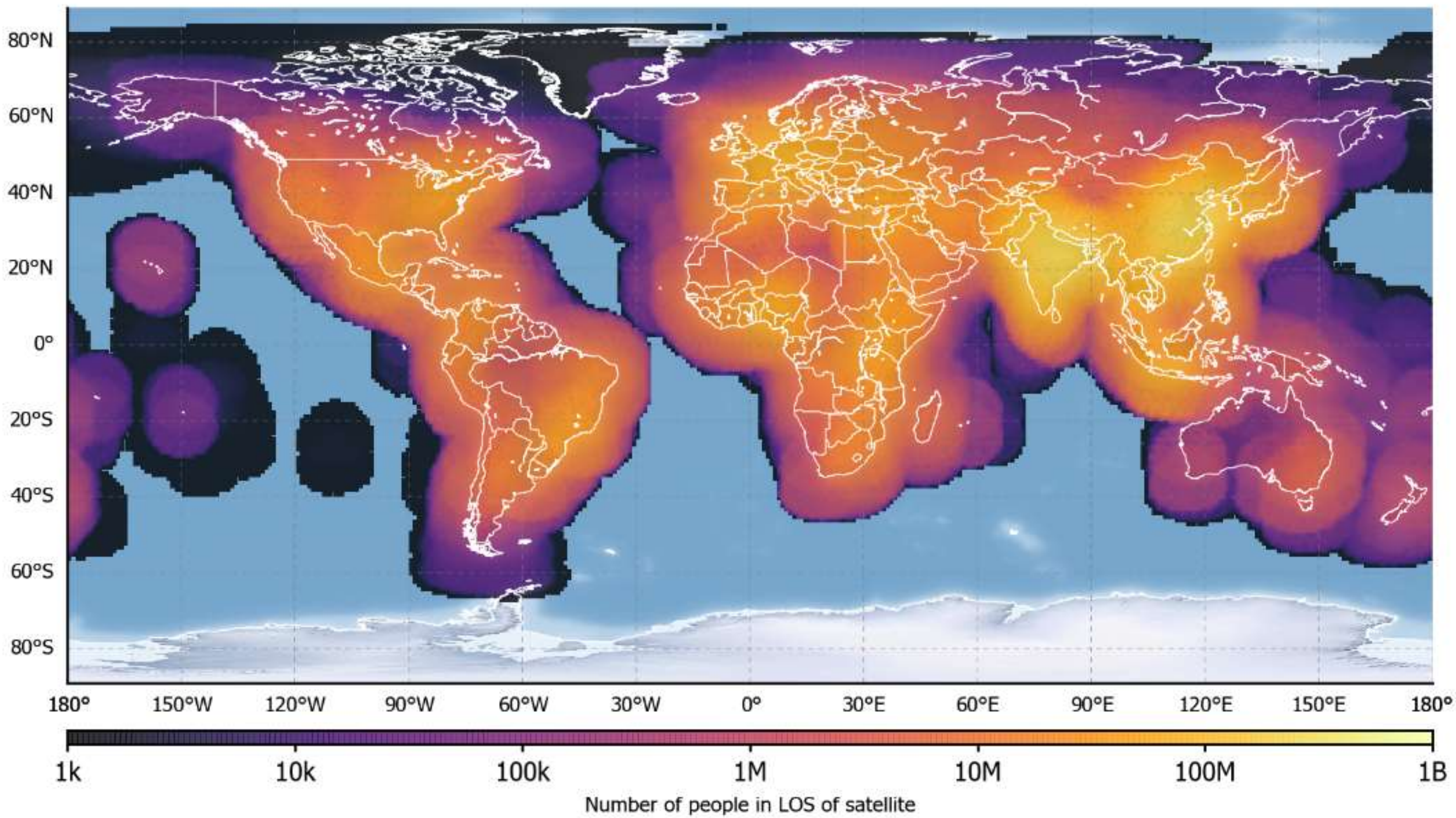
BACK-UP SLIDES

CONSTELLATION PROPOSALS CONSIDERED

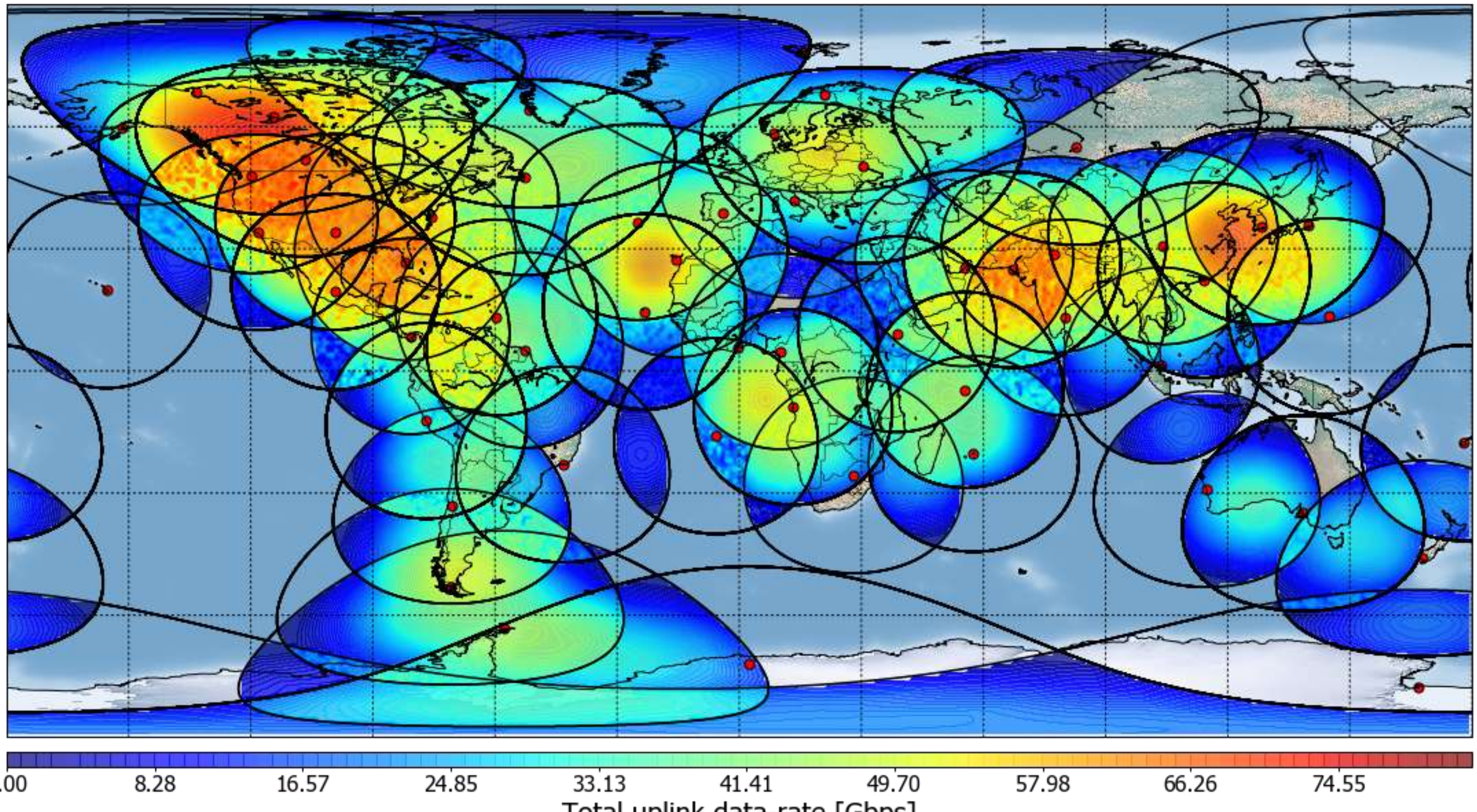
Table 1: Summary of proposed LEO constellations designs.

	OneWeb-Ka	OneWeb-V	Boeing - V	SpaceX-Ka	TeleSat - Ka	Telesat - V
FCC filing #	20160428-00041	20170301-00031	20160622-00058	20161115-00118	20161115-00108	20170301-00023
Filing date	4/28/2016	03/01/2017	6/22/2016	11/15/2016	11/15/2016	3/1/2017
# satellites	720	720 + 1280	2956	4425	117	117
# planes	18	34	74	83	11	11
Orbit type	LEO	LEO-MEO	LEO	LEO	LEO	LEO
Orbital info (#plane x #sat alt @ inc)	18x36 1200@87.9°	18x36 1200@87.9° 16x80 8465@45.5°	35x32 1200@45° 18x46 1210@55° 21x48 1000@88°	32x50 1150@53° 32x50 1110@53.8° 8x50 1130@74° 5x75 1275@81° 6x75 1325@70°	6x12 1100@99.5° 5x9 1248@37.4°	6x12 1100@99.5° 5x9 1248@37.4°
ISL	No	No	No	Yes, optical	Yes, optical	Yes, optical
Service band	Ku	V	V	Ku	Ka	V
BW service links	2 GHz	2 GHz	5 GHz	2 GHz	2.1 GHz	4.5 GHz
Service user-sat	12.75 - 13.25 GHz 14.0 - 14.5 GHz	48.2 - 50.2 GHz	47.2 - 50.2 GHz 50.4 - 52.4 GHz	14.0 - 14.5 GHz	27.5 - 29.1 GHz 29.5 - 30.0 GHz	47.2 - 50.2 GHz 50.4 - 51.4 GHz
Service sat-user	10.7 - 12.7 GHz	40.0 - 42.0 GHz	37.5 - 42.5 GHz	10.7 - 12.7 GHz	17.8 - 18.6 GHz 18.8 - 19.3 GHz 19.7 - 20.2 GHz	37.5 - 42.0 GHz
Min el. angle	55	45	45	40	10	?
Feeder band	Ka	V	V	Ka	Ka	V
BW feeder links	2.1 GHz	5 GHz	5GHz	2.1 GHz	2.1 GHz	4 GHz
Feeder sat-GW	17.8 - 18.6 GHz 18.8 - 19.3 GHz 19.7 - 20.2 GHz	37.5 - 42.5 GHz	37.5 - 42.5 GHz	17.8 - 18.6 GHz 18.8 - 19.3 GHz	17.8 - 18.6 GHz 18.8 - 19.3 GHz 19.7 - 20.2 GHz	37.5 - 42.0 GHz
Feeder GW-sat	27.5 - 29.1 GHz 29.5 - 30.0 GHz	42.5 - 43.5 GHz 47.2 - 50.2 GHz 50.4 - 51.4 GHz	47.2 - 50.2 GHz 50.4 - 52.4 GHz	27.5 - 29.1 GHz 29.5 - 30.0 GHz	27.5 - 29.1 GHz 29.5 - 30.0 GHz	47.2 - 50.2 GHz 50.4 - 51.4 GHz
# sim. gateways	1 (2 antennas)	1 (2 antennas)	?	1	2	2
D. GW antenna	2.4 m	1.2 - 3.4 m	?	1 - 3.5 m	3.5	1.8

DEMAND MAP


80°N
60°N
40°N
20°N
0°
20°S
40°S
60°S
80°S
180°
150°W
120°W
90°W
60°W
30°W
0°
30°E
60°E
90°E
120°E
150°E
180°
1k
10k
100k
1M
10M
100M
1B
Number of people in LOS of satellite

Data-rate @ 99.5 % for a 55 ground station ground segment using E-band feeder links



Coverage @ 99.5 % for a 55 ground station ground segment using E-band feeder links