The new frontier of EHF for Broadcast and Multimedia Satellite Services

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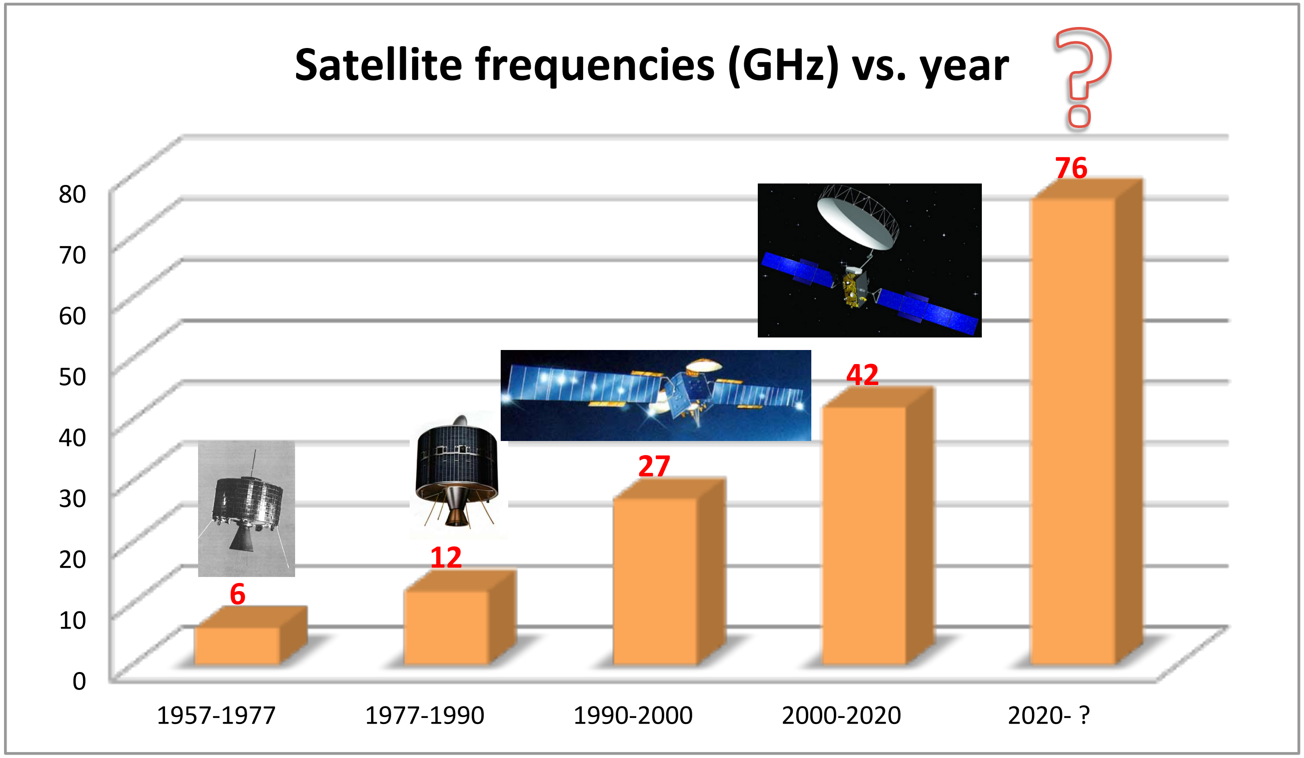
Outline

- *Introduction to EHF for satellite communications;*
- *Capacity formulation for single-beam and multi-beam satellites;*
- *EHF tropospheric propagation issues;*
- *Link budget parameterization and capacity curves;*
- *Capacity-limiting factor of EHF satellite links;*
- *EHF for broadcast and multimedia satellite services: some cases of study;*
- *Conclusion.*

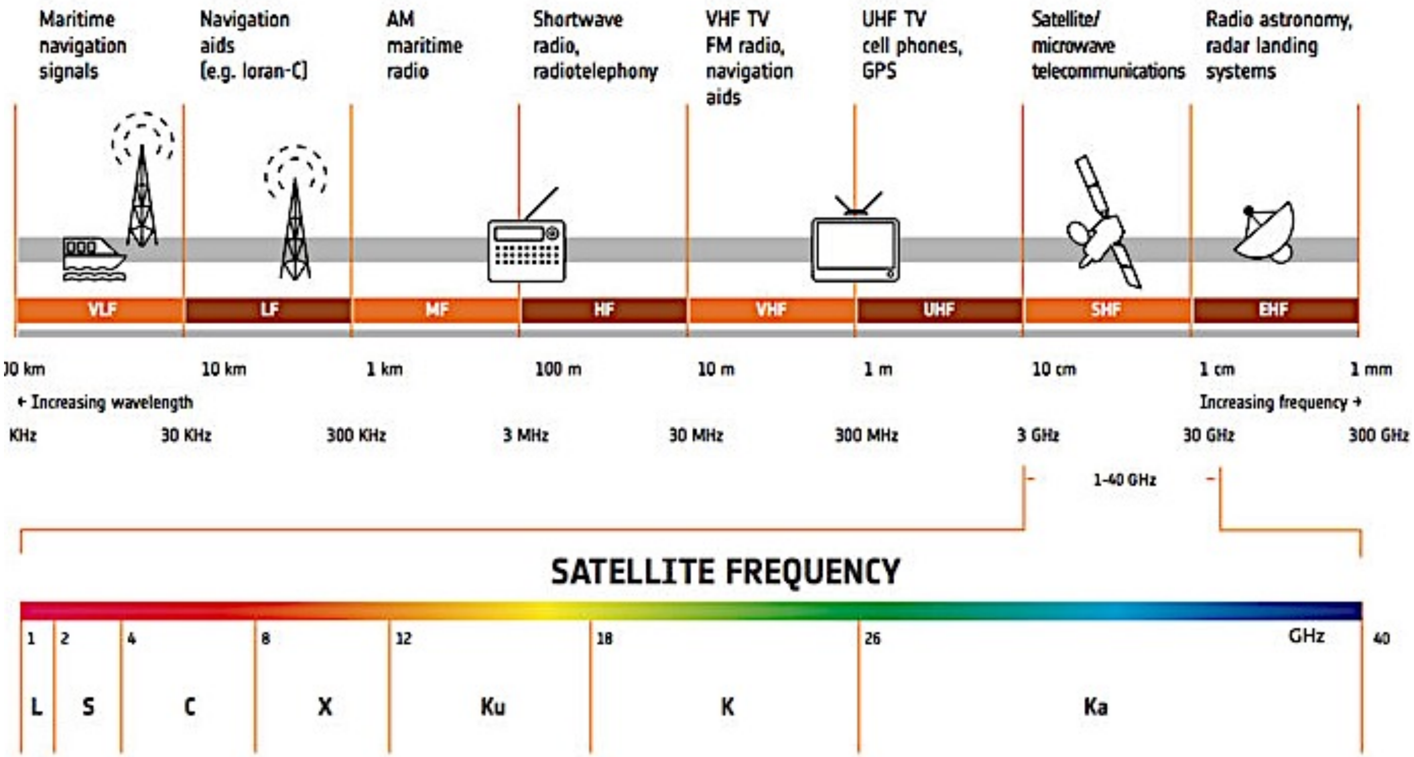
Shift to higher and higher frequencies for satellite communications (historical and technical)

- The plot bar allows to visualize at a glance the historical evolution of the spectrum usage in satellite communications:



Why?

- Higher frequencies mean <u>larger bandwidth portions available for superior capacity and new services</u> (see figure below, source: ESA):

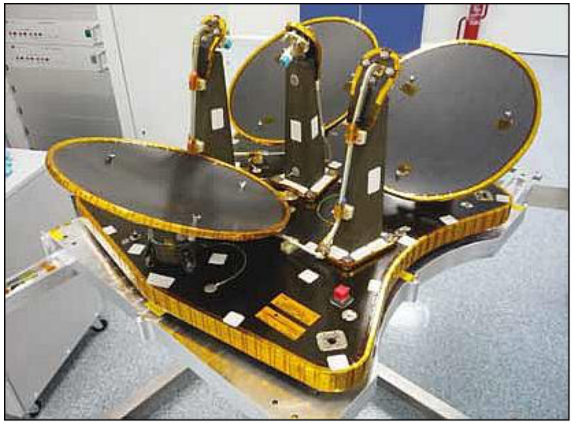


EHF allocation for satellite communications

- Beyond *Ka* band, some bandwidth portions in the domain of the **Extremely-High Frequencies (EHF)**, known also as mm-wave bands, have been allocated for satellite communications:

	Uplink	Downlink
Q/V-band	42.5-43.5 GHz 47.2-50.2 GHz 50.4-51.4 GHz	37.5-42.5 GHz
W-band	81-86 GHz	71-76 GHz

- A payload launched in the framework of ESA ALPHASAT mission is testing the Q/V band propagation (*"Aldo Paraboni payload"*, in memory of Prof. Aldo Paraboni, passed away in 2013, the pioneer of the use of mm-waves for satcoms) [4-5].



Introduction to EHF for satellite communications

Potential achievements

- Availability of very large and almost unused bandwidth spaces;
- High directivity and spatial resolution;
- Low transmission power (due to high antenna gain);
- Low probability of interference/ interception (due to narrow antenna beam-widths);
- Small antenna and equipment size;
- Reduced size of satellite and launch vehicles;
- Aggressive frequency reuse enabled in principle to multi-beam satellites (narrow antenna beam-widths)

Open issues

- Tropospheric propagation uncertainties;
- Accurate waveform design able at coping with the "dirty" RF environment typical of mm-wave domain [1-29];
- Tremendous bandwidth-delay product characterizing EHF geostationary links.

Capacity formulation for single/multi-beam satellites

Starting point: Shannon's formulations

- Power-limited capacity (geostationary satellite):

$$R = \left(\frac{C_{RX}}{N_0}\right)\frac{\beta}{2^{\beta}-1} \quad [b/s]$$

- *Beta*=spectral efficiency (b/s/Hz) $\beta \triangleq \frac{\rho \log_2(M)}{(1+\alpha)}$
- C_{RX}=received carrier power
- N_0=AWGN PSD

$$\left(\frac{C_{RX}}{N_0}\right) = \frac{C_{TX} g_{sat} D_{es}^2 \eta_a}{L_A T_{sys} \gamma}$$

- C_{TX}=transmitted carrier power
- G_{sat}=satellite antenna gain
- D_{es}=Earth-station antenna diameter
- Eta=antenna efficiency
- L_A=troposheric attenuation
- T_{sys}=system noise temperature
- Gamma=3.6377x10^{-7} [J·m^2/°K]

THE CROSSING POINT BETWEEN THE TWO CURVES PROVIDES THE TOPIC LINK CAPACITY [14]

- Bandwidth-limited capacity (single and multi-beam):

$$R = \beta W \; [b/s] \qquad W_{\text{single-beam}} = B \qquad W_{\text{multi-beam}} = N_{spot}\left(\frac{B}{K}\right)$$

Satellite antenna gain and earth-station antenna efficiency

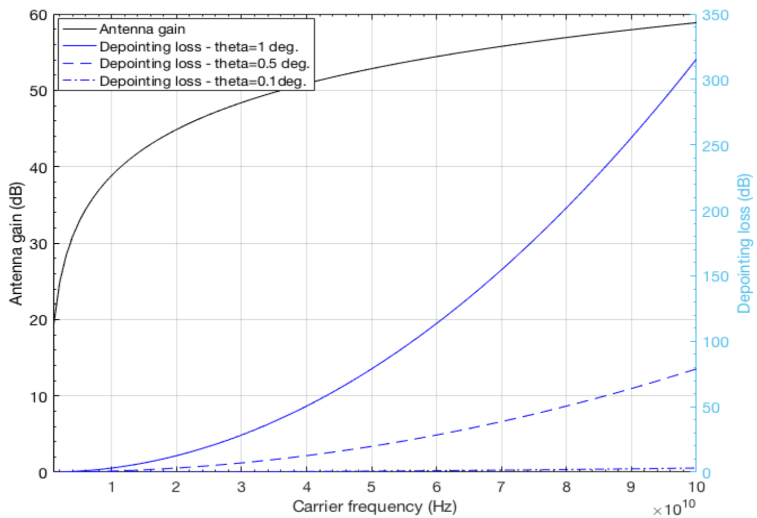
- The satellite antenna gain can be computed as follows [1]:

$$g_{sat} = 9.94 + 10\log_{10}\eta_{sat} + 20\log_{10}\left(D_{sat}\cdot f_c/c\right)(dB)$$

- The earth-station antenna efficiency is given by:

$$\eta_a = \eta_{es}/L_{pe} \qquad L_{pe} \approx 12\left(\frac{\theta\cdot D_{es}\cdot f_c}{65c}\right)^2 (dB)$$

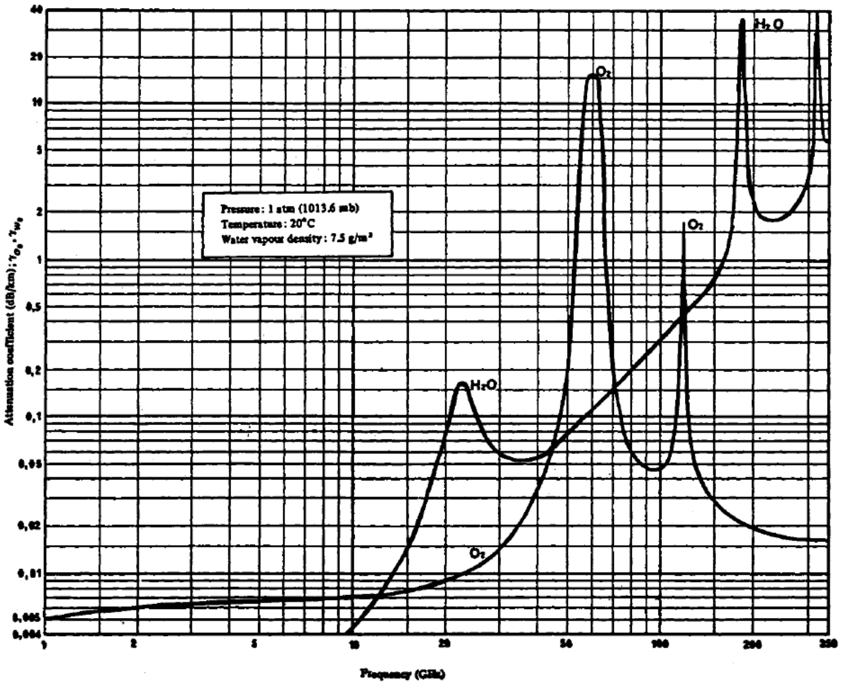
NOTICE THAT THE POINTING ACCURACY IS A CRITICAL ISSUE IN EHF SATELLITE TRASMISSION: the pointing error theta should be limited to 0.1° (for W-band, a margin of 3dB should be anyway considered in the link budget!)



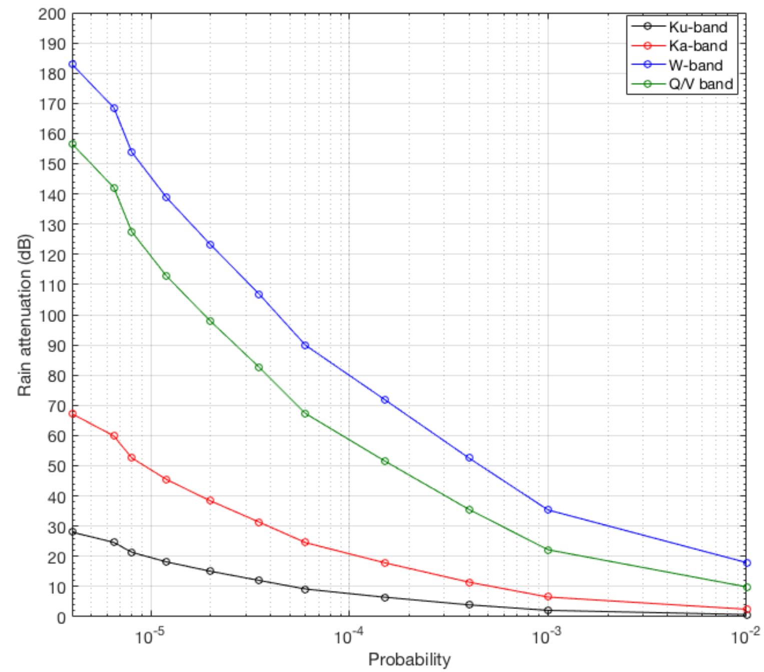
Namely: the term L_A of the link budget equation

- The most significant atmospheric attenuations for EHF satellite links are due to **Oxygen**, **water vapor** and **rain**:

$$L_A = L_{O_2} L_{H_2O} L_{RAIN}$$



O_2 and H_2O absorption curves [15]: both Q/V and W band frequencies are far from dangerous peaks



Estimated rain attenuation (ITU model): rain attenuation is severe in the EHF bandwidth

Link budget parameters

- Numerical values, mostly taken by [1] and [14]:

	Ku-band	Ka-band	Q/V band	W- band
B	1.5 GHz	3.5 GHz	5 GHz	5 GHz
K	4[14]	4[14]	4	4
C_{TX} (dBW) single beam	29[14]	29	29	29
C_{TX} (dBW) multi-beam	39.7	38.97	40	40
N_{spot}	12[14]	100[14]	140[14]	140
D_{es}	0.6 m. [14]	1.2 m. [14]	1 m.	1 m.
η_{es}	0.7	0.7	0.7	0.7
η_{sat}	0.7	0.7	0.7	0.7
θ	0.1°	0.1°	0.1°[1]	0.1°[1]
O_2 absorption (dB/Km)	0.008	0.009	0.065	0.15
H_2O absorption (dB/Km)	0.007	0.08	0.057	0.1

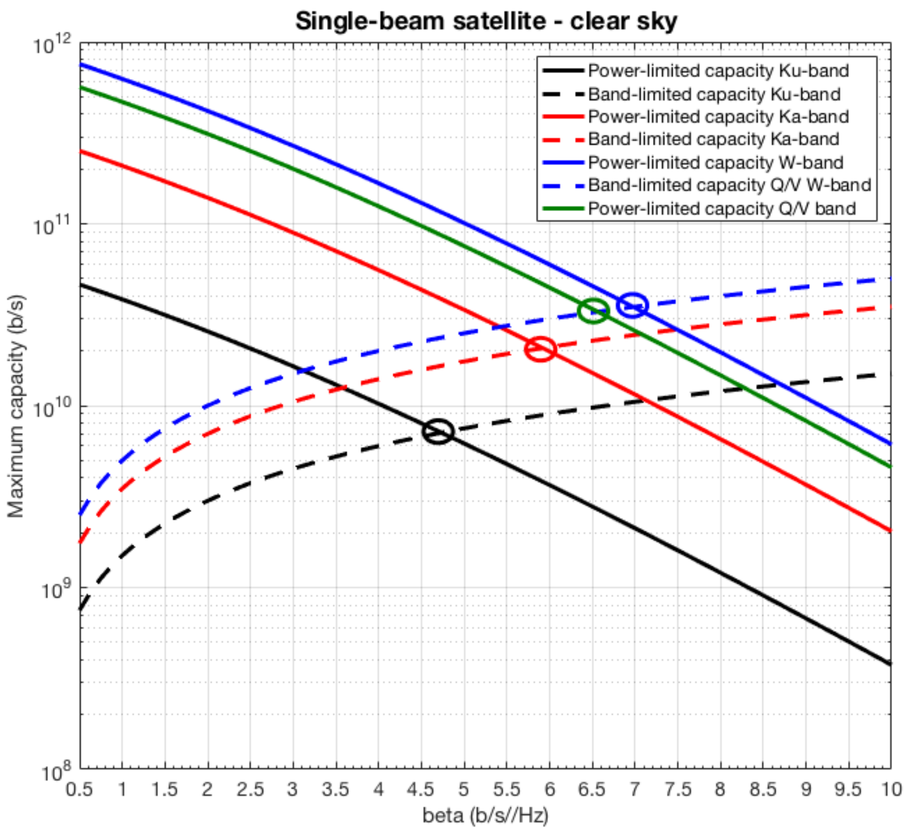
Estimated rain attenuation for 99% link availability:

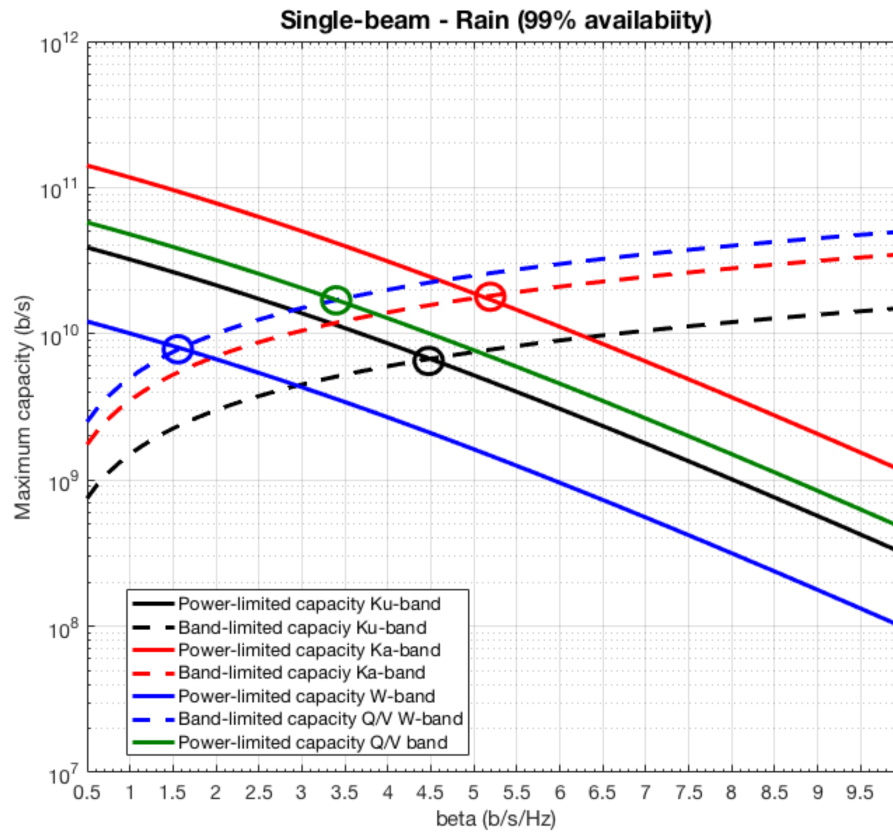
- 9.9 dB *(Q/V band)*
- 17.94 dB *(W band)*

Both values taken by the curves of slide 8

Capacity curves: single beam satellites

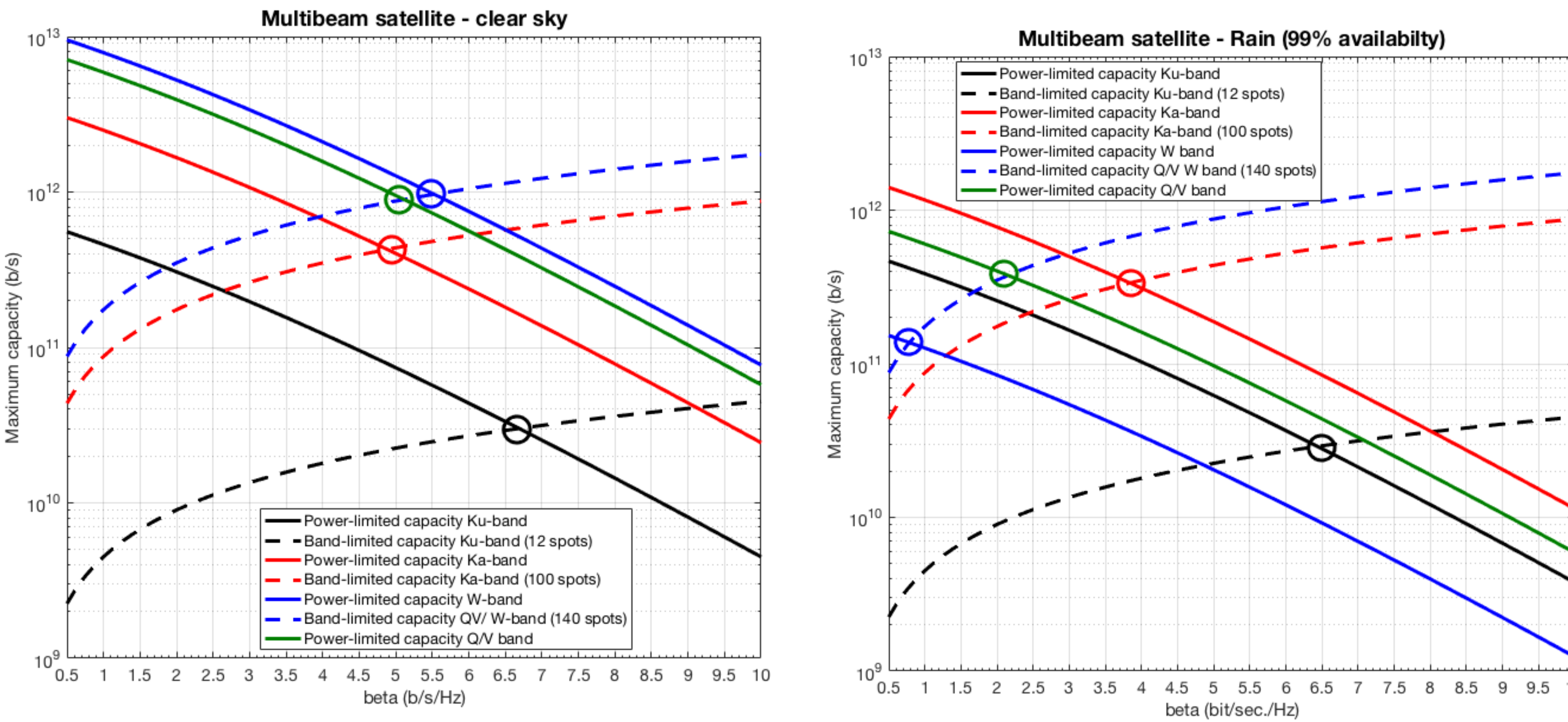
- Q/V and W-band provide the highest capacity in clear-sky conditions. In case of rain, W-band is seriously impaired and performs poorer than Ka-band.





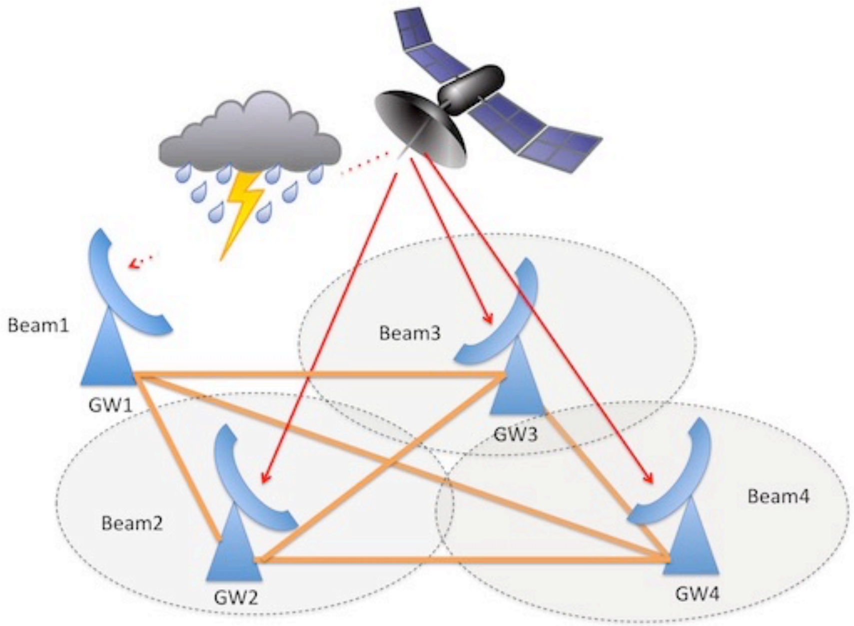
Capacity curves: multi beam satellites

- Under clear-sky conditions, W band breaks the wall of 1 Tb/s capacity. In case of rain, Q/V slightly outperforms Ka band.



Rain attenuation countermeasures

- Rain attenuation severely limits link availability of EHF satellite transmission;
- Adaptive Coding and Modulation (ACM) is an arrangement conceived by DVB-S2 that can be considered also for EHFs, provided that the thresholds for the different ACM modalities are reformulated [20-21];
- Another interesting (and challenging) solution relies on the use of site diversity and smart gateways [22-23]:



The re-routing of information flows to the tampered gateway through terrestrial optical links is a critical task due to delays and latencies. However, the potential increment of link availability would really be beneficial [22].

Capacity-limiting factors of EHF satellite links

Interference in multi-beam satellites

- Beams are not ideally insulated. Therefore multi-beam interference arises and introduces a correction in the computation of Shannon's capacity:

$$R = \left(\frac{C_{RX}}{N_0}\right)\frac{\beta}{2^{\beta}-1} - \beta\left(\frac{I}{N_0}\right)$$

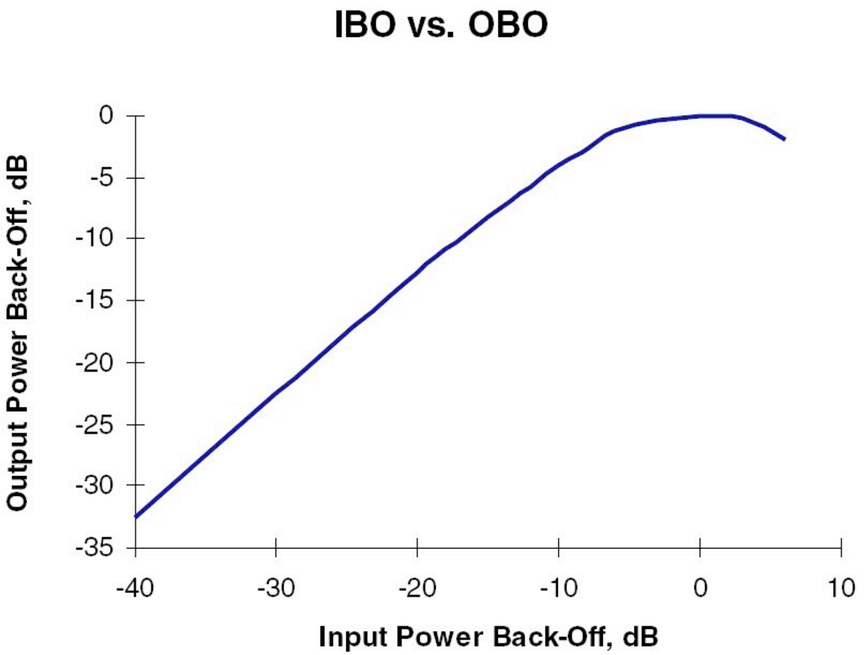
- EHF seems to present some evident advantages in reduction of *I*, with respect to the lower frequency bands, due to the narrow beam-width, allowing aggressive frequency reuse;

- Results shown in [25] about the multi-beam detection fully confirm this claim (see section II.E of the paper).

"Dirty" RF environment: nonlinear distortions

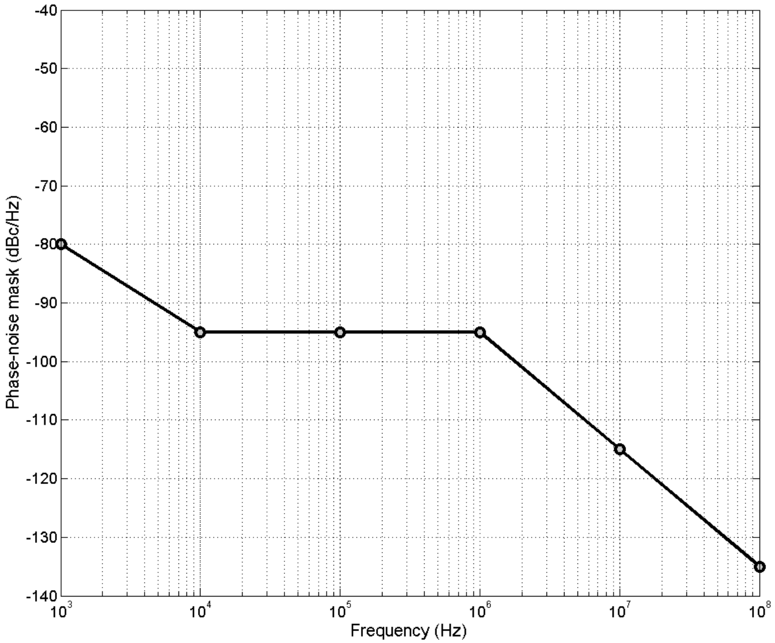
- The RF section of EHF satellite links is "dirty", because it introduces distortions and phase noise;
- Nonlinear HPA distortions are common to satellite links at lower frequencies, but their impact on power-constrained link budget may be heavy:

10-12 dB of OBO needed to resort to linear amplification will severely limit link capacity. Suitable waveform solutions should be considered to limit saturation effects (PSWF, CE multicarrier modulations [29-31], etc.)

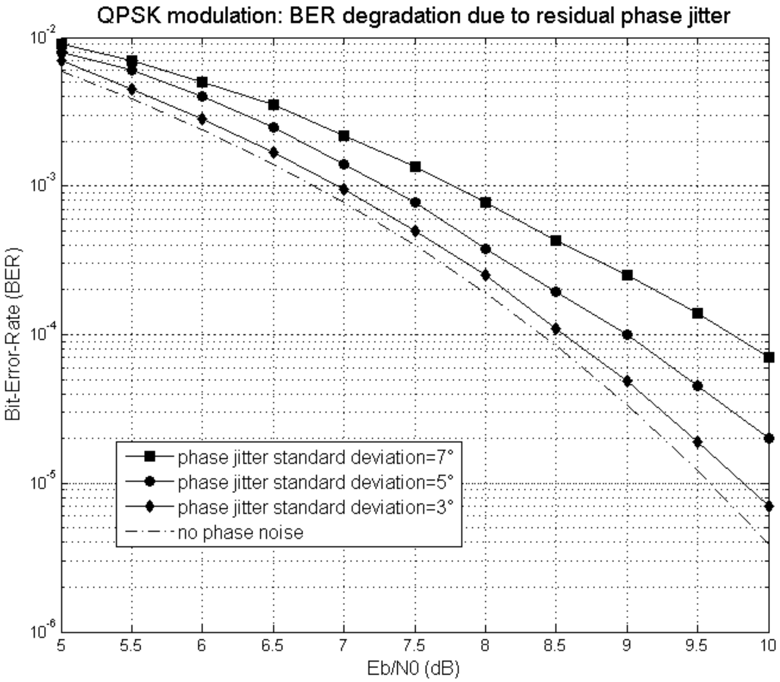


"Dirty" RF environment: phase noise

- Phase noise is a significant impairment in EHF satellite links;
- The cost of a low-noise high-frequency oscillator may be too high for commercial applications;
- Resulting phase jitters affecting coherent demodulation systems may involve performance losses of many dBs [1]:



Phase noise mask of a 91 GHz oscillator [1]



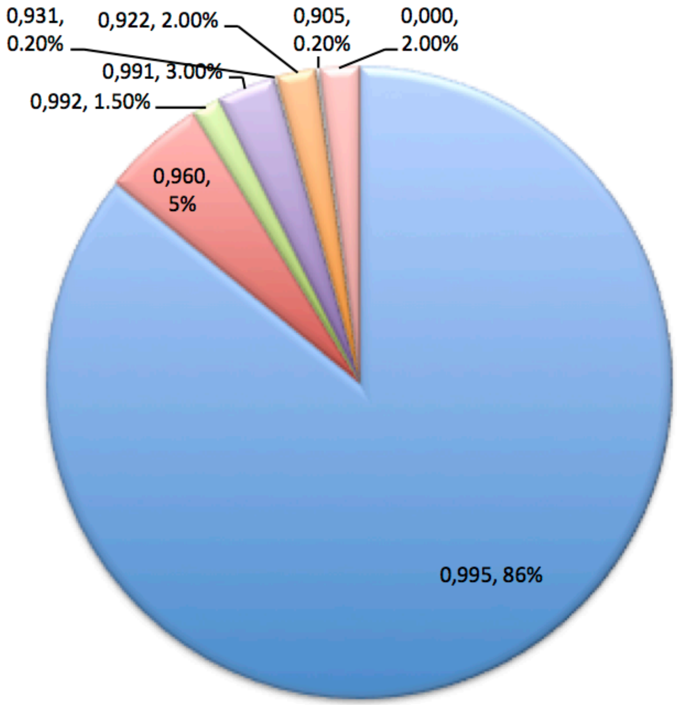
Effect of phase noise on QPSK [1]

Case of study #1: HDTV satellite broadcasting (1)

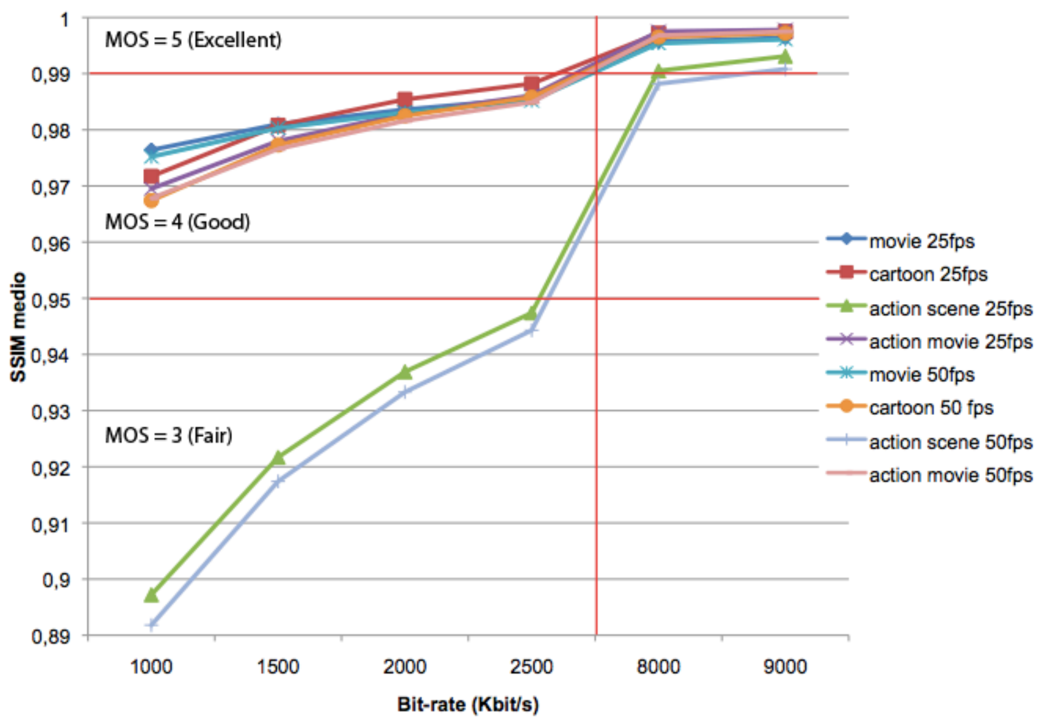
- DVB-S2 standard offers two alternative solutions to increment the link availability in case of rain event:
  - Variable Coding and Modulation (VCM), where the videos at different rate share in time the same physical frame;
  - Adaptive Coding and Modulation (ACM), where the best-quality video is transmitted on the basis of specific channel feedback;
- In[39], it is demonstrated that ACM provides advantages for very small beam sizes and against annual propagation variations: this is just the case of EHF satellite broadcasting;
- Results shown in [10], where end-to-end HDTV satellite broadcasting in W-band has been simulated, including in the simulations all RF impairments analyzed before, fully support the ACM solution.

Case of study #1: HDTV satellite broadcasting (2)

- Results of [10] are given in terms of SSIM quality indicator (a measure of Quality-of-Experience strictly correlated with MOS):



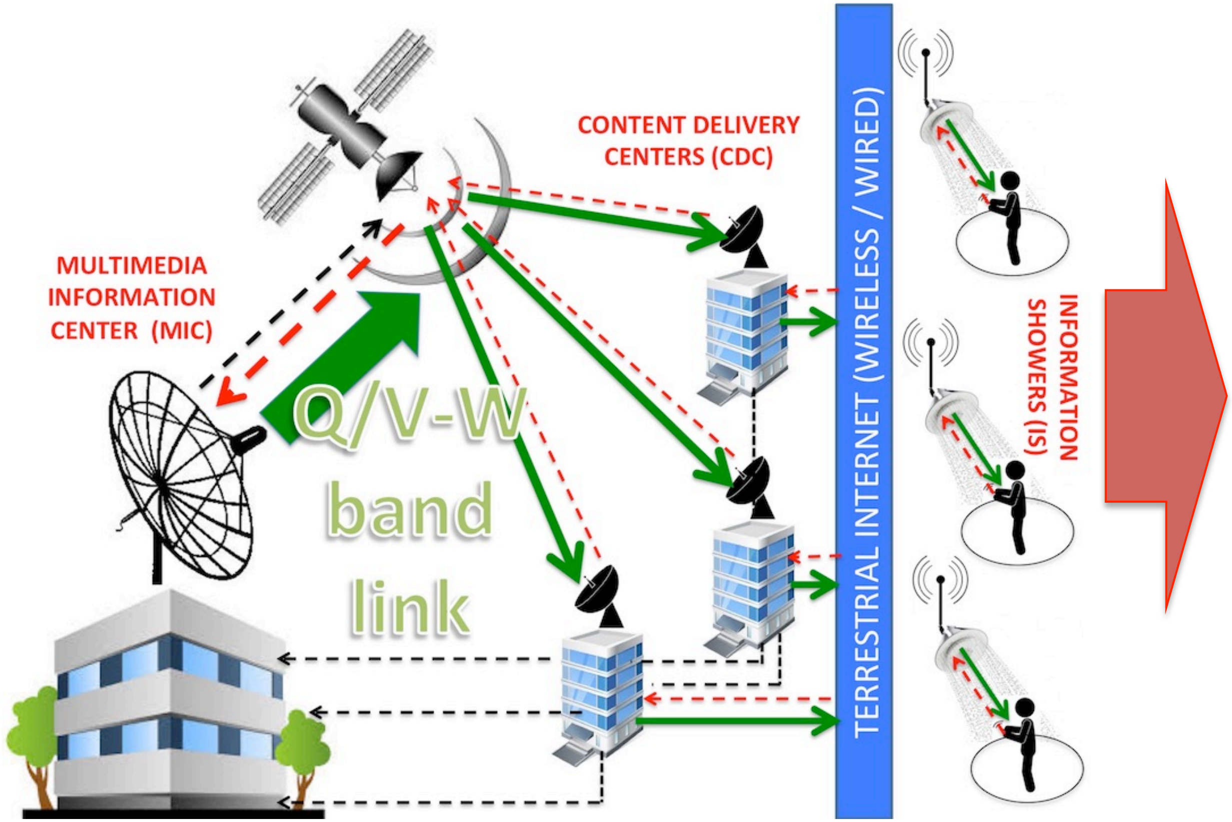
SSIM achieved by ACM during a simulated rain event (HDTV transmission of an action movie) [10]



SSIM (and MOS) vs. rate for different typologies of broadcasted videos

Case of study #2: multimedia content delivery

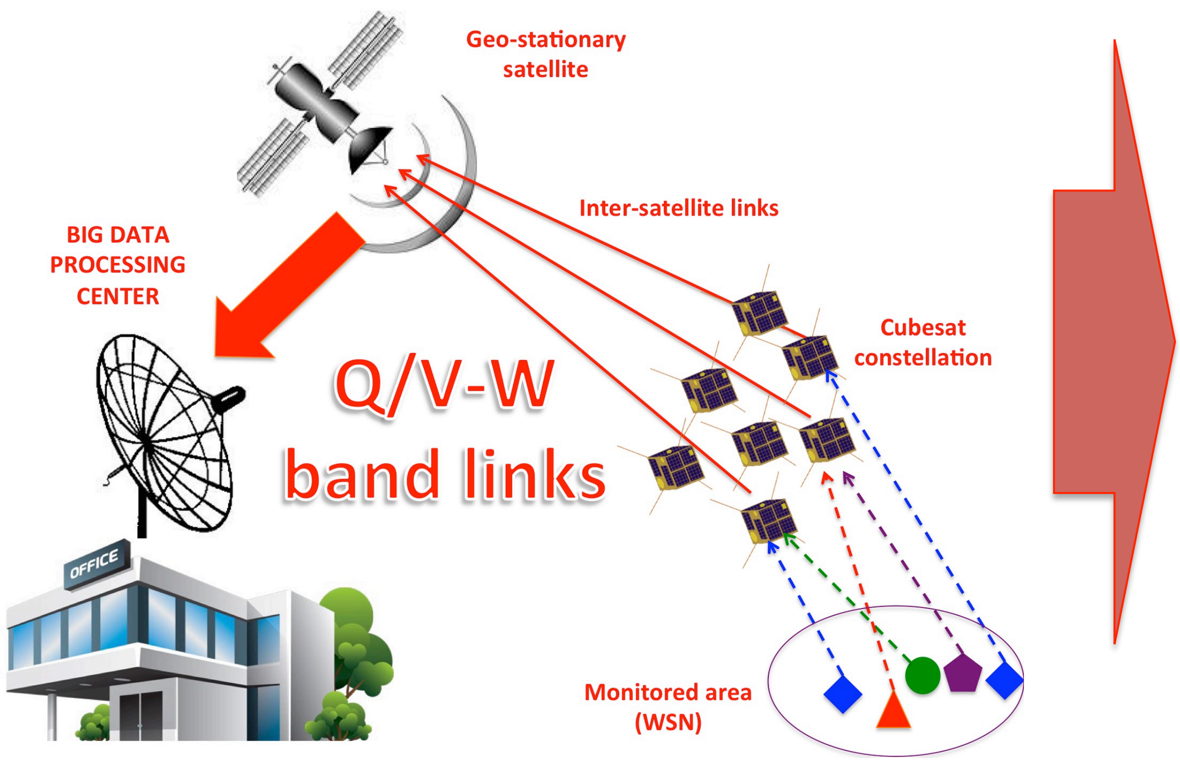
- Satellite links are very beneficial for multimedia content delivery applications, <u>because they can effectively complement 4G terrestrial network segments</u> [11];
- In the figure below, a possible EHF satellite-based architecture for multimedia content delivery in a 5G framework is shown:



The "information shower" is a multi-gigabit/s hotspot, whose max. coverage range is 5-10 meters. It will be supported by mm-wave transmission (71-76 GHz) (but, some references [43] also consider 200 GHz frequency range at distances of 1 m.)

Case of study #3: Internet of Remote Things (IoRT)

- The remote monitoring of vast areas using smart sensors may take great advantages from the use of satellites, in particular when terrestrial links become unavailable in case of natural disasters or attacks [46];
- A broadband IoRT architecture integrating small cubesats and EHF geostationary satellites is proposed in the figure below:



The link between monitored area and the cubesat swarm transmits in the low frequency range (e.g. S-band). ISL multi-beam link can be implemented in the EHF domain in order to allow broadband multiplexing of information and reduced beam interference.

IP-based services: the potential "deadly bottleneck"

- 99% of commercial data services are nowadays supported by the TCP/IP protocol (Internet-based);
- The very large bandwidth availability assured by EHF may be useless due the bandwidth-delay product: the potential deadly bottleneck of EHF satellite connections;
- Indeed, the congestion window should be sized on the basis of the unacknowledged "in-flight" received data. In a 100 Gb/s connection, the window size would be 6.75 Gigabytes;
- Some solutions have been considered in the "TCP for satellite" standardization in order to reduce the impact of RTT on QoS (e.g. TCP spoofing with Performance Enhancing Proxies [50]);
- If multi-gigabit satellite links will be really implemented, such kind of mechanisms inspired by DTN, should be revised and enhanced.

Conclusion

- Opportunities and challenges inherent to the utilization of Extremely Higher Frequency (EHF) bands for broadcast and multimedia satellite services have been explored;
- The "raw" capacity analysis evidenced the full potential of Q/V and W band for multi-gigabit (and even terabit) multi-beam satellite connections;
- However, adequate countermeasures against rain fading should be considered in order to avoid unexpected capacity pitfalls;
- Accurate waveform design is required in order to exploit the available power/bandwidth resources without undue waste;
- The most promising applications where EHF satellite connection can offer a valuable support seem: HDTV broadcasting, multimedia content delivery, and IoRT;
- Favorable convergence with 5G terrestrial systems is expected.

Acknowledgements

- To Prof. Marina Ruggieri of University of Rome "Tor Vergata" (Italy) and her research group for almost 20 years of interesting and fruitful research cooperation in EHF satellite communications;

- In memory of Prof. Aldo Paraboni, a great scientist and a wonderful person;

- And THANK YOU for your attention and patience …

QUESTIONS ?