Multibeam satellite systems with frequency reuse

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2020-2021

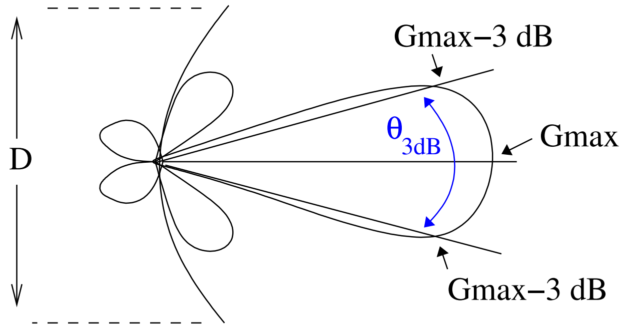
Plan

Plan

Coverage and Antenna Gain

Reminder

Antenna pattern:



For a circular antenna with diameter D and efficiency η:

$$G_{max} = \eta \left(\frac{\pi D f}{c} \right)^2$$

$$\theta_{3dB} = 70 \left(\frac{c}{f.D} \right)$$

where f refers to the carrier frequency, c to the speed of light, and $\lambda = c/f$ to the wavelength

Coverage and Antenna Gain

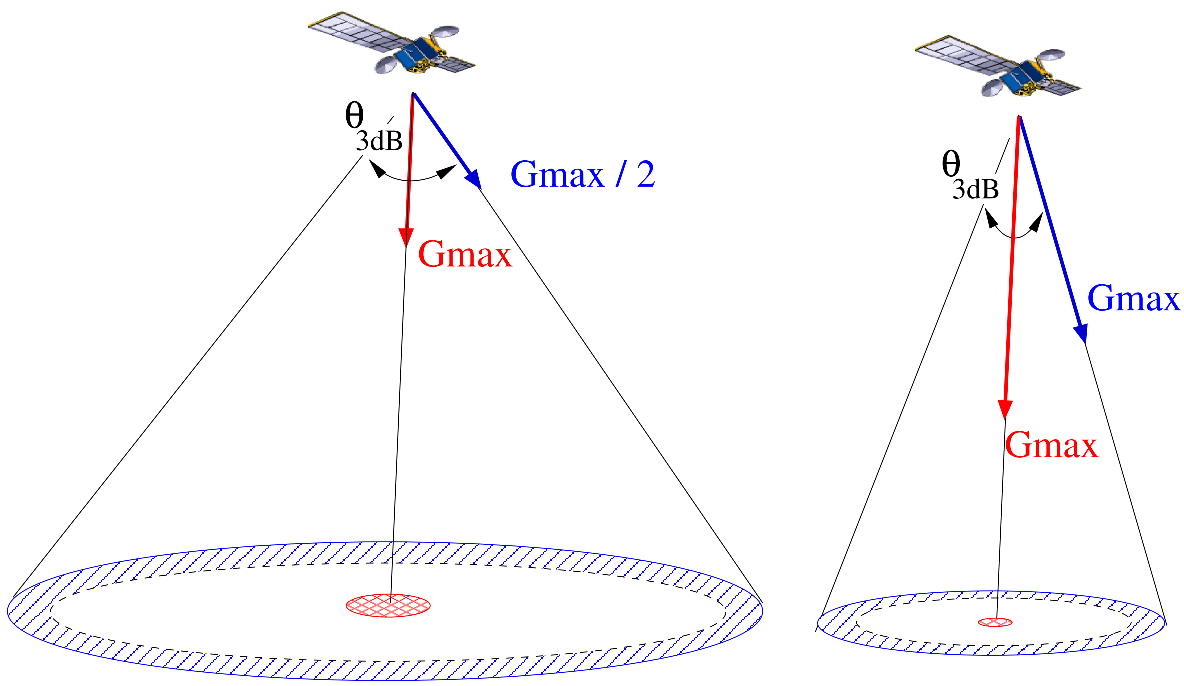
Reminder

- The satellite antenna gain characterizes the beam directivity
- The 3 dB aperture angle characterizes the coverage area where the antenna gain exceeds $G_{max}/2$
- The satellite transmit EIRP and receive G/T parameters are proportional to the antenna gain in the pointed direction
- The relationship between the antenna maximum gain (at boresight) and the 3 dB aperture angle is fixed and independent of the frequency:

$$\boxed{G_{max} = \eta \left(\frac{70\pi}{\theta_{3dB}}\right)^2}$$

☞if $\eta = 0.6,\ G_{max} = \frac{29000}{(\theta_{3dB})^2}$

Coverage and Antenna Gain



Coverage and Antenna Gain

Global satellite coverage

- A straightforward solution to provide a wide satellite coverage is to define a single beam, designed so as to fit the service area
- In such case, the satellite antenna gain is directly related to the beam width
- For a geostationary satellite, a global coverage addressing the whole field of view implies a beam width $\theta_{3dB} = 17.5^\circ$
  ☞Considering an average antenna efficiency $\eta = 0.6$, the satellite antenna gain will not exceed
  $G_{max}(dBi) = 10\log_{10}(29000) - 20\log_{10}(17.5) = 20\ dBi$

Coverage and Antenna Gain

Narrow beam coverage

- A narrow beam coverage is suited to provide a service over a concentrated area
- 3 dB aperture angle for a narrow beam: between 0.5° and some degrees
- The antenna gain in the beam is all the higher as the beam size decreases
- Users located outside the satellite beam (though in the satellite field of view) are not addressed

Coverage and Antenna Gain

Conclusion

The design of a single beam satellite implies a trade off:

- Large coverage and limited antenna gain ?
- Narrower coverage with improved antenna gain ?

☞Multibeam satellite system

Considering a satellite coverage with several narrow beams, allows to simultaneously expect:

- a high antenna gain
- a wide service area

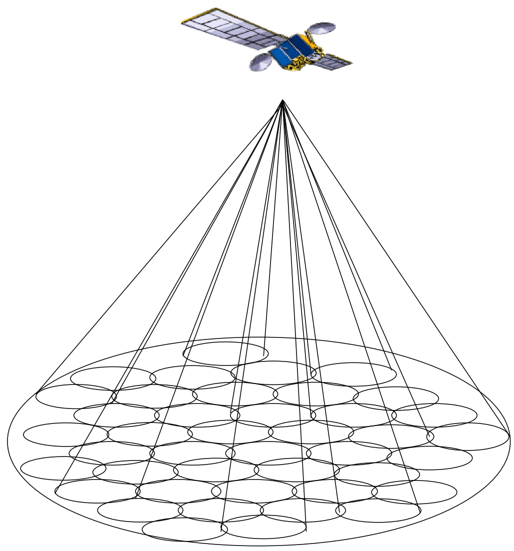
Coverage and Antenna Gain

Multibeam satellite system

- A large coverage is provided through several narrow beams
- The average satellite antenna gain in a given coverage increases as the size of the beams decreases
- High frequency bands (Ku, Ka band) are the most suited to provide narrow beams
- The number of beams to be provided by a satellite may be limited by payload complexity and mass issues:
  - Multibeam antenna manufacturing → new technologies (feeds and reflectors)
  - Beam Interconnection → accommodation contrained connectivity aboard the satellite

Coverage and Antenna Gain

Multibeam satellite system

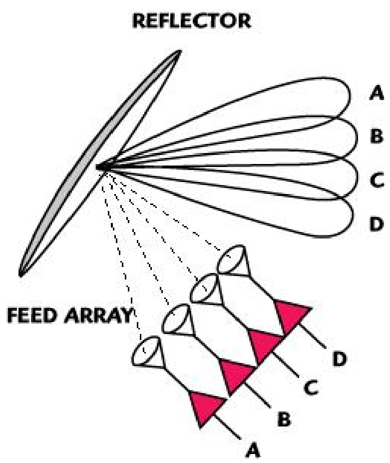


Example: *As long as the interference remains low*, a multibeam solution with 100 beams of width $\theta_{3dB} = 1.7^\circ$ will show a 20 dB up- and down-link budget improvement w.r.t a global coverage solution with a single beam and $\theta_{3dB} = 17.5^\circ$

- ▶ relaxed ground station specifications *or*
- ▶ Higher system throughput (provided that sufficient power and frequency resources are available)

Multibeam Antennas

Reflector antennas



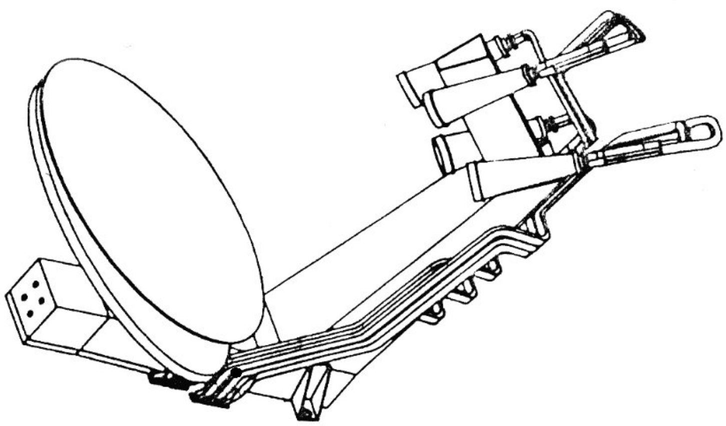
- Multiple beams are generated thanks to multiple antenna sources (or feeds).
  ☞Solution 1: single feed per beam
  ☞Solution 2: multiple feeds per beam

Multibeam Antennas

Reflector antennas

Solution 1: single feed per beam

- The feed horn location w.r.t the reflector focal point determines the beam direction
- Example below with double reflector (one per polarization)



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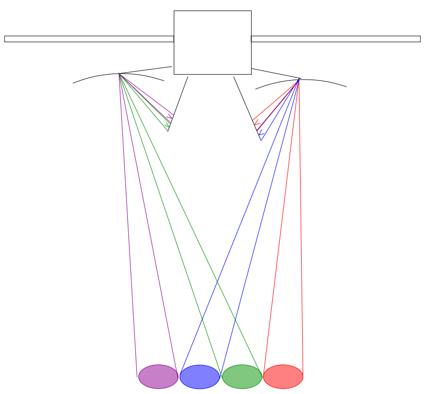
Multibeam Antennas

Reflector antennas

Solution 1: single feed per beam

- Due to the feed horn accommodation constraints in the reflector focal plane, several antennas are required to provide a continuous coverage with single feed per beam technology.
- 2 antennas (including reflector and feeds) per beam line
- 4 antennas (including reflector and feeds) for a continous area
- The beams typically intersect at $G_{max} - 4dB$

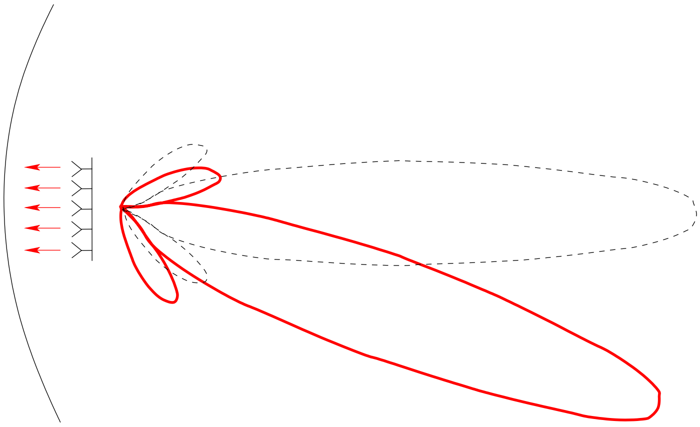


Multibeam Antennas

Reflector antennas

Solution 2: multiple feeds per beam

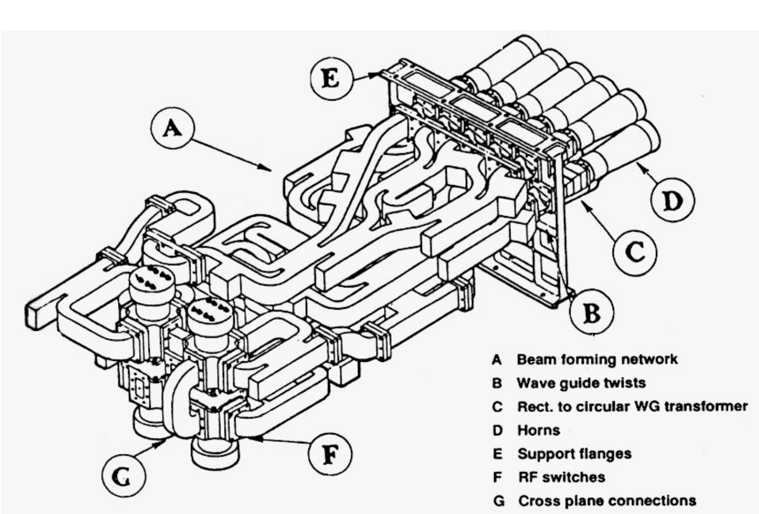
- The same signal is fed into several antenna sources
- Beams are formed by controlling the relative source phases and amplitudes



Multibeam Antennas

Reflector antennas

Solution 2: multiple feeds per beam



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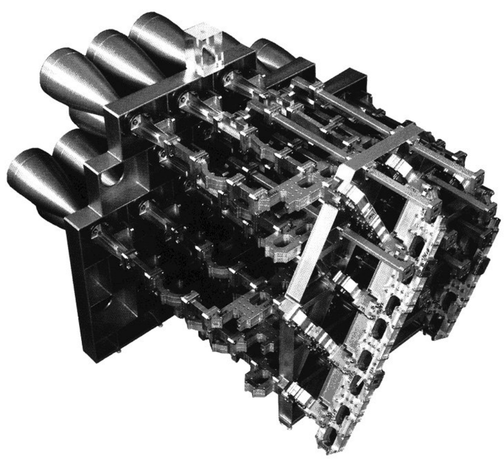
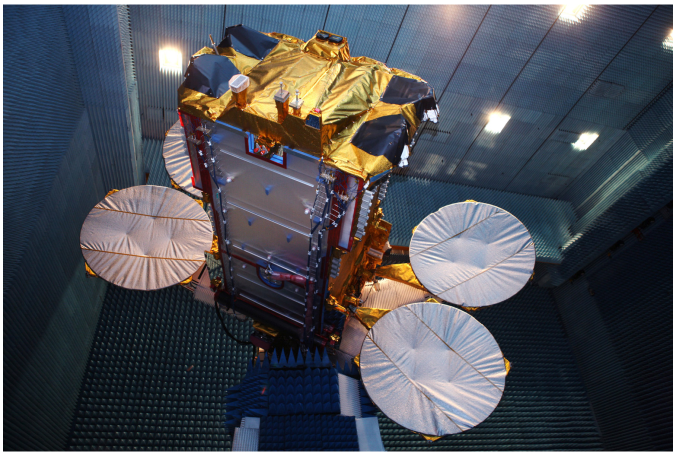
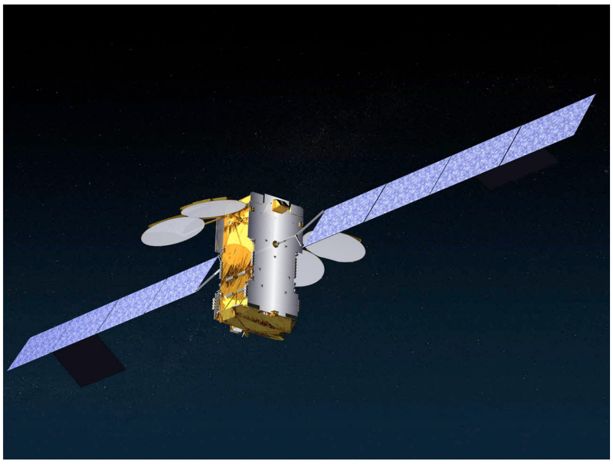


Ka band source network

Multibeam Antennas

Reflector antennas



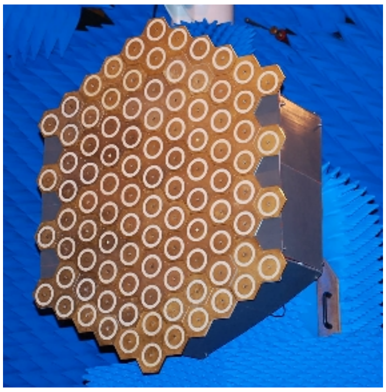


Ka-Sat (ADS manufacturing): Ka-band multibeam satellite operated by Eutelsat, launched in Dec. 2010.

Multibeam Antennas

Direct radiating antennas

- Beam forming can be provided by direct radiating antennas
- The signal is radiated into space without reflector
- The beams are obtained by weighting the corresponding signals by specific amplitude / phase coefficients (one per radiating element and per beam)
- Convenient antenna solution for multibeam LEO satellite constellations such as Iridium (in L band) and Globalstar (in L and S bands)



Multibeam Antennas

Direct radiating antennas

Satellite Globalstar 2 (Thales Alenia Space): direct radiating active antennas in L and S band

Plan

Multibeam Coverage

Frequency Re-use

Interference issues in multibeam satellite systems

Frequency Re-use

Motivation

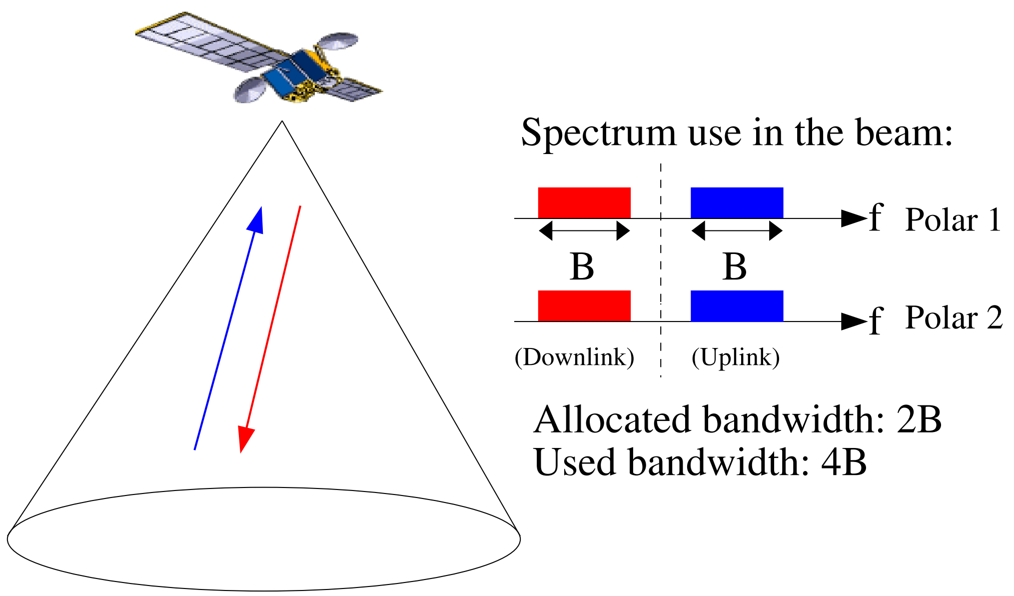
- The usable spectrum at a given orbital postion is limited
- Using spectrally efficient high order modulations is power consuming
- On the other hand, powerful error correcting codes enable low SNR operation

☞In spite of additionnal interference, the frequency re-use among multiple beams usually appears as the best option to increase the satcom system throughput

- Several approaches may be found:
  - Orthogonal polarization based frequency re-use
  - Spatial isolation based frequency re-use
  - A combination of both

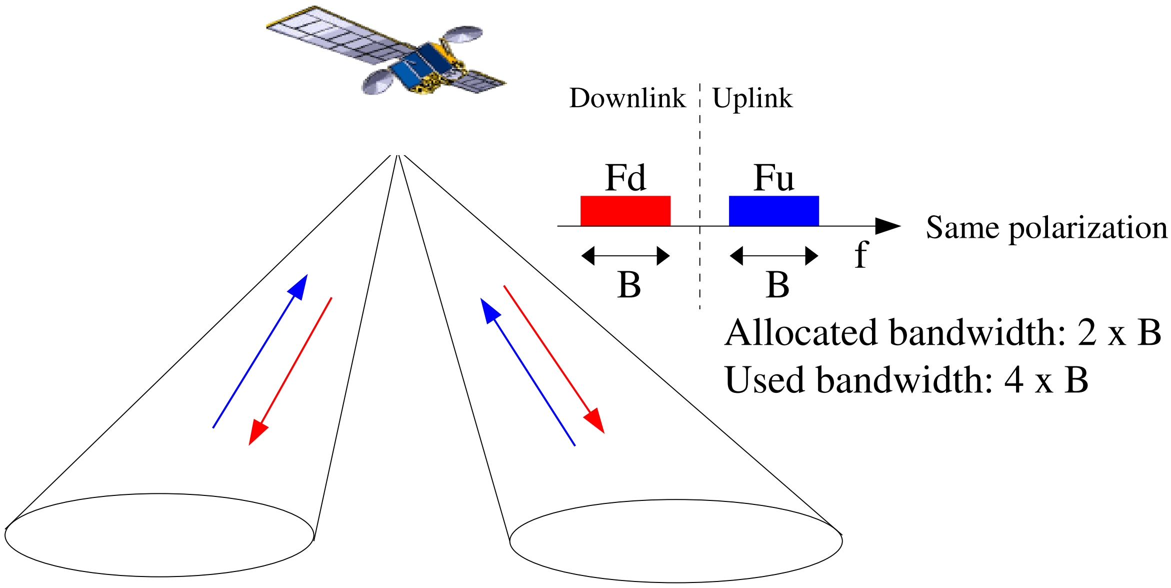
Frequency Re-use

Orthogonal polarization based frequency re-use



Frequency Re-use

Spatial isolation based frequency re-use



Frequency Re-use

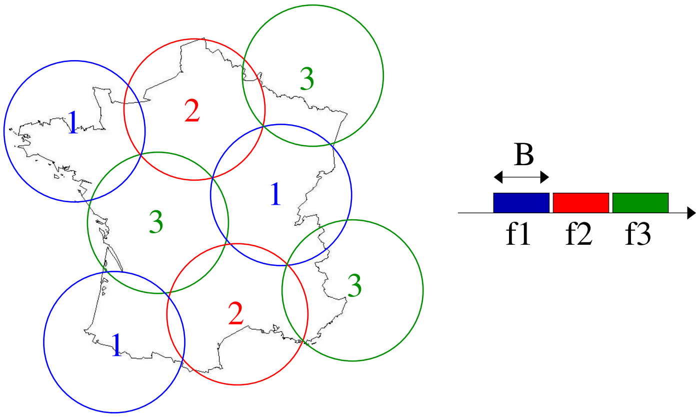
Frequency re-use factor

The average number of times that the same spectrum is used in the coverage is called Frequency re-use factor

- Orthogonal polarization based frequency re-use: $F \leq 2$
- Spatial isolation based frequency re-use: $F \leq N$ where N is the number of beams in the coverage
- Combining orthogonal polarization and spatial isolation: $F \leq 2N$

Frequency Re-use

Frequency re-use factor: example



Sub-band 1 is used in 3 beams, sub-band 2 is used in 2 beams and sub-band 3 is used in 3 beams:

$$F = \frac{3+2+3}{3} = 2.7$$

- ▶ The system *equivalent* bandwidth is $B_{eq} = 2.7 \times B$

About orthogonal polarization based frequency re-use

Orthogonal polarizations

- Vertical / Horizontal linear polarizations *or*
- Left / Right hand side circular polarizations

Antenna constraints

Satellite and ground antennas are impacted:

- Polarization discrimination can be ensured at source level *or* at reflector level
- Antenna cross-polarization isolation requirements
- Possibly complex processing to jointly optimize the antenna performance on both polarizations

About orthogonal polarization based frequency re-use

Polarization mismatch

Cross-polarization interference may occur in the receiver due to:

- Non ideal cross-polarization of ground and satellite antennas
- Rain depolarization
- Ground and satellite antenna misalignement
- Satellite attitude control uncertainty

☞Due to this interference, orthogonal polarization based frequency re-use is usually combined with spatial isolation based frequency re-use

About spatial isolation based frequency re-use

Principle:

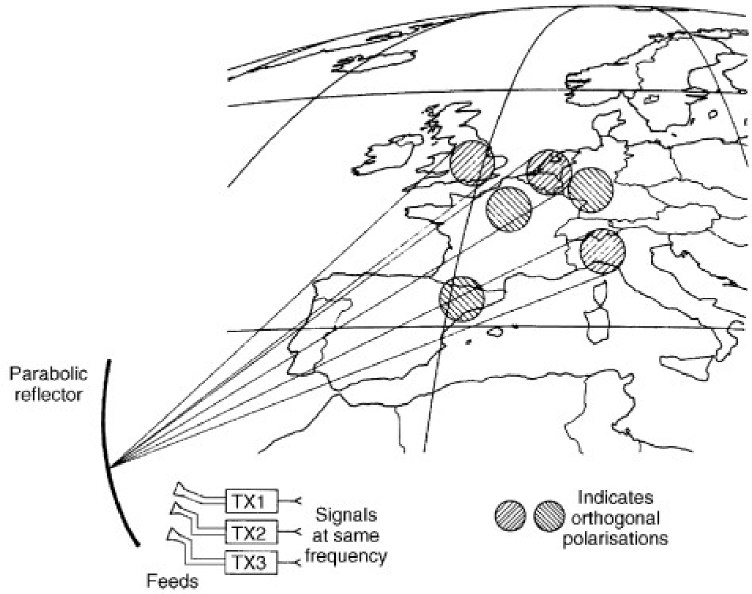
The same frequency band is used in several beams
☞Multi-beam coverage related approach

Constraints

- A frequency re-use interference is generated, the impact of which depends on the beam isolation
- The interference level is related to the satellite antenna radiation pattern and to the angular spacing between the beams operated in the same frequency sub-band

About spatial isolation based frequency re-use

Sparse multi-beam coverage



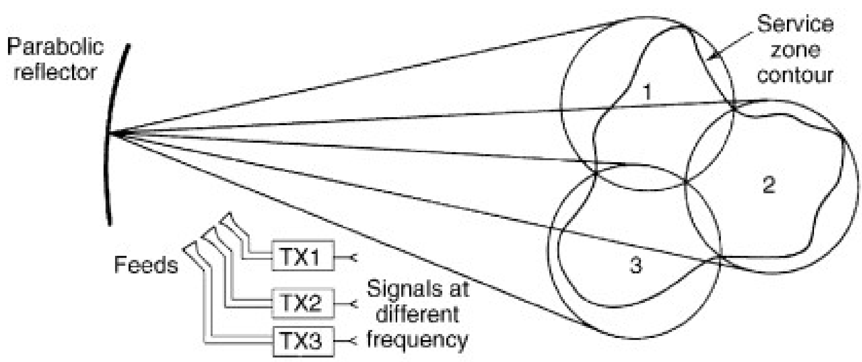
Source: G. Maral et M. Bousquet, *Satellite Communication Systems*, 5th edition, Wiley

- Typical use: permanent beams over areas with strong capacity demand, or steerable beams for situational needs
- Orthogonal polarizations may improve the signal isolation among unsufficiently distant beams

About spatial isolation based frequency re-use

Continuous multi-beam coverage

- Regular beam layout, typically with rectangular or hexagonal lattice
- The same frequency sub-band cannot be used in neighbouring beams



Source: G. Maral et M. Bousquet, *Satellite Communication Systems*, 5th edition, Wiley

About spatial isolation based frequency re-use

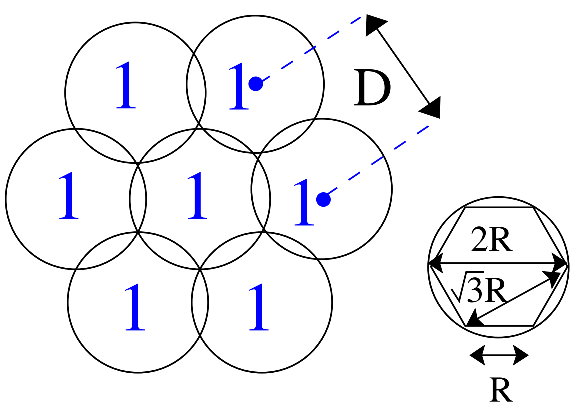
Regular frequency re-use patterns

- The elementary frequency sub-bands allocated to the beams are commonly referred to as frequency re-use channels
- Considering regular channel allocation patterns allows to maximize the angular spacing between beams sharing the same frequency resource
- In a given frequency band, the higher the number of channels
  - the better spacing between beams using the same channel
    ☞less interference, improved link budget
  - *but* the lower the frequency reuse factor
    ☞lower global system throughput

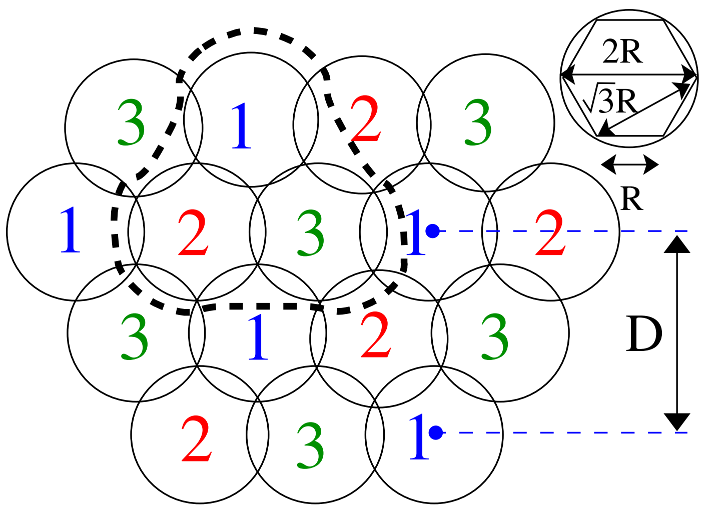
About spatial isolation based frequency re-use

Regular frequency re-use patterns

(hexagonal lattice)



$K = 1$
$D = \sqrt{3}R$

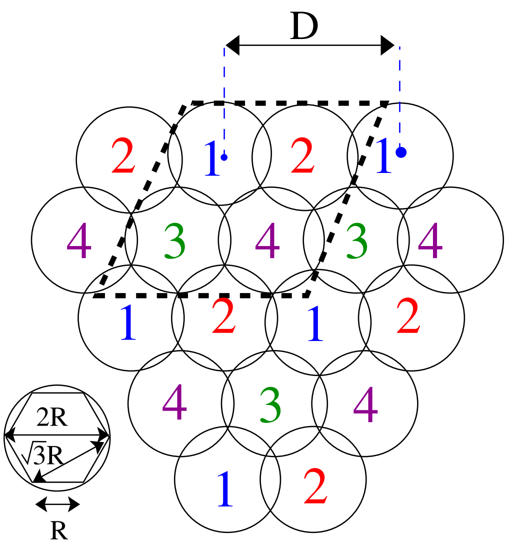


$K = 3$
$D = 3R$

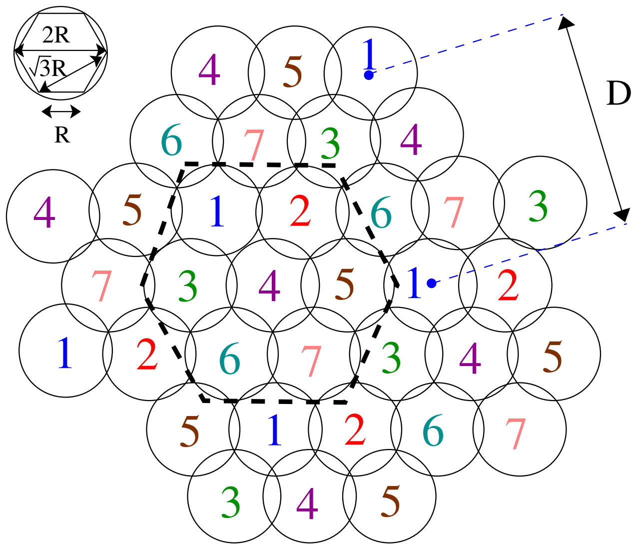
About spatial isolation based frequency re-use

Regular frequency re-use patterns

(hexagonal lattice)



$K = 4$
$D = 2\sqrt{3}R$



$K = 7$
$D = \sqrt{21}R$

About spatial isolation based frequency re-use

Regular frequency re-use patterns

Notations:

- K the number of beams in the elementary frequency re-use pattern
- A_S the whole coverage area and A_c a satellite beam area
- $F = \frac{A_s}{KA_c}$ the frequency re-use factor
- B_s the whole frequency bandwidth dedicated to the system
- η the modulation and coding scheme spectral efficiency

Then the system total throughput is

$$C = \eta \times B_s \times F = \boxed{\frac{\eta B_s A_s}{KA_c}}$$

Plan

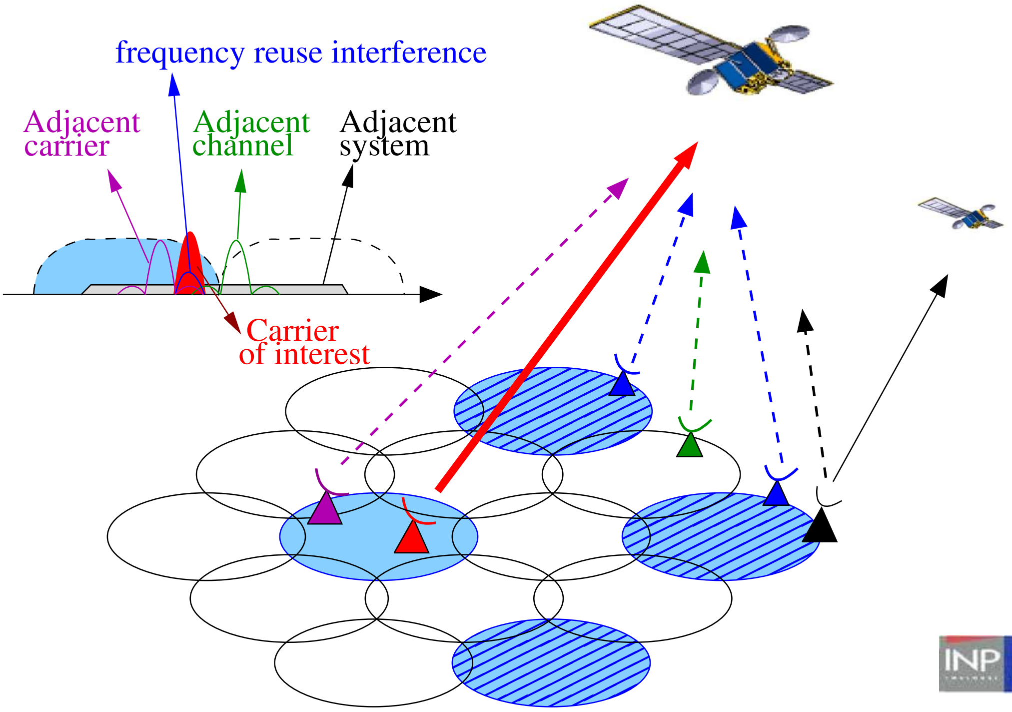
Interference issues in multibeam satellite systems

Sources of Interference

- Frequency reuse interference is induced between beams operated in the same frequency band, depending on the frequency reuse pattern
- Adjacent carrier interference is related to the non ideal signal spectral shaping which may induce carrier overlapping, in beams where several signals are frequency multiplexed
- Adjacent channel interference may occur between beams operated in neighbouring sub-bands and unsufficiently isolated
- Adjacent system interference refers to unwanted signal jamming due to other communication systems in the receiver antenna radiation field

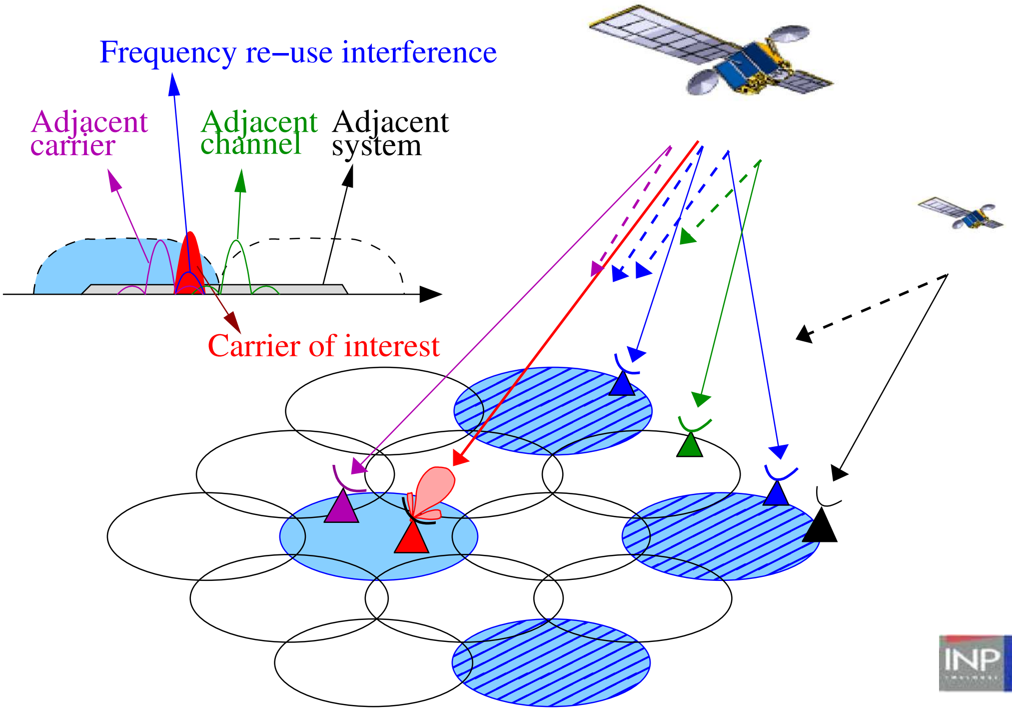
Interference issues in multibeam satellite systems

Example: uplink with FDMA multiple access



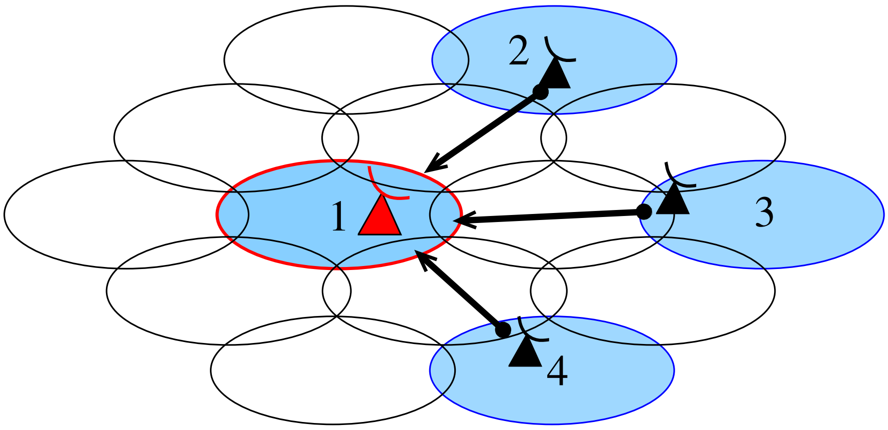
Interference issues in multibeam satellite systems

Example: downlink with FDMA multiple access



Frequency re-use interference on the uplink

Uplink frequency re-use interference is due to the reception in the antenna beam of interest, of signals issued from transmitting stations located in other beams operated in the same frequency band.



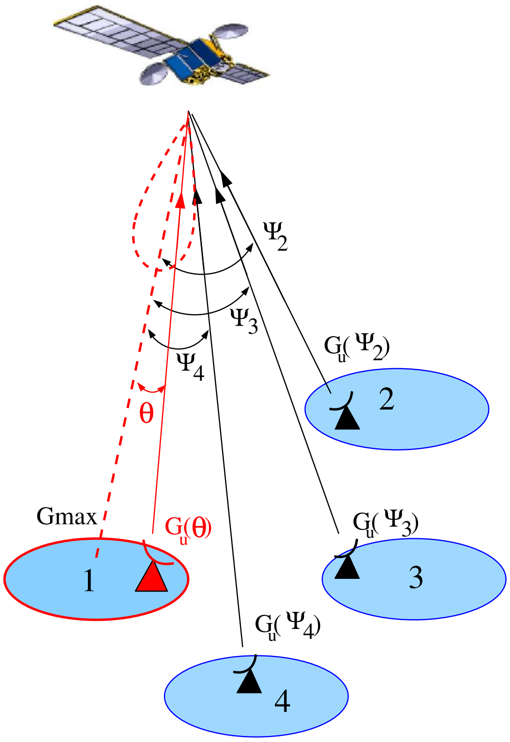
Frequency re-use interference on the uplink

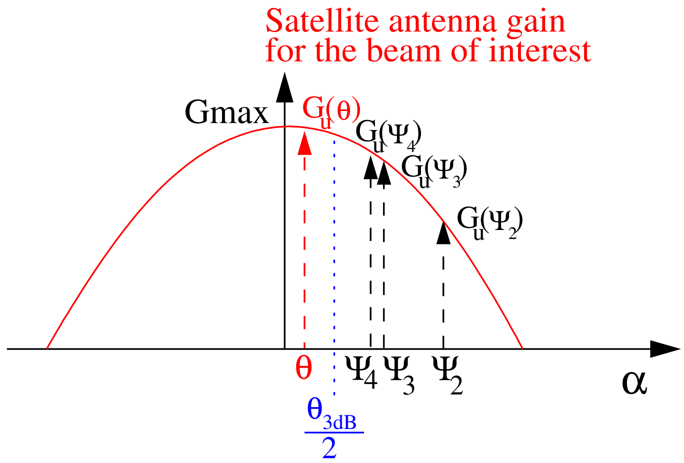
The ratio between the power of the signal of interest and the cumulated power of the interfering signals at the satellite input is characterized by the ratio:

$$\frac{C}{I} = \frac{P_u/L_u.G_u(\theta_u)}{\sum_i P_i/L_i.G_c(\Psi_i)}$$

- P_u and P_i are respectively related to the signal power at the output of the station of interest (useful signal), and at the output of the interfering stations
- L_u and L_i refer to the propagation loss, repectively for the link of interest and for the interfering links
- $G_u(\theta)$ is the satellite antenna gain (for the beam of interest) in the direction of the user of interest
- $G_u(\Psi_i)$ is the satellite antenna gain values (for the beam of interest) in the direction Ψ_i of the interfering station i

Frequency re-use interference on the uplink





Frequency re-use interference on the uplink

The signal to interference ratio $(C/I)_U$ related to frequency re-use on the uplink depends on:

- the location of the user of interest in the beam of interest
- the number of interfering stations in other beams, transmitting at the same moment in the same frequency band as the user of interest
- the location of the interferers relatively to the center of the beam of interest

Frequency re-use interference on the uplink

Exercise: computation of the $(C/I)_U$ ratio in a worst case

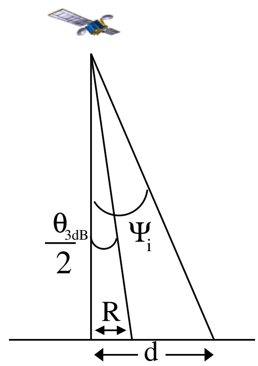
Assumptions:

- The user of interest is located at the edge of the beam
- 6 interferers are located at the edge of their respective beams, at the worst location w.r.t the beam of interest, using simultaneousy the same frequency band
- The beam radius is denoted as R. It is assumed that the beams intersect at $G_{max} - 3dB$.

- The following approximation will be used in the following (valid for high satellite elevation):

$$\tan \Psi_i = \tan \frac{\theta_{3dB}}{2} \times d/R$$

$$\Psi_i \simeq \frac{\theta_{3dB}}{2} \times d/R$$



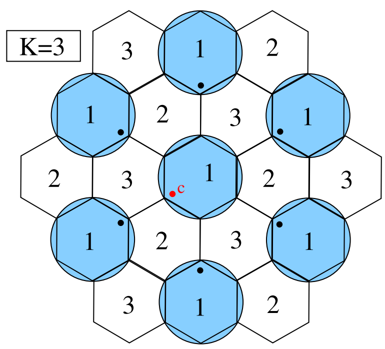
Frequency re-use interference on the uplink

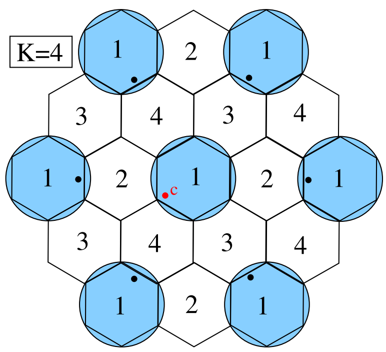
Exercise (continued)

- It is assumed that the following quadratic approximation is suited to characterize the satellite antenna gain G_u for the beam of interest, over an extended area including the location of the interferers:

$$G_u(\alpha) \simeq G_{max} - 12\left(\alpha/\theta_{3dB}\right)^2 \;\; (dBi)$$

- The two following configurations will be considered:

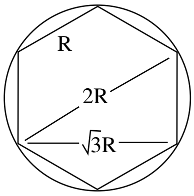




Frequency re-use interference on the uplink

Exercise (continued)

1. The user of interest being located at the edge of the beam, express the antenna gain for the beam of interest $G_u(\theta)$ in the direction of this user, as a function of the maximum gain G_{max} at the center of the beam
2. Express the distance separating the center of the beam of interest from the interfering stations as a function of R, for a 3-colour re-use scheme (K=3) and for a 4-colour reuse scheme (K=4)



3. Express the angular spacing Ψ_i as a function of θ_{3dB} in both cases

Frequency re-use interference on the uplink

Exercise (continued)

4. In both cases, express the satellite antenna gain for the beam of interest in the direction of the interferers $G_u(\Psi_i)$, as a function of G_{max}
5. Assuming that all interfering stations transmit with the same power as the station of interest, and considering identical propagation losses for all users, compute the ratio C/I in the case where K=3 and in the case where K=4
6. It is assumed that the signal to noise ratio C/N reaches 5 dB when the interfering signals are not active. Compute the ratio $C/(N+I)$ when all interferers are active, in both considered cases

Frequency re-use interference on the downlink

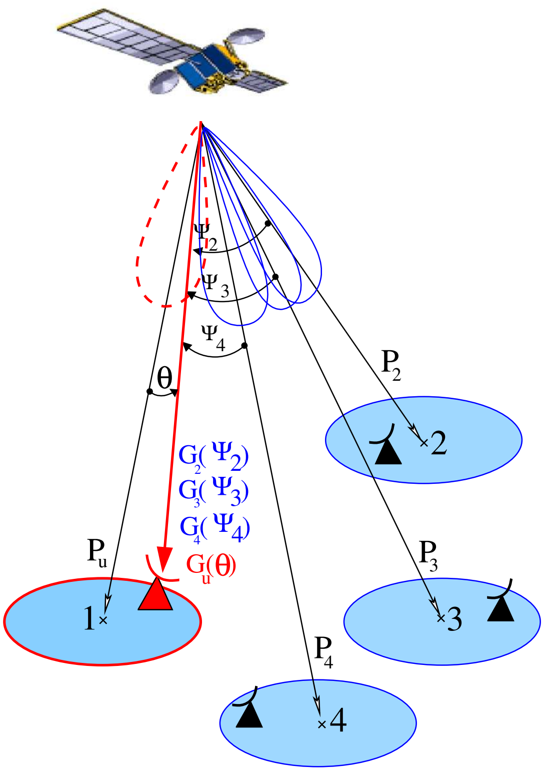
For an isolated system, the signal to interference ratio $(C/I)_D$ related to the downlink frequency re-use depends on:

- the location of the user of interest in the beam of interest
- the number of beams operated in the same frequency band as the beam of interest
- the angular spacing between the center of the beam of interest and the center of the interfering beams

The ratio $(C/I)_D$ does not depend on the location of the receiving stations in the interfering beams

Multibeam Coverage Frequency Re-use Interference issues in multibeam satellite systems

Frequency re-use interference on the downlink



Frequency re-use interference:

$$\left(\frac{C}{I}\right)_D = \frac{P_u/L.G_u(\theta)}{\sum_i P_i/L.G_i(\Psi_i)}$$

Frequency re-use interference on the downlink