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Signal Processing for High Throughput Satellite Communications
The Force Awakens

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- Audience

Outline

Part I : Setting the stage
- 4S : Systems, Scenarios, Services, Standards
- 2C : Channels, Challenges

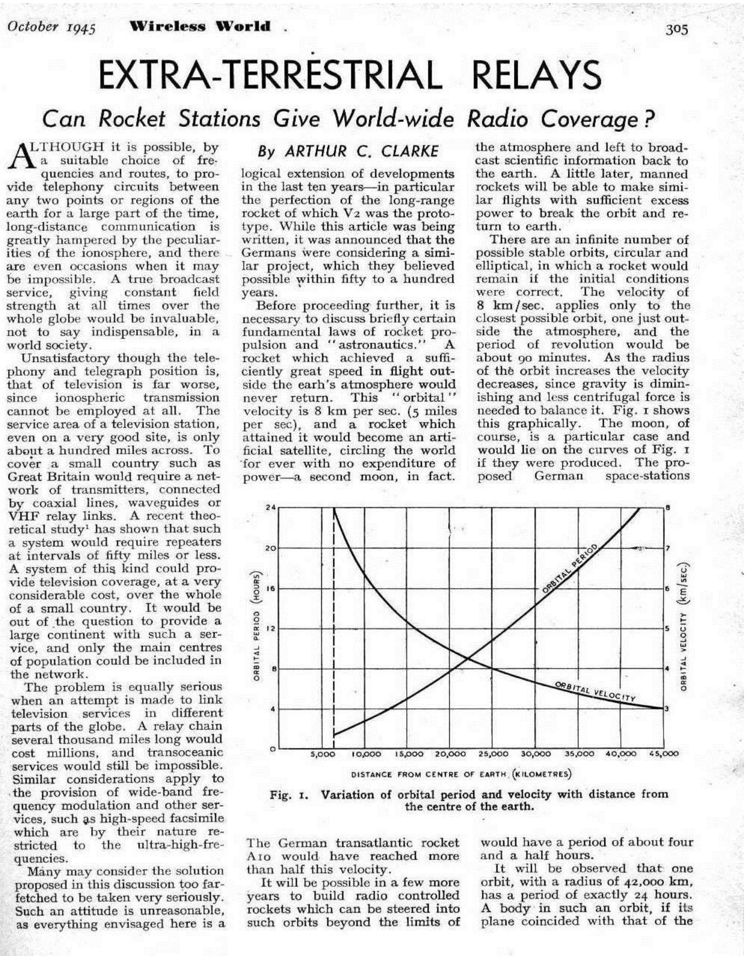
Part II : The Interference Menace and SP strike back
- Origin and Impact
- Mitigation using SP Techniques

Part III : Cognitive SatComs: A New Hope
- Motivation and Scenarios
- Impact

Part IV : Sneak Peek and Conclusions
- Next generation architectures

Satellite Systems : Introduction

- Initial Concept
  - Extra-terrestrial Relays
- Traditional Association
  - TV Broadcasting
  - Remote Sensing
- Changing trends
  - Ubiquitous Connectivity



October 1945 **Wireless World** . 305

EXTRA-TERRESTRIAL RELAYS

Can Rocket Stations Give World-wide Radio Coverage?

By ARTHUR C. CLARKE

ALTHOUGH it is possible, by a suitable choice of frequencies and routes, to provide telephony circuits between any two points or regions of the earth for a large part of the time, long-distance communication is greatly hampered by the peculiarities of the ionosphere, and there are even occasions when it may be impossible. A true broadcast service, giving constant field strength at all times over the whole globe would be invaluable, not to say indispensable, in a world society.

Unsatisfactory though the telephony and telegraph position is, that of television is far worse, since ionospheric transmission cannot be employed at all. The service area of a television station, even on a very good site, is only about a hundred miles across. To cover a small country such as Great Britain would require a network of transmitters, connected by coaxial lines, waveguides or VHF relay links. A recent theoretical study[1] has shown that such a system would require repeaters at intervals of fifty miles or less. A system of this kind could provide television coverage, at a very considerable cost, over the whole of a small country. It would be out of the question to provide a large continent with such a service, and only the main centres of population could be included in the network.

The problem is equally serious when an attempt is made to link television services in different parts of the globe. A relay chain several thousand miles long would cost millions, and transoceanic services would still be impossible. Similar considerations apply to the provision of wide-band frequency modulation and other services, such as high-speed facsimile which are by their nature restricted to the ultra-high-frequencies.

Many may consider the solution proposed in this discussion too far-fetched to be taken very seriously. Such an attitude is unreasonable, as everything envisaged here is a logical extension of developments in the last ten years—in particular the perfection of the long-range rocket of which V2 was the prototype. While this article was being written, it was announced that the Germans were considering a similar project, which they believed possible within fifty to a hundred years.

Before proceeding further, it is necessary to discuss briefly certain fundamental laws of rocket propulsion and "astronautics." A rocket which achieved a sufficiently great speed in flight outside the earh's atmosphere would never return. This "orbital" velocity is 8 km per sec. (5 miles per sec), and a rocket which attained it would become an artificial satellite, circling the world for ever with no expenditure of power—a second moon, in fact. The German transatlantic rocket A10 would have reached more than half this velocity.

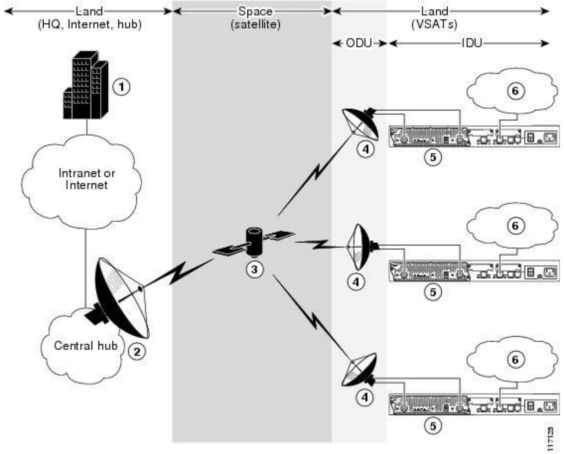
It will be possible in a few more years to build radio controlled rockets which can be steered into such orbits beyond the limits of the atmosphere and left to broadcast scientific information back to the earth. A little later, manned rockets will be able to make similar flights with sufficient excess power to break the orbit and return to earth.

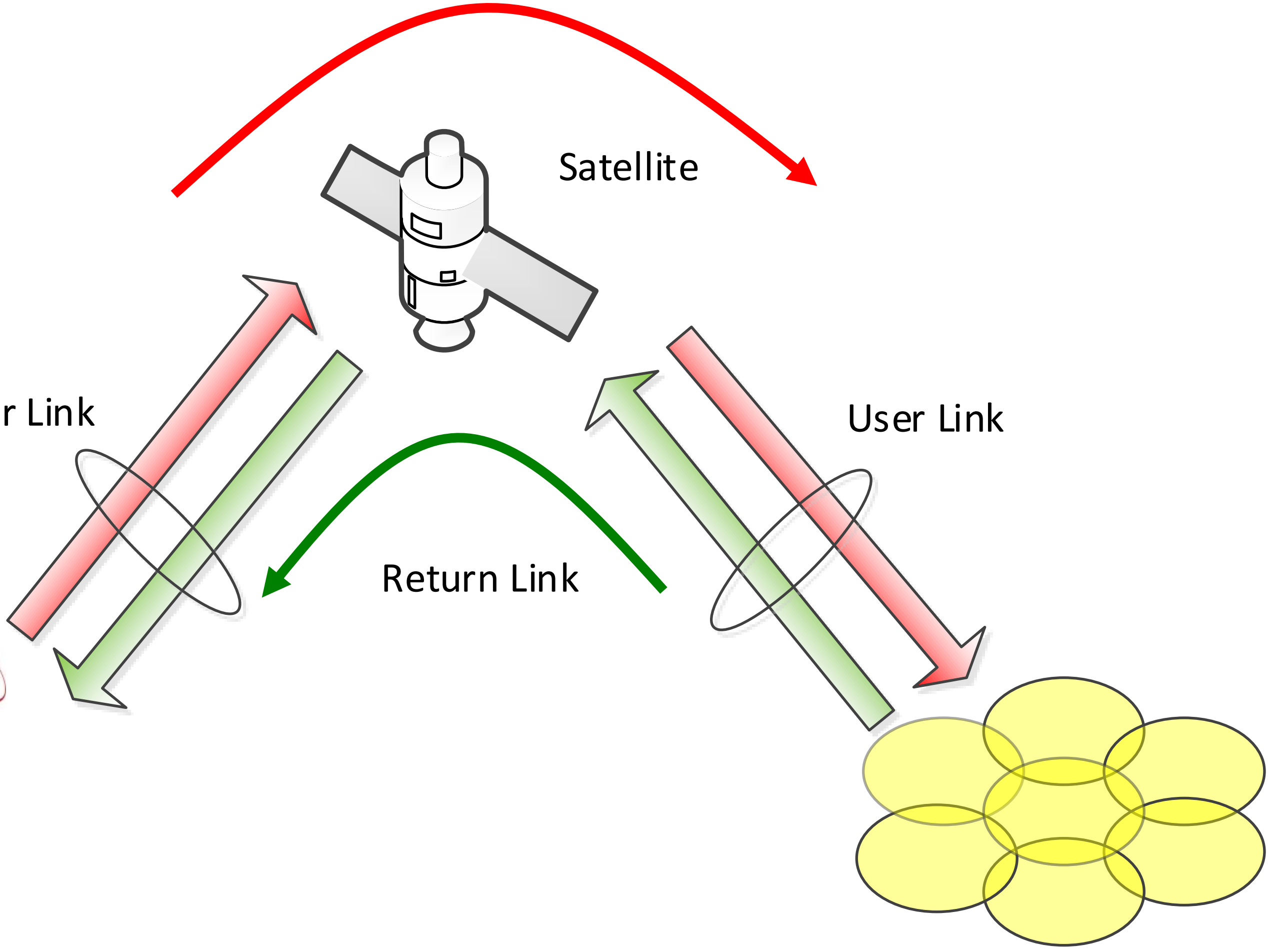
There are an infinite number of possible stable orbits, circular and elliptical, in which a rocket would remain if the initial conditions were correct. The velocity of 8 km/sec. applies only to the closest possible orbit, one just outside the atmosphere, and the period of revolution would be about 90 minutes. As the radius of the orbit increases the velocity decreases, since gravity is diminishing and less centrifugal force is needed to balance it. Fig. 1 shows this graphically. The moon, of course, is a particular case and would lie on the curves of Fig. 1 if they were produced. The proposed German space-stations would have a period of about four and a half hours.

It will be observed that one orbit, with a radius of 42,000 km, has a period of exactly 24 hours. A body in such an orbit, if its plane coincided with that of the

Fig. 1. Variation of orbital period and velocity with distance from the centre of the earth.

Traditional Satellite Communication System






Forward Link

Satellite

Feeder Link

User Link

Return Link

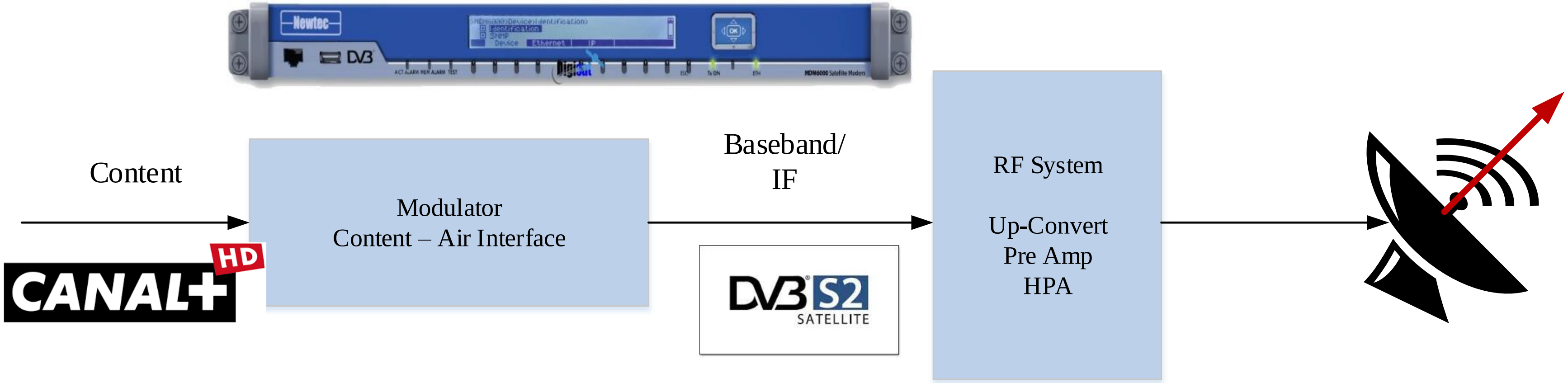
User Beams

Ground Segment

- Communications and control systems
  - Earth Station/ Gateway
  - Critical Infrastructure
  - Ground or Mobile Platforms
- Ground Station Network
  - Connections to earth stations, terrestrial network
- Typically “well endowed”
  - Power, Antenna Size, Redundancy

Typical Dish size
25.9m, 18 m C-band (Goonhilly, UK)
19 m, 8 m Ku-band (Goonhilly, UK)
13.5m, 9.1m Ka-band (ViaSat)

Ground Segment : Functionality/ Constraints



Content

Modulator
Content – Air Interface

Baseband/
IF

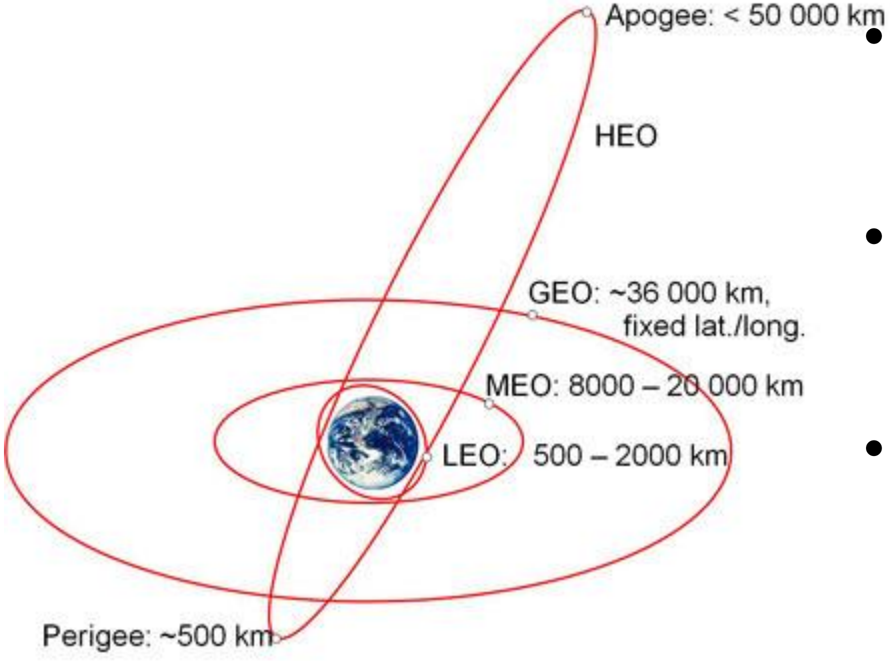
RF System

Up-Convert
Pre Amp
HPA

Similar system for receiving from satellite

- Processing Complexity not an issue
  - Advanced algorithms in the Modulator/ Demodulator
- Power
  - Typically not a constraint
- Constraint on transmission
  - Spectral Mask

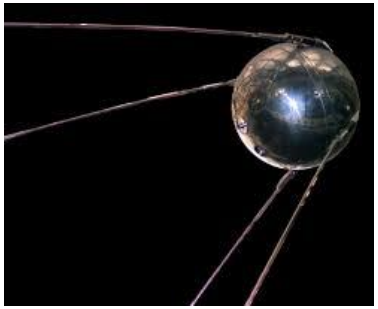
Space Segment : Orbits



- Orbital Classification
  - GEO, MEO, LEO
  - Van-Allen radiation belts
- GEO Stationary
  - Satellite visible 24hrs
  - Fixed Elevation
- LEO, MEO, HEO ……
  - Satellite in relative motion
  - Limited visibility per satellite

Orbit	Altitude range (km)	Period/ hrs	Delay ms	Global Coverage
LEO (Low Earth)	150-1000	1.5-1.8	7.5	78 (LEOSAT)
MEO (Medium Earth)	6,000-20,000	3.8-6	75	12 (O3b)
GEO	36,000	24	270	3 (I4/ alphasat)

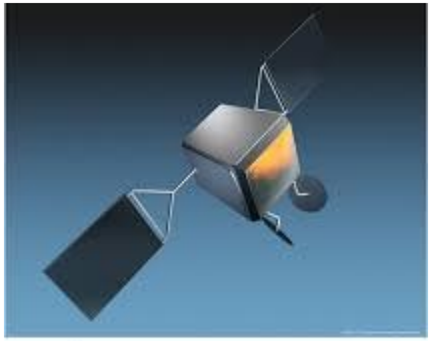
Space Segment : Communication Satellites



Sputnik 1, ‘57

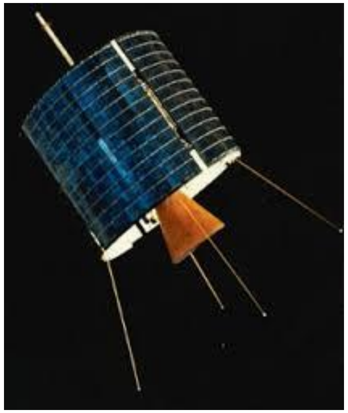
Telstar 1, ‘62

Iridium, ‘97



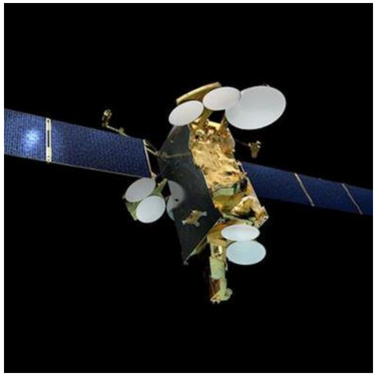
OneWeb, 2017+

Syncom 3, ‘64



Intelsat 1, ‘65

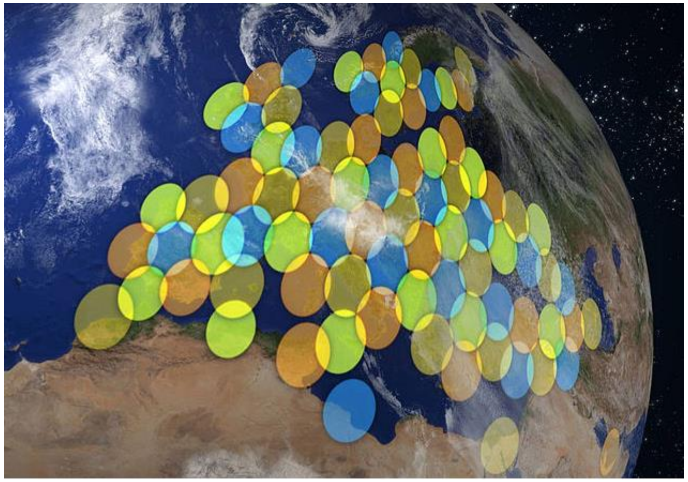
ViaSat 1, 2011

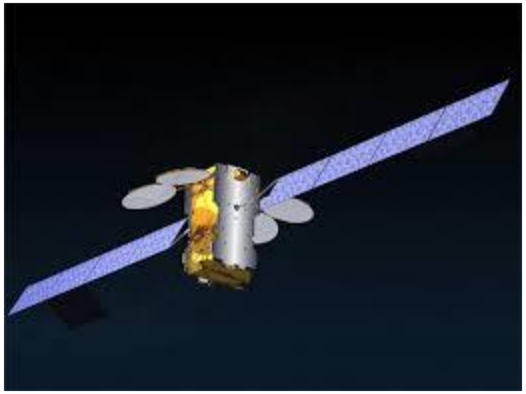


SES12, 2017

Multibeam Satellite Systems

- Single Beam Coverage
  - Traditional systems, Wide coverage
- Multiple beams
  - Smaller beams -> Directive transmission
    - Higher gain, better reception/ smaller antennas
  - Possibility to re-use frequency
    - Enhanced spectral efficiency
  - Other flexibility
    - Transmit power, frequency plan, routing



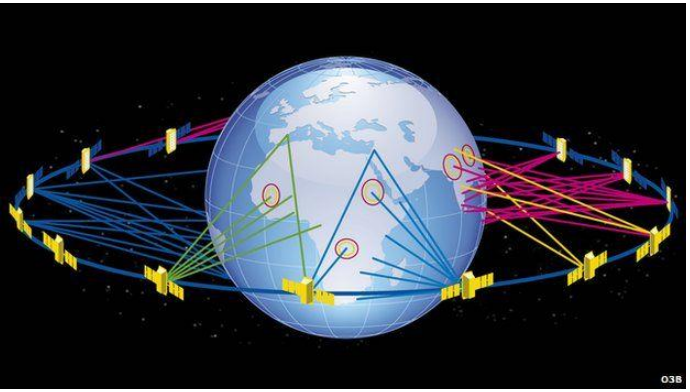


82 narrow spot beams are flying in KA-SAT (Eutelsat), launched in Dec. 2010 covering Europe – System throughput ~90Gbps

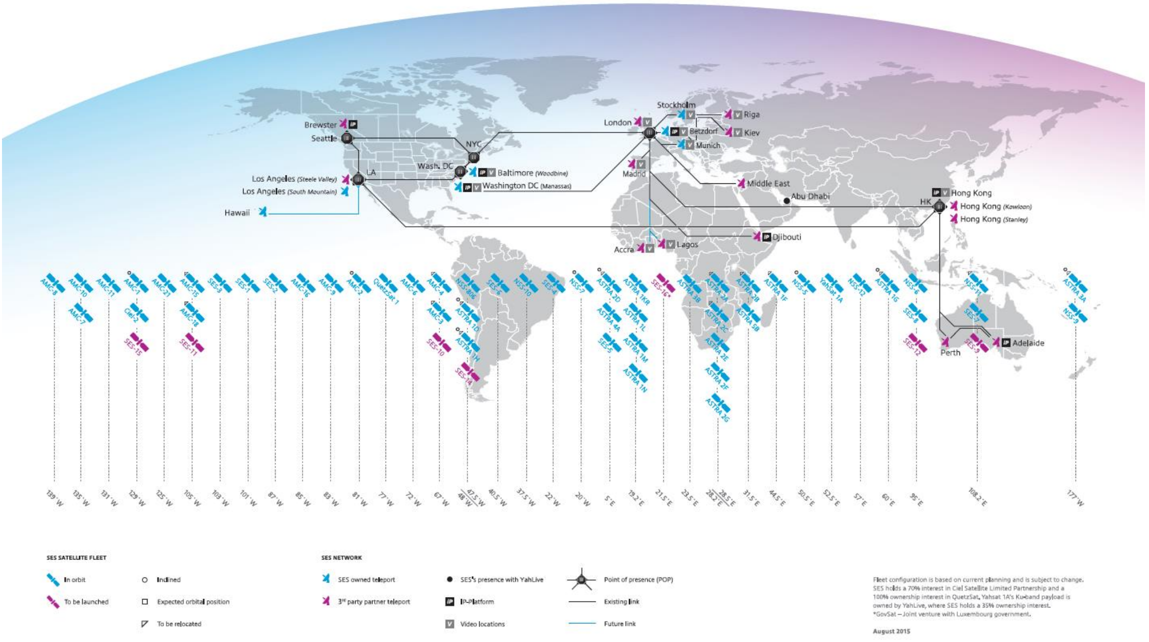
Cellular reuse ?

Space Segment : Satellite Constellations

Large LEO Constellations



O3b MEO Constellations

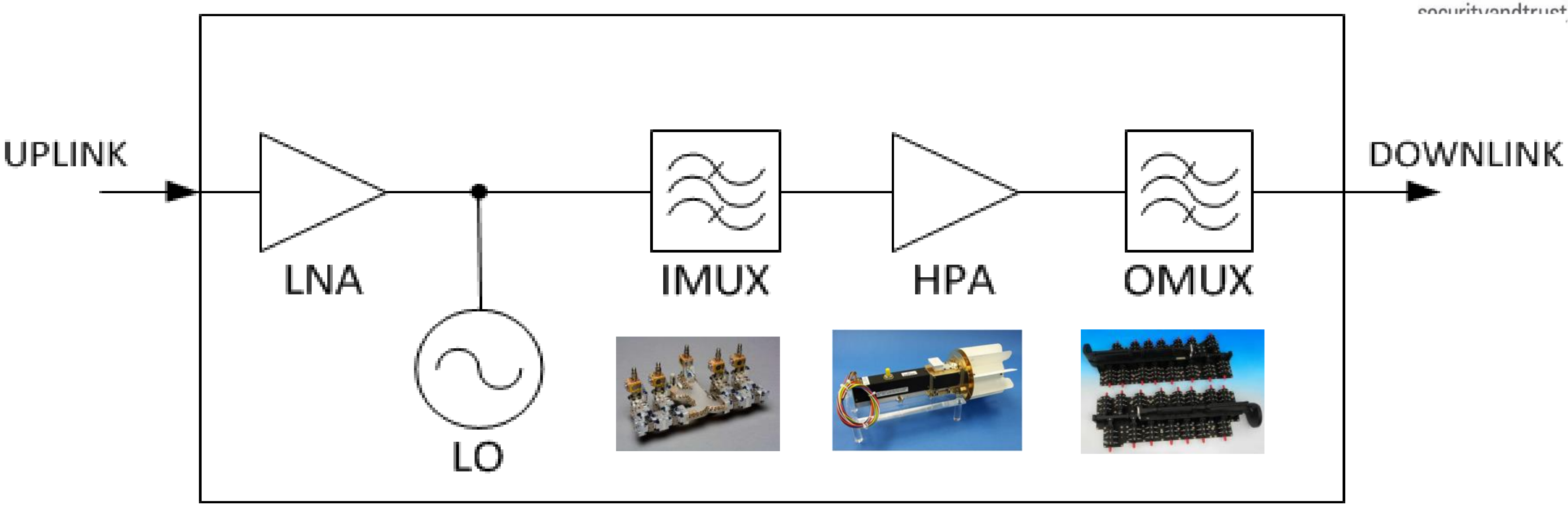


Fleet configuration is based on current planning and is subject to change. SES holds a 70% interest in Ciel Satellite Limited Partnership and a 100% ownership interest in QuetzSat, Yahsat 1A's Ku-band payload is owned by YahLive, where SES holds a 35% ownership interest. *GovSat – Joint venture with Luxembourg government.

August 2015

SES GEO Fleet

Traditional bent-pipe satellite: Functionality



Component	Functionality
LNA	Front end Low Noise Amplifier
LO	Local Oscillator : Frequency conversion
IMUX	Input Multiplexing Filter : Rejects out of band noise
HPA	High Power Amplifier
OMUX	Output Multiplexing Filter : Rejects out of band emissions

Pic Courtesy: Thales, L-3

Innovative Launch Technologies

SpaceX is disrupting the launch business

- Reuse of launch system (Falcon 9)
- Ion thruster (electric propulsion) for GEO deployment
- Drastic cost reduction
- First commercial launcher to deliver to ISS
- Several successful commercial satellite launches
  - Re-usable rockets

Space Segment Constraints

Mass

- Launch costs, Fuel on-board (life-time)
- Addition of components increases mass

Reliability

- Life time: 12-15 years
- Space hardened components
  - Analogue components : time-tested
  - Digital components : few

Power

- Solar powered, total and max power limited
  - Communications, control etc.
- Preferable: passive components
  - Limited on-board digital processing
- Amplifier at high efficiency

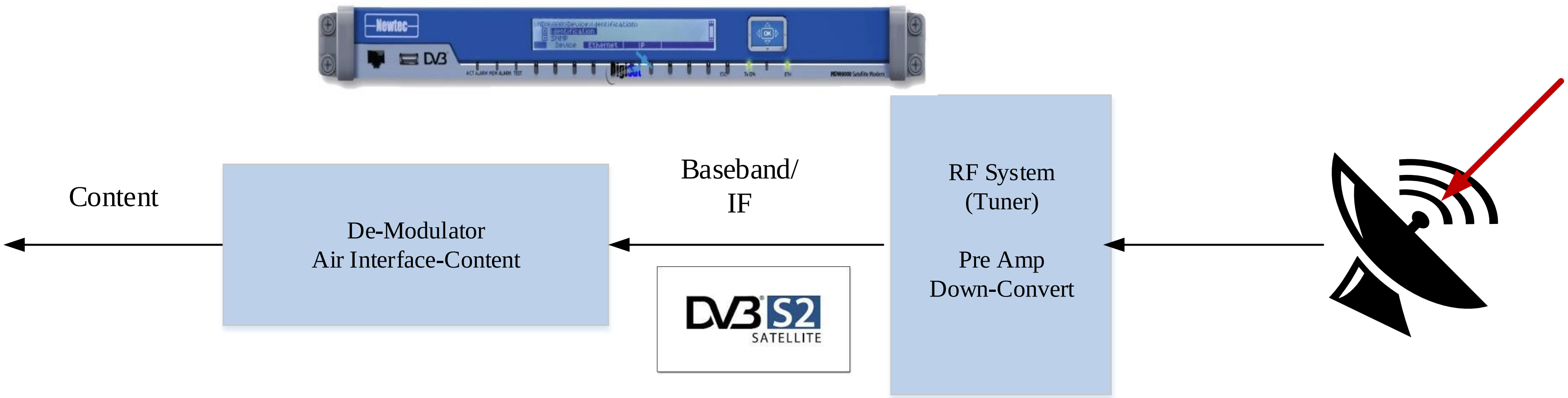
Future proof

- Waveform Agnostic processing

User Segment

- Different classes of equipment
- Mobility Classification
  - Mobile Terminal (satellite phone)
  - Nomadic Terminal (News Gathering)
  - Fixed Terminal (VSAT)
- Functionality based classification
  - Terminal or Access provision
- Service Level based classification
  - Consumer grade
  - Professional grade

User Segment: Functionality and Constraints



Content

De-Modulator
Air Interface-Content

Baseband/
IF

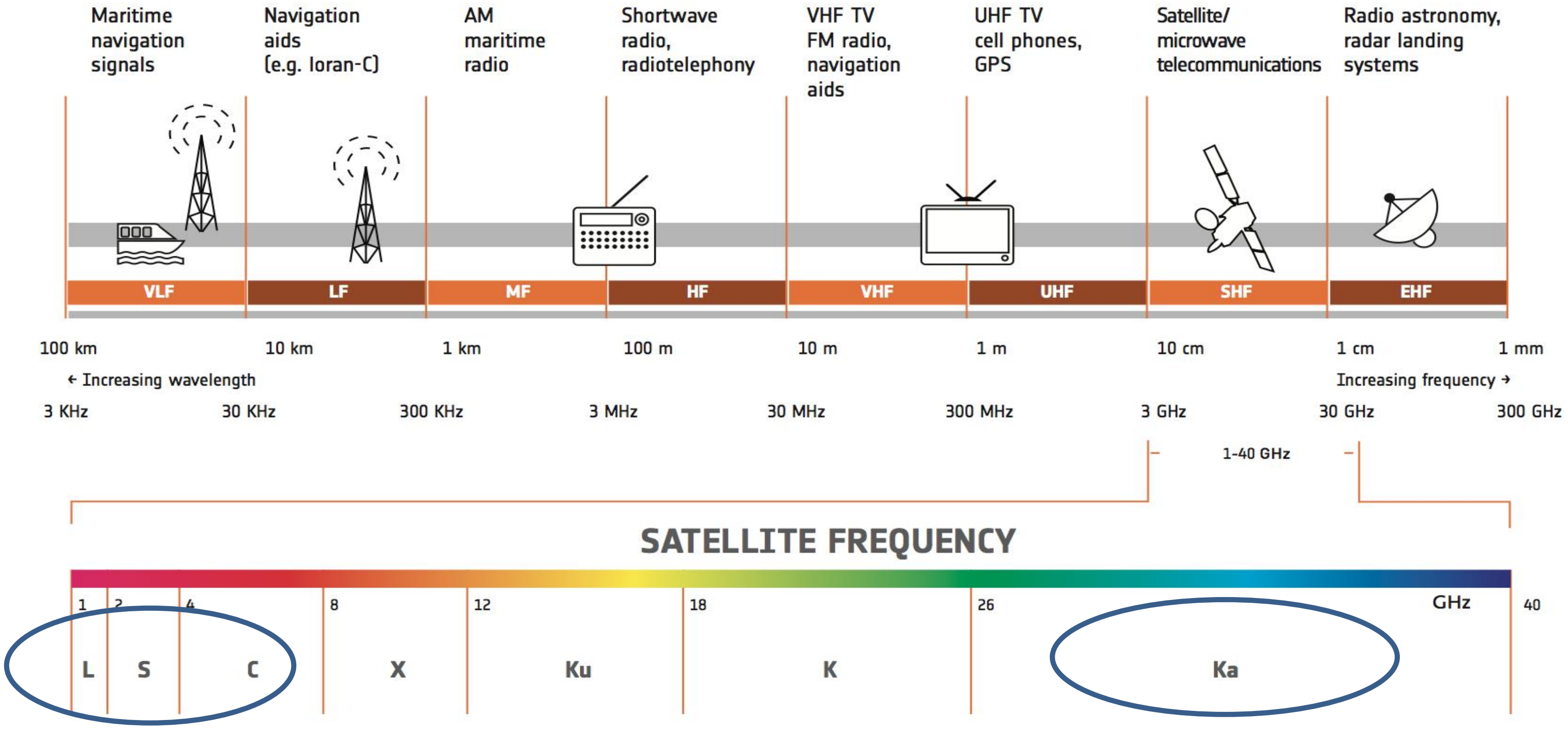
RF System
(Tuner)

Pre Amp
Down-Convert

Similar system for transmitting to satellite

- Processing Complexity and Power (uplink)
  - Issue in consumer grade
    - No wideband processing
  - Not an issue in professional grade
    - Wideband processing possible
- Constraint on transmission
  - Spectral Mask

Spectrum Used (source ESA)



Sub 6GHz Shared with terrestrial services

Shared with terrestrial services (microwave links)

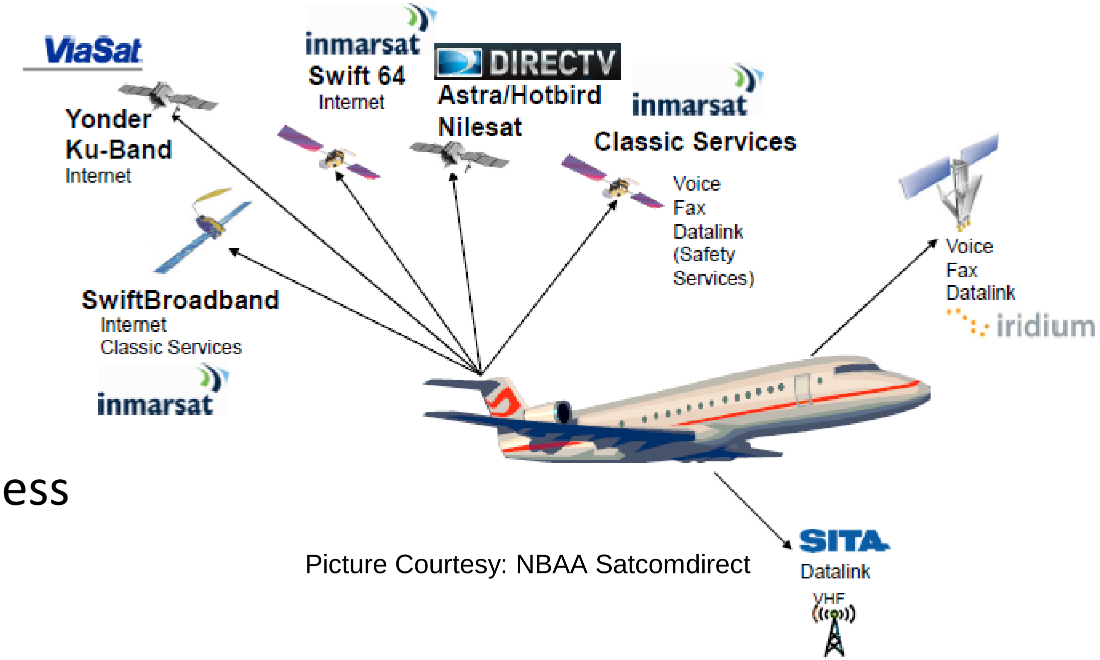
Services

- Traditional:
  - Broadcast: Satellite DTH (Direct-to-Home) TV
    - Still the core business but meeting increased competition
    - Linear TV on the decline
    - One way communication, no interaction
- New services and applications must be developed
  - Broadband: Internet access
    - Growing business – targets rural areas and developing countries
    - Two way communication, user state available at transmitter
  - Mobile/Maritime/Aeronautical satellite services is potentially a growing market
    - Ubiquitous coverage
- 5G backhauling, broadcast/multicast services

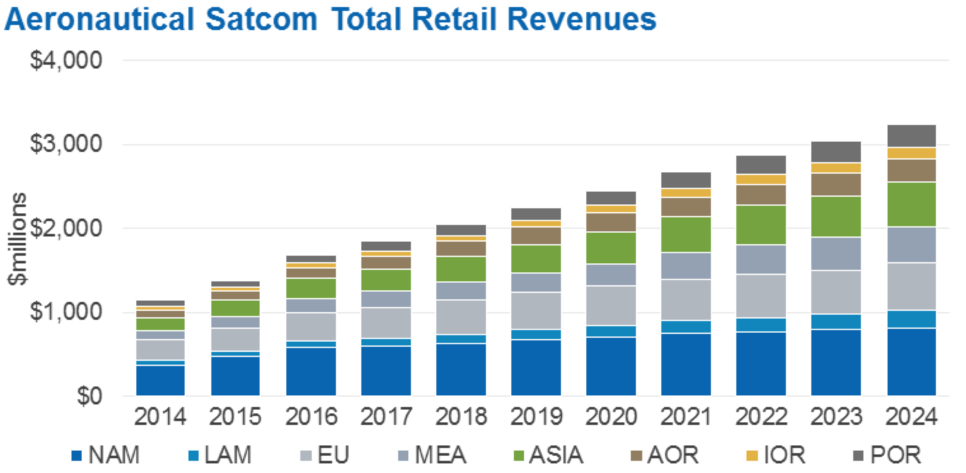
Aeronautical Mobile Satellite Services

Emerging Market for Broadband & Telemetry

- Services
  - Commercial airlines
    - Passenger internet access
    - Operational services
  - Safety and maintenance
    - ADS-B
    - Telemetry data….
- Bands
  - L (Inmarsat), Ku (Intelsat Epic)
  - Ka band : Global Express



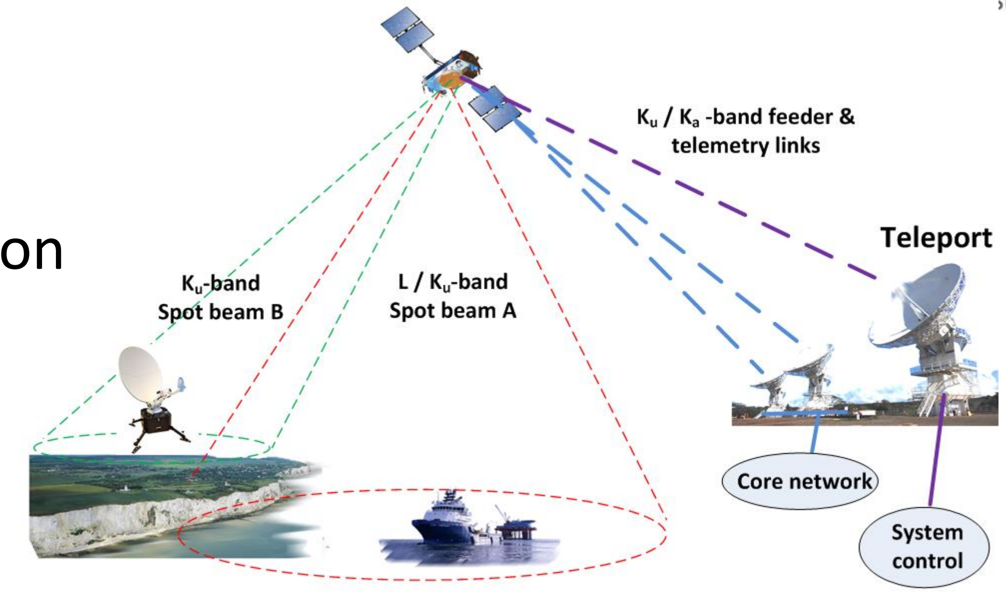
Picture Courtesy: NBAA Satcomdirect

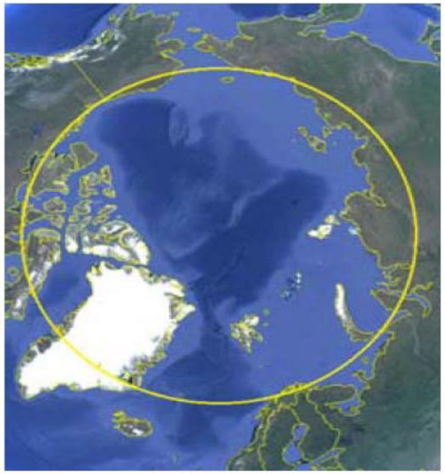


Source : NSR

Maritime Mobile Satellite Services

- Niche Market
- Broadband Services
- LEO for global communication
  (Iridium, Globalstar)
- GEO for broadband (Inmarsat)

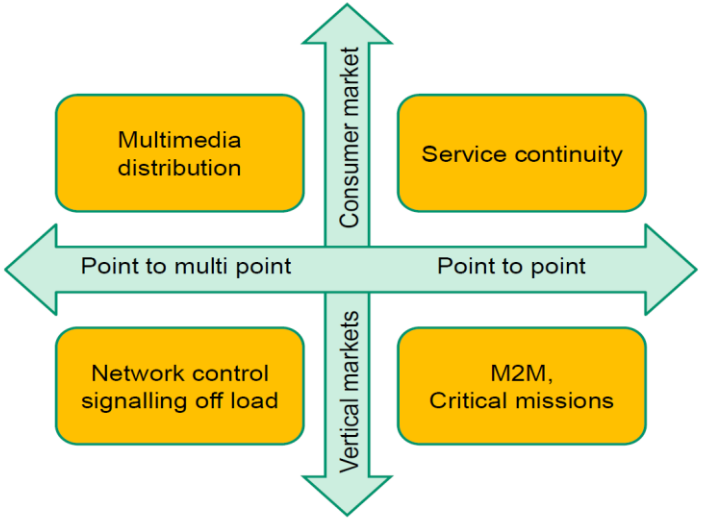




- Coverage in the Arctic
- Provisioning more frequencies for ship-ship, ship-shore communications
  - Satellite to enhance coverage
- Challenges
  - Low SNR
  - Low Bandwidth Multiple Access Channel

5G SatComs in Networld2020

- Networld2020 : European Technology Platform for communications networks and services.
- Multimedia distribution
  - Broadband-broadcast convergence
- Service continuity
  - Seamless handovers
- Machine to Machine
  - Energy efficiency and security
- Network control signaling offload
  - Non-Geo satellites



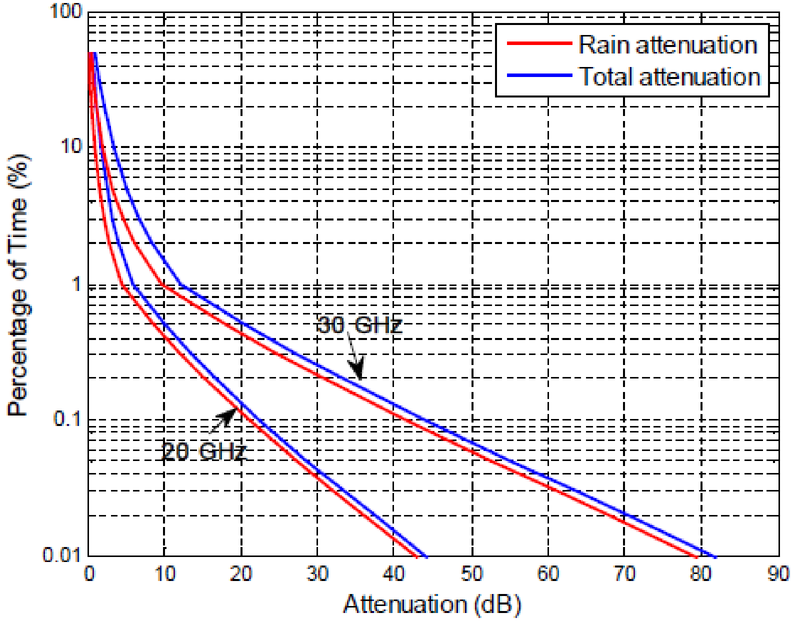
Link Budget

Ka-band VSAT (SATELLITE -> VSAT TERMINAL ONLY)	
Satellite	
EIRP (Max)	60 dBW
Bandwidth	10 MHz
Frequency band	19.7– 20.2 GHz (Ku band)
Service	
Broadband interactive, Carrier rate **Roll_off : 0.25, BW = 10MHz**	8 MBaud
Minimum C/N for decoding	S2x goes to -5 dB and lower.
Terminal	
Rx antenna Gain	40 dBi (Midband)
Rx Bandwidth	10 MHz
Noise Temperature	~250K
Link Budget calculation	
OBO (depends on number of carriers)	3 dB
G_R	40 dB
Receiver G/T	15 dB/K
FSL	210 dB
Beam Edge Loss	-3dB
Clear sky atm. loss + Polarization loss + pointing loss + rain attenuation (fade margin)	-5dB
Terminal Noise	
Boltzmann Constant	-228.6 dBW/ K/Hz
System Noise Temperature (taking into account rain attenuation)	24 dBK (~250 K)
Noise Bandwidth (10 MHz)	70 dBW
Received noise power	-134 dbW
C/N (beam centre)	16 dB
C/N (beam edge)	13 dB
C/I (multibeam, beam edge) **C/I (multibeam, beam centre)**	5 dB 15 dB
C/I3	15dB
C/I (adj satellite)	25 dB
C/(N+I) : clear sky, beam centre	10.5 dB
C/(N+I) : clear sky, beam edge	4 dB

Exploiting antenna gain
LoS !!

Channels : Fixed Terminals

- Position fixed to ensure LoS channel
  - No scatterers at Satellite
- Tropospheric effects
  - Attenuation due to rain
  - Cloud attenuation
  - Scintillations
  - Gaseous absorptions
  - Signal depolarization
- Ionospheric effects (< 3 GHz)
  - Faraday rotation

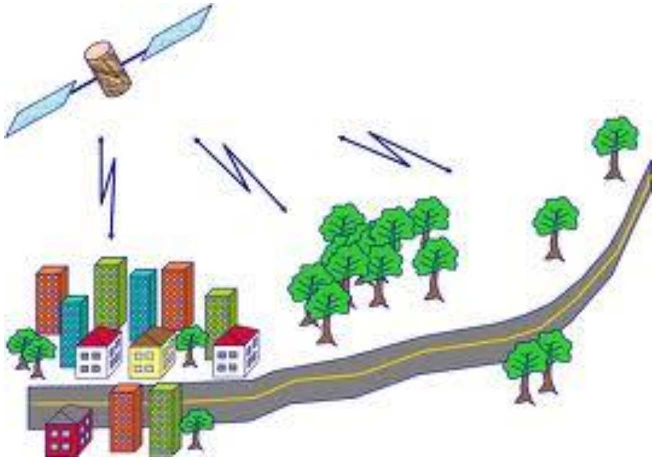


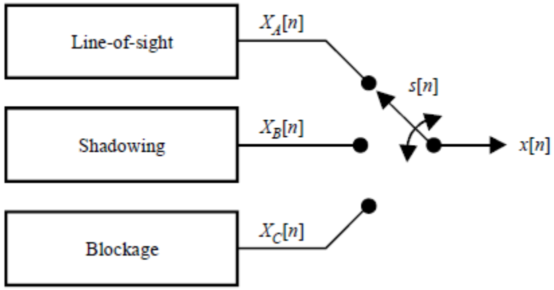
Channels : Fixed Terminals

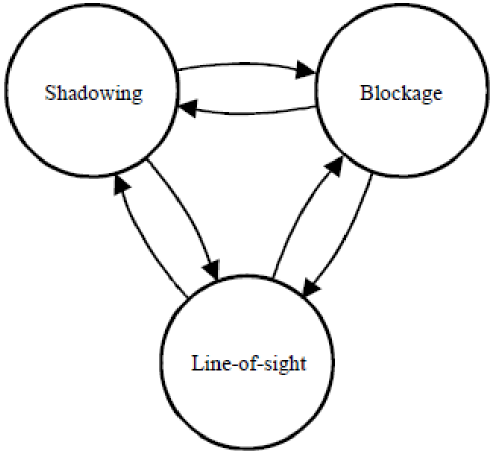
System	Models
Negligible rain attenuation	AWGN
Rain Attenuation (in dB)	Log normal, Gamma (depending on amount of rainfall)
Cloud blockage	Log normal -- On/ off
Scintillations	Fast Fading

Channels : Mobile Terminals

- Longer-term variations : variations due to changes in scenarios
  - Line of Sight
  - Blockage
  - Shadowing
- 3 state Markov model

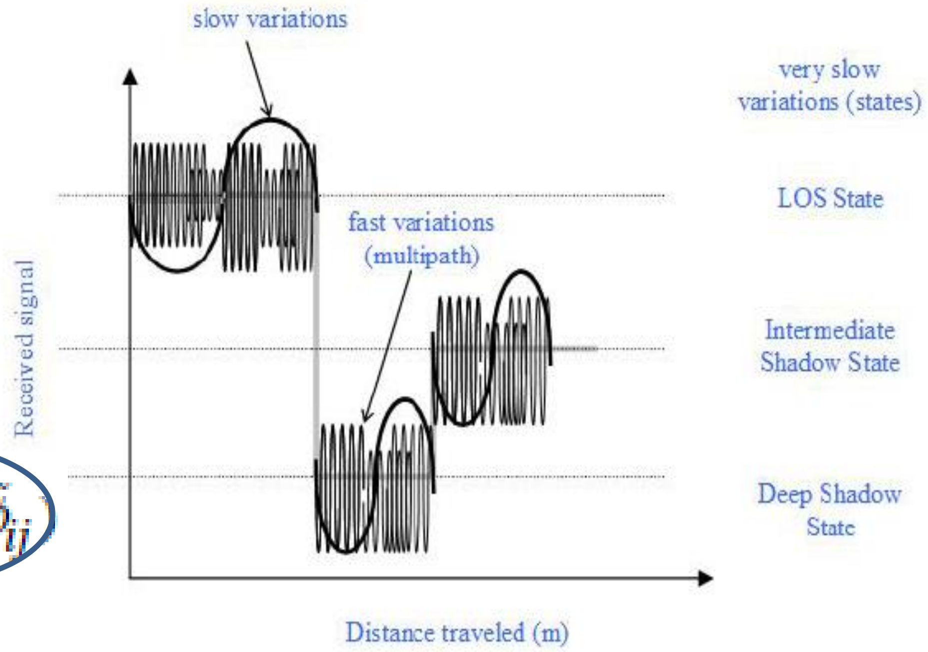






Land Mobile Satellite (LMS) Channel

- Short-term variations
  - Shadowing of the LoS component
  - Scattering leading to NLoS components
- Typical Model
  - Loo



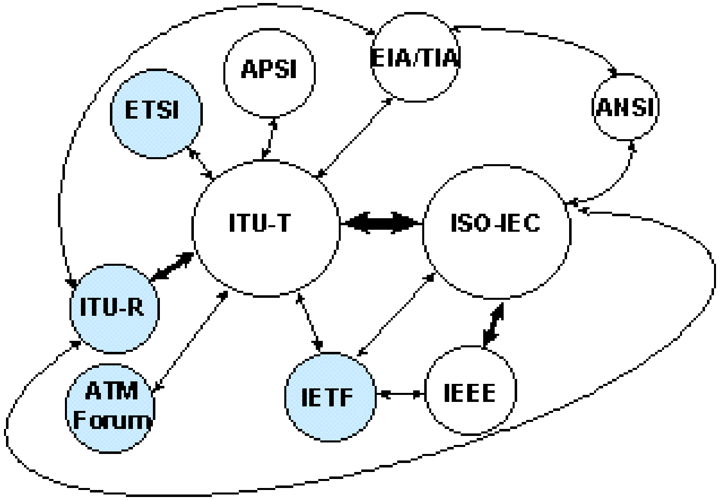
$$|h_{ij}|\exp(j\phi_{ij}) = |\bar{h}_{ij}|\exp(j\bar{\phi}_{ij}) + |\tilde{h}_{ij}|\exp(j\tilde{\phi}_{ij})$$

LoS Component
- Log-normally distributed amplitude
- Parameters : Mean, Standard Dev
- Uniform phase

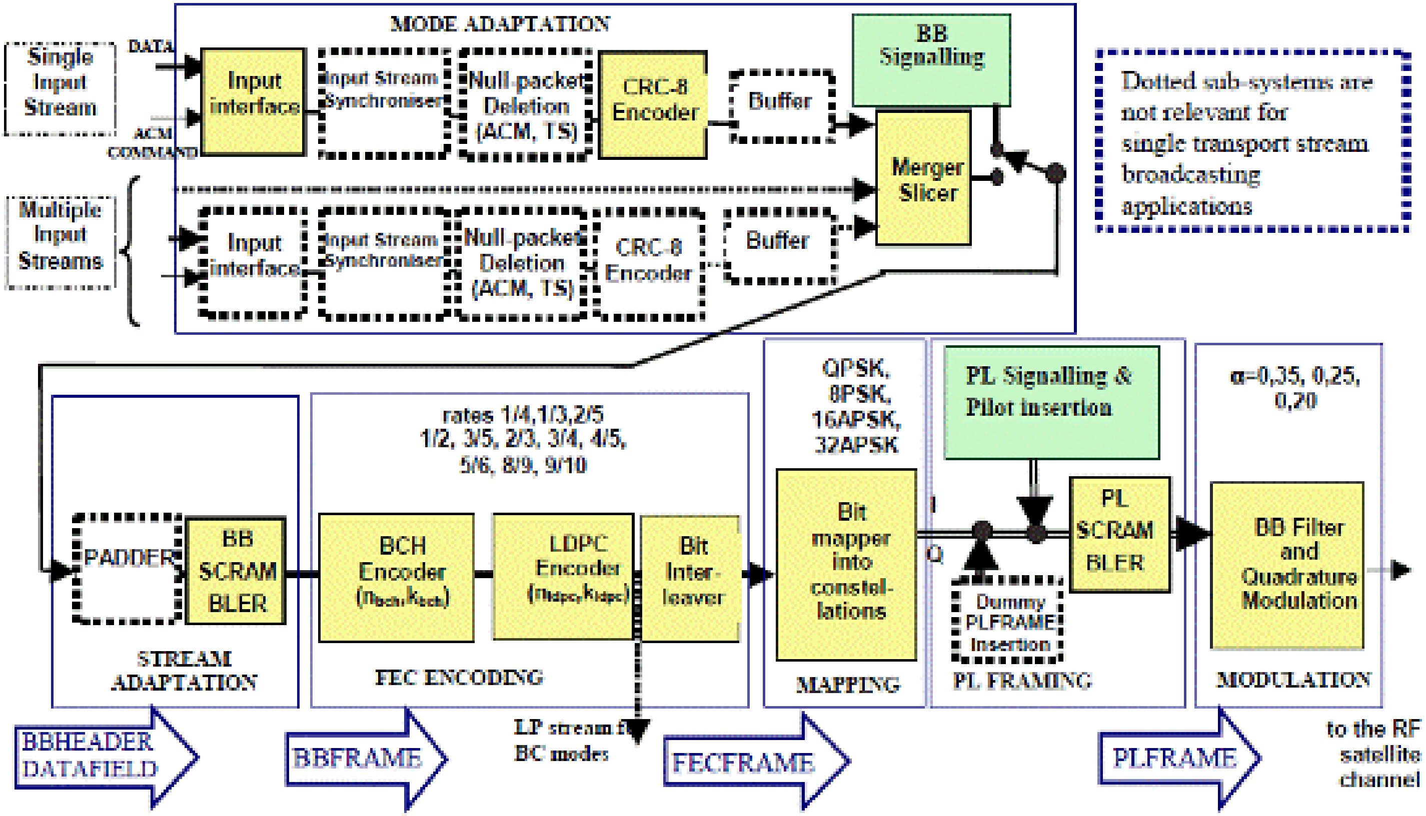
NLoS Component
- Rayleigh distributed amplitude
- Parameter : Power
- Uniform phase

Satellite Communication Standards

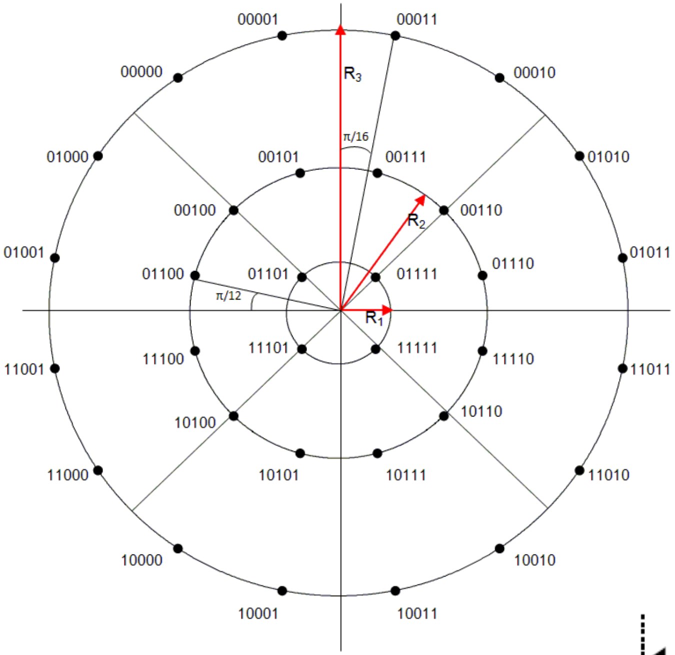
- Canvas of standard bodies
  - Proprietary aspects
- DVB : well known family
  - SH (satellite-handheld)
  - S. (Satellite)
  - RCS (return channel over satellite)
- Focus : DVB-S2
  - Extension S2x



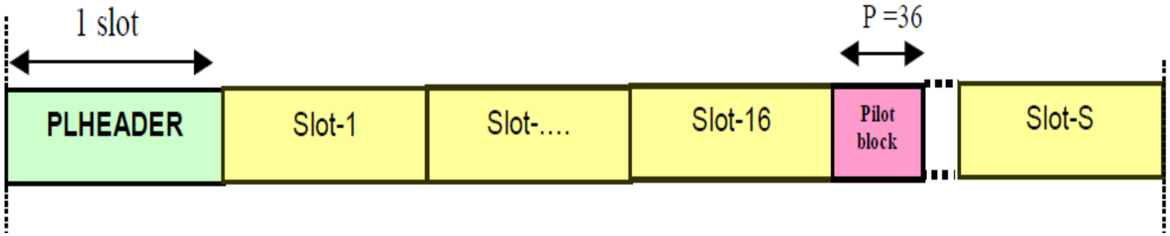
DVB-S2 PHY Layer



Physical Layer of DVB-S2



- Forward Error Correction
  - Inner : LDPC, Outer : BCH
- Bit Interleaving
- Modulation
  - BPSK, QPSK, APSK



- Framing
  - Pilot insertion, scrambling
- Single Carrier Waveform
  - Roll-offs : 0.05-0.35

Satellite Networks – Technical Challenges

- Design of a Communication Network rather than broadcast link capable of delivering multiple services
- Satellite Communications (SatCom) striving to increase offered capacity (analogous to terrestrial developments LTE, 5G)
- Reduce **the cost per bit** via satellite
- Broadband Internet penetration still low in rural areas
- Cope with changes in traffic evolution via satellite
  - Traditional broadcasting of audio & video is changing: HDTV, 3DTV
  - New services: P2P, Video-on-Demand, non-linearTV, growing Internet traffic
  - Traffic imbalance between uplink/downlink is reducing
- Different challenges to increase capacity and deliver reliable services for:
  - Fixed satellite terminals (Fixed SatCom)
  - Mobile satellite terminal (Mobile SatCom)

SatCom vis-à-vis Terrestrial

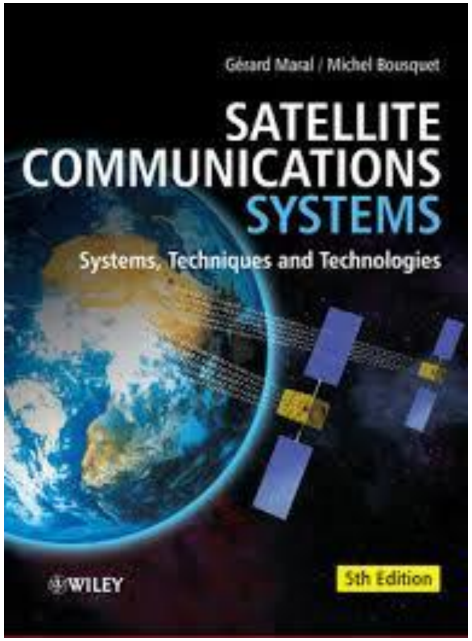
- After satellite launch, no possibility of making big modifications
  - Manufacturers & operators very conservative wrt novel DSP approaches
  - Effort to add extra processing to the Gateway instead of on-board → vast majority of commercial satellites are transparent (bent-pipe) – this is changing!
- Long propagation delay, especially for GEO (~0.5s for round-trip)
- SatCom extremely power limited (GEO is ~36,000km away)
  - Necessary to operate close to saturation in non-linear HPA → intermodulation & non-linear impairments
  - In mobile SatCom deep urban reception not feasible → low coding rates and long time interleaving are needed
- Large differences in terms of wave propagation & channel characteristics
  - SatCom > 10GHz: rain & cloud attenuation, gaseous absorption, scintillations
  - Mobile SatCom: Fading depends on elevation – line-of-sight component often necessary
  - Longer coherence time for channel

Summary

- Satellite Systems
  - Orbits, Segments
- Scenarios
  - Broadcasting, Broadband
- Services
  - DTH, Internet, Backhauling, 5G
- Standards
  - DVB-S2
- Channels
  - AWGN, Log-normal, LMS
- Challenges

Calvin and Hobbes

References



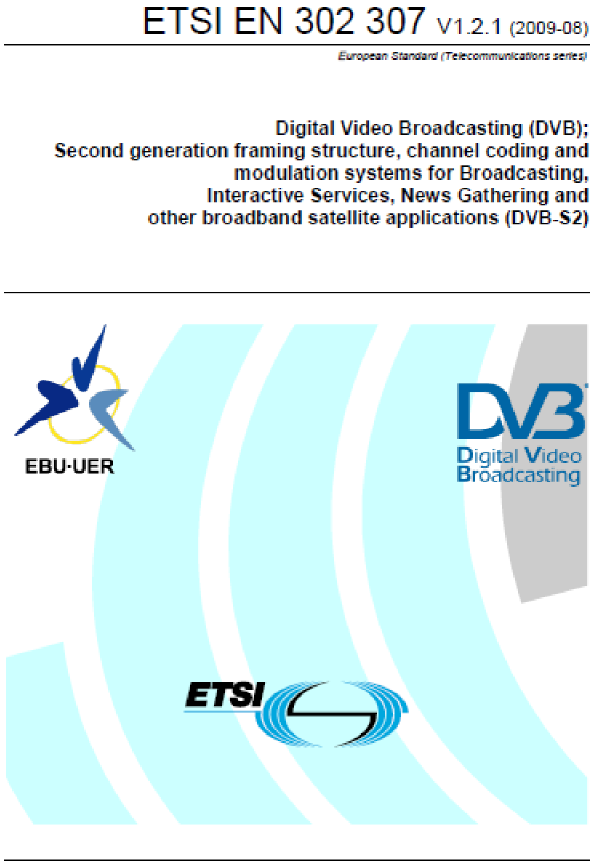
Gérard Maral / Michel Bousquet

SATELLITE COMMUNICATIONS SYSTEMS

Systems, Techniques and Technologies

WILEY

5th Edition



ETSI EN 302 307 V1.2.1 (2009-08)

European Standard (Telecommunications series)

Digital Video Broadcasting (DVB);
Second generation framing structure, channel coding and
modulation systems for Broadcasting,
Interactive Services, News Gathering and
other broadband satellite applications (DVB-S2)

Cooperative and Cognitive Satellite Systems

Enhancing Throughput in SatCom
The menace of interference

Sources of Impairments

- Noise (dominated by receiver)
- Channel fading
- Intra System Interference
  - Intermodulation
    - Non-linear operation of the High Power Amplifier
  - Co-channel
    - Reuse of frequencies in multibeam systems
  - Adjacent transponder (adjacent channel interference)
  - Cross polarization
- Inter System Interference
  - Adjacent Satellite interference
  - Misalignments, jamming etc

Need to mitigate interference

- To enhance higher spectral efficiency
  - – High Rate Broadcast Applications (UHDTV, 3DTV)
  - – High Rate Broadband Internet (5G)
  - – Reduce the cost per bit
- To obtain higher on-board power efficiency
  - – Energy is a fundamental but scarce resource
    - To achieve the required Link-budget
  - – Optimize the payload architecture
    - Enabling HW resource sharing
    - Reduce on-board HW/cost/weight
    - Increase the number of payloads

Satellite Link : Impairments and Traditional Mitigation

Impairments	Mitigation Technique	Remarks
Downlink Noise	Improved System FEC	System dimensioning for noise pursued using link budgets
Fading on the downlink induced by propagation	Adaptive Coding and Modulation (ACM), Variable Coding and Modulation (VCM), Power Control	Traditional Fade Mitigation technique, useful for minor variations; Link provisioned for worst case attenuation to achieve certain availability VCM→ Broadcast, ACM→ Interactive
	Temporal diversity	Long interleavers (upto 10s) are used for LMS → suitable for broadcasting
Interference	Power control	Considered as noise and link provisioned using link budgets

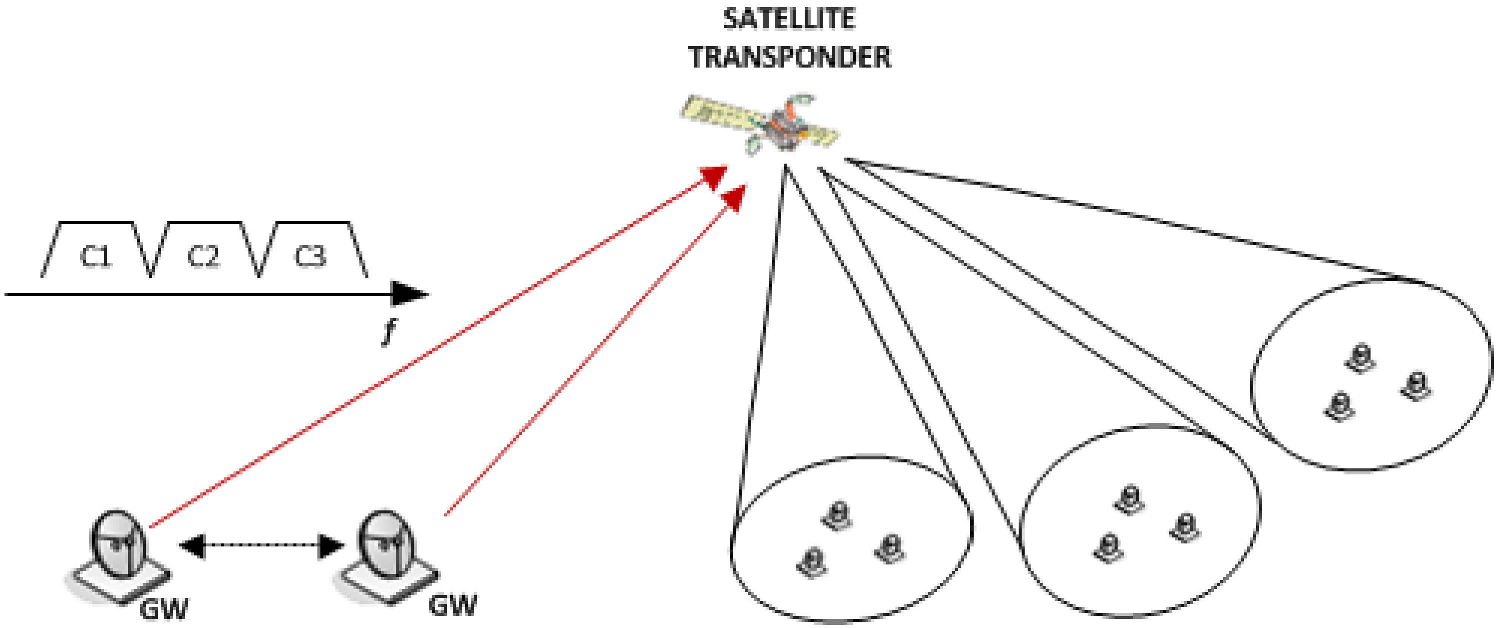
Traditional and novel approaches

- Traditional approach
  - Link budget based
    - Static and conservative
  - Does not exploit structure, additional information

- Novel approach : Use of advanced Signal processing algorithms
  - Model, identify, estimate
  - Exploit available information
  - Adapt

Study Case 1: Non-linear interference caused by Power Amplification

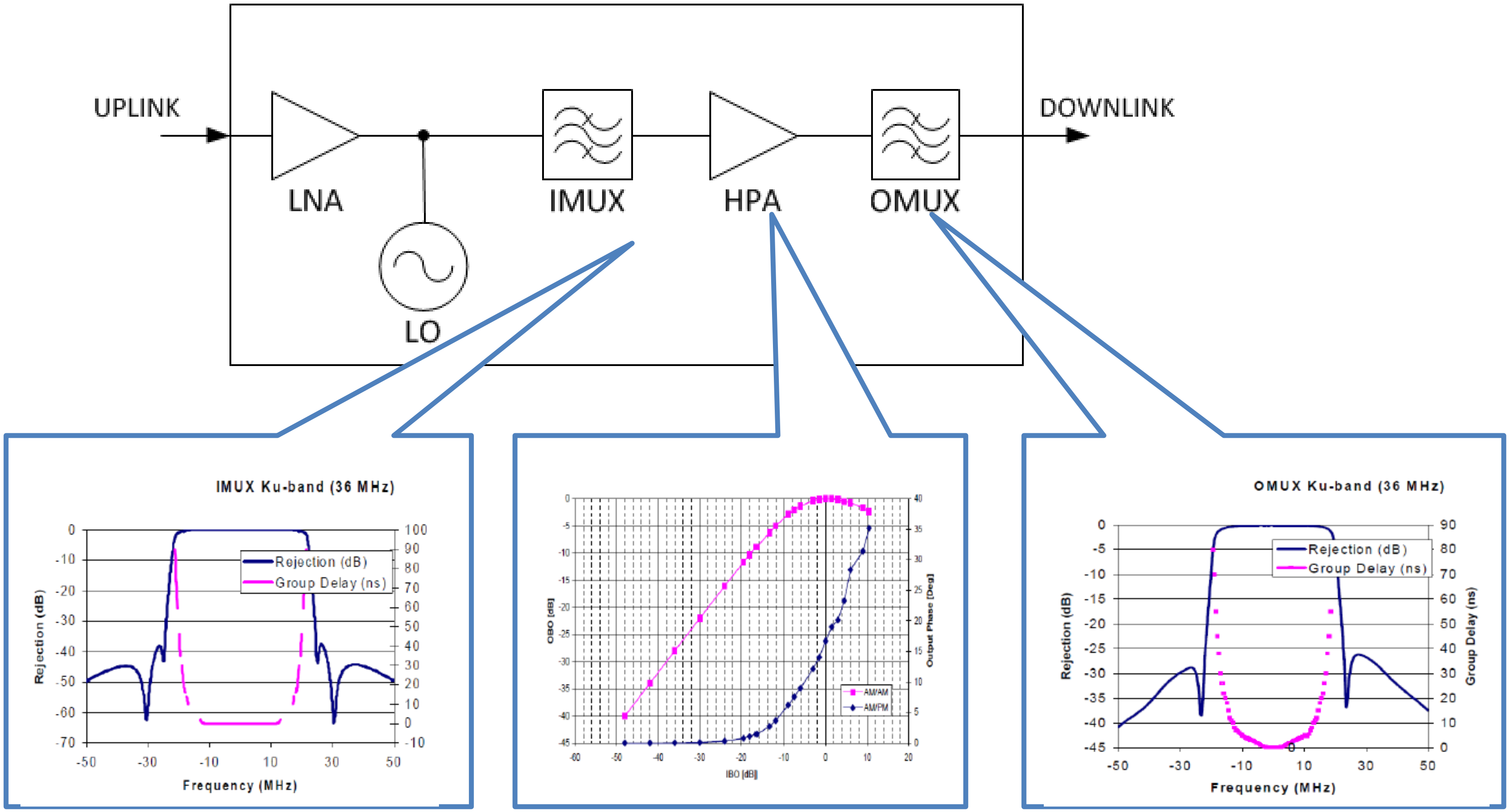
Scenario



- Multicarrier / Multi-GW Transmission:
  - Multicarrier payload:
    - Joint Filtering (MUX)
    - Joint Power amplification (HPA)

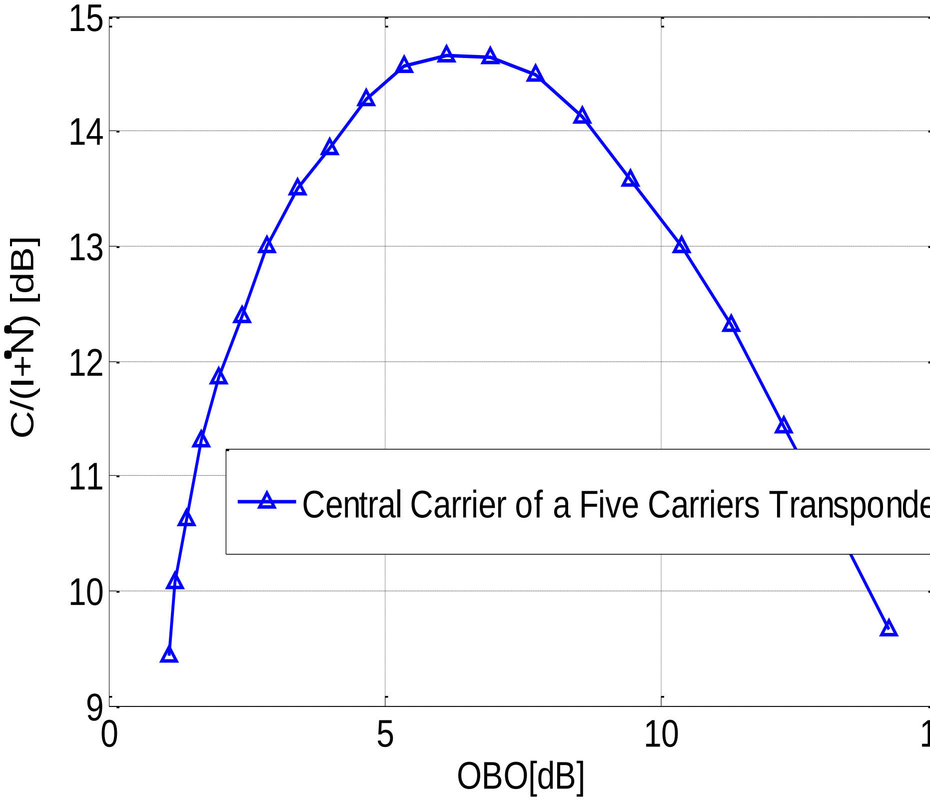
Advantages:
- Hardware saving
- Payload mass saving
- On-ground flexibility

Satellite Transponder Imperfections



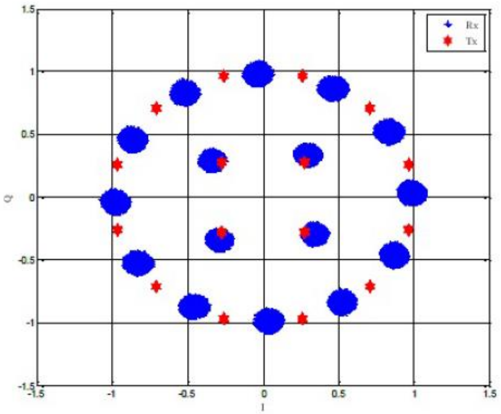
Performance Metrics and Problem Definition

- Transponder Bandwidth Utilization:
  - $S_{eff} = \frac{R}{W_T}$ [bit/s/Hz]
- On-board power efficiency:
  - $OBO = \frac{P}{P_{SAT}}$
- Spectral and Power efficiency trade-off

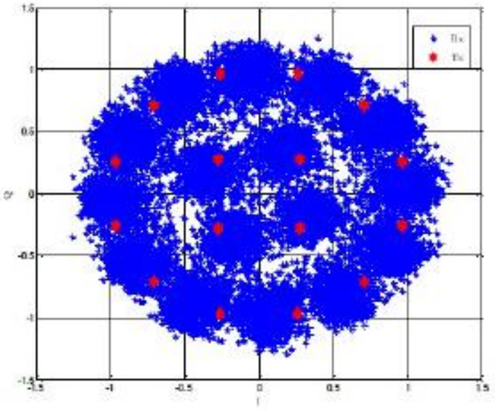


Multicarrier Non-linear Interference

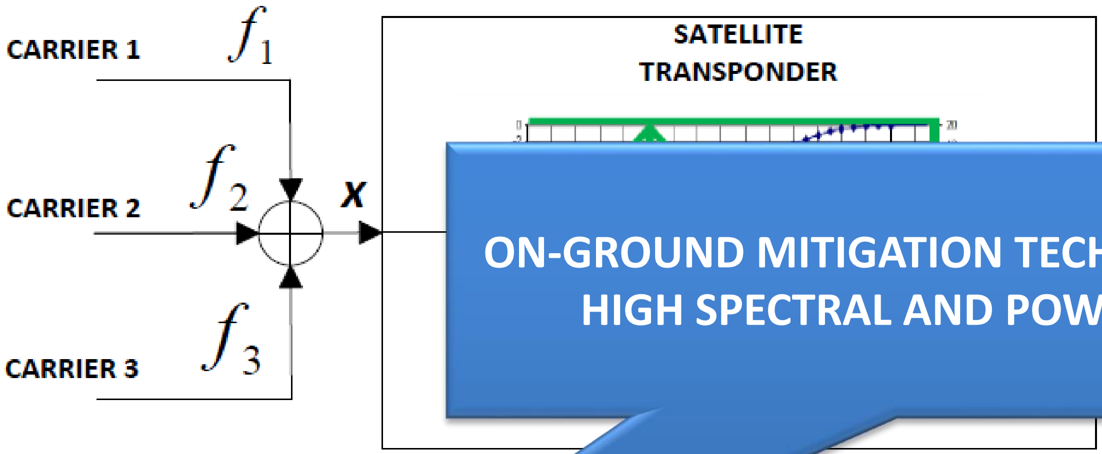
- Single Carrier Distortion
  - Warping
  - Clustering
    - Inter-Symbol Interference (ISI)



- Multiple Carrier Distortion
  - Intermodulation Products
    - Adjacent Channel Interference (ACI)



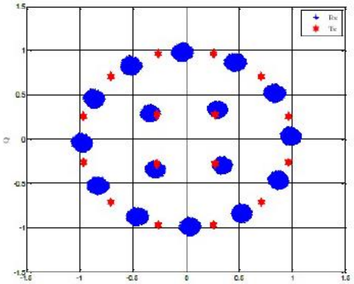
On-board Multiple Carrier Amplification



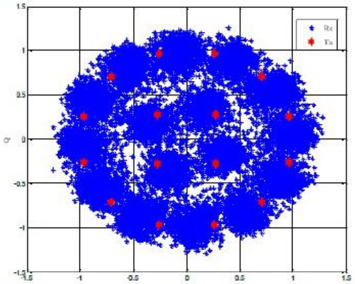
ON-GROUND MITIGATION TECHNIQUES ENABLING HIGH SPECTRAL AND POWER EFFICIENCY

- \+ Payload Hardware/Mass savi
- \+ Flexibility
- – ~~Strong ACI due to I ermodulation products~~
- – ~~Strong ISI at the transponder edge~~
- – ~~High penalty in power efficiency (OBO)~~

SINGLE CARRIER

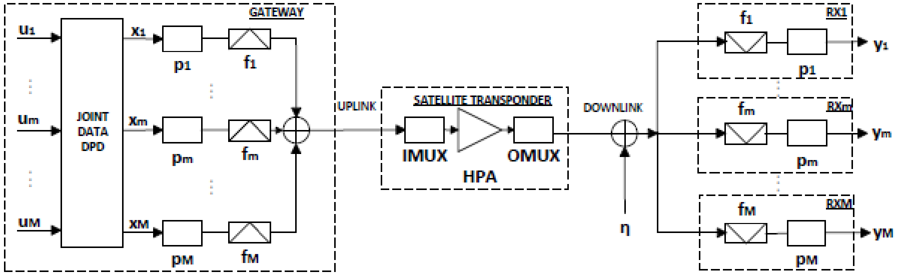


MULTIPLE CARRIER



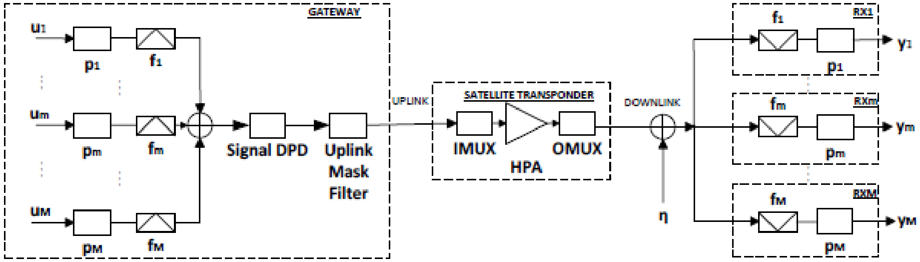
Predistortion

- Data Predistortion:
  - Operating on the modulated symbols
  - Based on polynomial or Look-Up Table
  - ISI and ACI pre-cancelling



$$x(n) = f(u(n), \cdots, u(n-K))$$

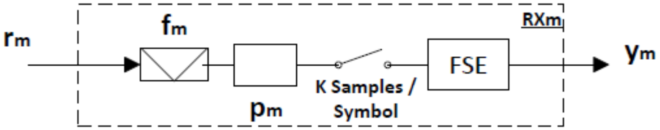
- Signal Predistortion:
  - Operating on the waveform
  - Based on polynomial or Look-Up Table
  - An attempt to invert the channel function



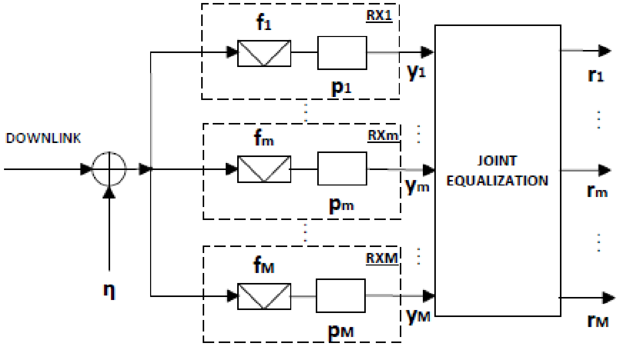
$$z(nT_o) = f(s(nT_o), s((n-1)T_o), \cdots, s((n-K)T_o))$$

Equalization

- Single Carrier Fractionally Spaced Equalization:
  - Processing multiple samples per symbol
  - Improve tolerance to sampling error
  - ISI cancellation
  - Centroids decoding to improve performance



- Multiple Carrier Equalization:
  - Joint processing at receiver
  - Based on polynomial function and filter
  - Performs an MMSE cancellation of ISI and ACI



Case Study : Data Predistortion

- Modelling the non-linear channel
  - Channel : Feeder link, Satellite transponder, downlink
  - Focus on AWGN downlink, ideal feeder link
  - Identifying the parameters of the channel
  - Mechanism for their identification
- Modelling the predistorter
- Methodology for parameter identification
  - Direct
  - Indirect
- Performance Assessment
- Reference : Roberto Piazza, M. R. Bhavani Shankar, Bjorn Ottersten, "Data Predistortion for Multicarrier Satellite Channels based on Direct Learning," *IEEE Transactions on Signal Processing*, Volume 62, Issue 22, pages 5868-5880, November 2014.

Channel Modelling for Data Predistortion

- Third order Volterra baseband model

$$y(n) = \sum_{k=0}^{K} h_p^{(1)}(k)x(n-k) + \sum_{k_1,k_2,k_3} h^{(3)}_{k_1,k_2,k_3}(k_1,k_2,k_3)x(n-k_1)x(n-k_2)x(n-k_3)^* + \eta(n)$$

Kernel
co-efficients

- Multicarrier signal

$$x(n) = \sum_{m=0}^{M-1} u_m(n)e^{-j[2\pi m(\Delta f)+\varphi_m]}$$

- Baseband model for carrier *m*

$$y_m(n) = \sum_{p}\sum_{k=0}^{K} h^{(1)}_{p,m}(k)u_p(n-k) +$$

$$+ \sum_{(p_1,p_2,p_3)\in\Omega_{m,3}} \sum_{k_j}^{K} h^{(3)}_{p_1,p_2,p_3,m}(k_1,k_2,k_3)u_{p_1}(n-k_1)u_{p_2}(n-k_2)u_{p_3}(n-k_3)^* e^{2\pi(f_{p_1}+f_{p_2}-f_{p_3}-f_m)nT_s} + \eta_m(n)$$

Channel Modelling for Data Predistortion

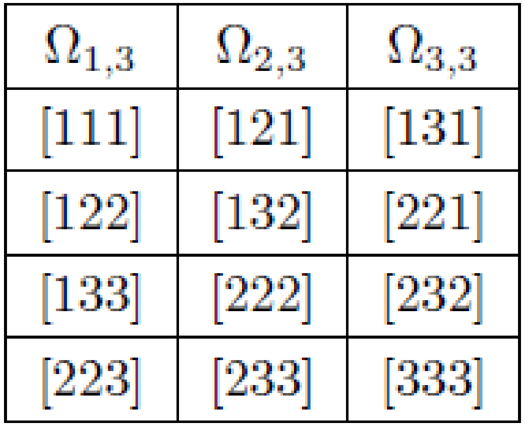
- Parameters for identification
  - Memory depth : *K*
  - Coefficients : $h_{p,m}^{(1)}(k)$, $h_{p_1,p_2,p_3,m}^{(3)}(k_1,k_2,k_3)$
- Output linear in coefficients
  - Standard Linear Least Squares
- Low complexity model : Memory polynomials

$$y_m(n) = \sum_{p}\sum_{k=0}^{K} h_{p,m}^{(1)}(k)u_p(n-k) +$$

$$+ \sum_{(p_1,p_2,p_3)\in\Omega_{m,3}} \sum_{k}^{K} h_{p_1,p_2,p_3,m}^{(3)}(k)u_{p_1}(n-k)u_{p_2}(n-k_2)u_{p_3}(n-k)^* e^{2\pi(f_{p_1}+f_{p_2}-f_{p_3}-f_m)nT_s} + \eta_m(n)$$

Intermodulation Analysis

- Third degree terms analysis:
  - $\Delta f_m \triangleq f_{p_1} + f_{p_2} - f_{p_3} - f_m$
- In-band distortion intermodulation terms
  - $\Delta f_m = 0$
- Example:
  - Three equally spaced carriers



$\Omega_{1,3}$	$\Omega_{2,3}$	$\Omega_{3,3}$
[111]	[121]	[131]
[122]	[132]	[221]
[133]	[222]	[232]
[223]	[233]	[333]

Predistortion Model

- Memory Polynomial Multicarrier Model:
  - Less complex then full Volterra
  - Linear in the parameters

$$\mathbf{u}(n) = [u_1(n), \ldots, u_M(n)]$$

$$\phi^{\{d\}}_{m_1,\ldots,m_d}(\mathbf{u}(n)) = \prod_{j=1}^{(d+1)/2} u_{m_j}(n) \prod_{j=(d+1)/2+1}^{d} u^*_{m_j}(n)$$

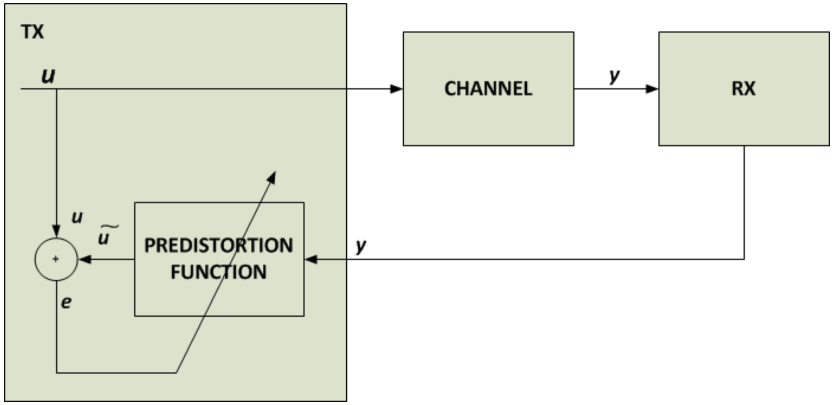
$$x_m(n) = \sum_{d=1}^{D_d} \sum_{(m_1,\ldots,m_d)\in\Omega_{m,d}} \sum_{k=0}^{K_d} w_{m_1,\ldots,m_d,m}(k)\,\phi^{\{d\}}_{m_1,\ldots,m_d}(\mathbf{u}(n-k))$$

$$\Rightarrow \boxed{x_m(n) = \boldsymbol{w}_m^T\left[\boldsymbol{\phi}_m(\boldsymbol{u}(n))\right]}$$

- Parameters Estimation $\boldsymbol{w}_m = [\{w_{m_1,\cdots,m_d,m}(k)\}]$:
  - Indirect Estimation
  - Direct Estimation

Indirect Estimation

- Idea : Pre inverse is same as post inverse
- General Characteristics:
  - The predistorter is estimated as a MMSE equalizer
  - Low complexity derivation and implementation
  - Receiver noise is in input to the predistortion during estimation



- The Optimization Problem:
  - Cost Minimization:

$$min\ E\{\left|\left|u(n)-\tilde{u}(n)\right|\right|^2\}$$

Standard Multiple Carrier Indirect Estimation Method

- Standard Indirect Estimation:
  - It can be reduced to standard LS
  - Channel Inverse Estimation:
    - Model input **z**(n)
    - Desired model output **v**(n)

$$v_m(n) \approx {\Phi_m}^T(\mathbf{z}(n))\mathbf{w}_m$$

$$\mathbf{v}_m = [v_m(1)\ldots v_m(N)]^T$$

$$\Phi_m = \begin{bmatrix} {\Phi_m}^T(\mathbf{z}(0)) \\ \vdots \\ {\Phi_m}^T(\mathbf{z}(N)) \end{bmatrix}$$

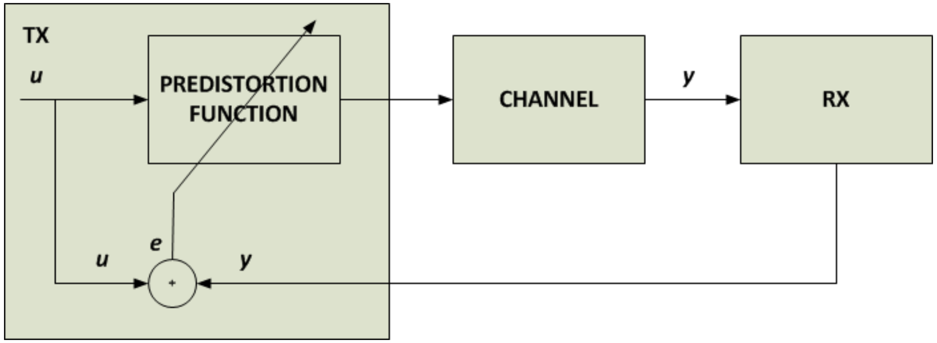
$$\boxed{\mathbf{w}_m = (\boldsymbol{\Phi}_m^H \boldsymbol{\Phi}_m)^{-1} \boldsymbol{\Phi}_m^H \mathbf{v}_m}$$

Direct Estimation

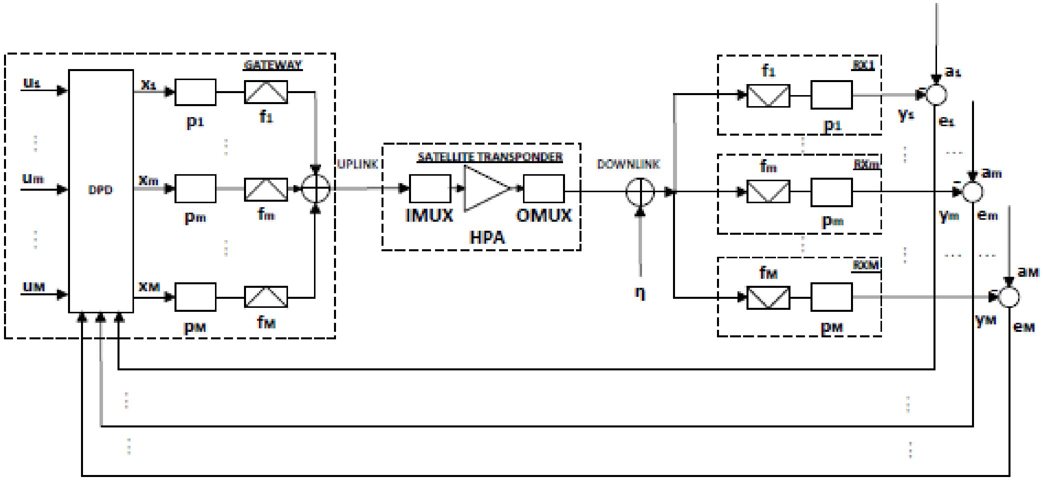
- General Characteristics
  - **Directly** targets minimization of interference at RX
  - High complexity derivation and implementation

- The Optimization problem
  - Cost minimization

$$min\ E\{||u(n) - y(n)||^2\}$$



Multiple Carrier Predistortion based on Direct Estimation/Learning



Error Definition:

$$e_m(n) = u_m(n) - y_m(n)$$

- Possible Optimization Approaches:

Individual Cost Function	Joint Cost Function
$E\{C(\mathbf{w}_m(n))\}$ with $C(\mathbf{w}_m(n)) = \lvert e_m(n)\rvert^2$	$E\{C(\mathbf{w}_1(n),\cdots,\mathbf{w}_n(n))\}$ with $C(\mathbf{w}_1(n),\cdots,\mathbf{w}_n(n)) = \sum_m \lvert e_m(n)\rvert^2$
Least Mean Squares (LMS)	LMS
Recursive Least Square (RLS)	RLS

Direct Estimation Joint RLS

- M carriers : Single optimization problem:
  - Error: $e_m(n) = u_m(n) - y_m(n)$
  - Carrier Cost function minimized w.r.t

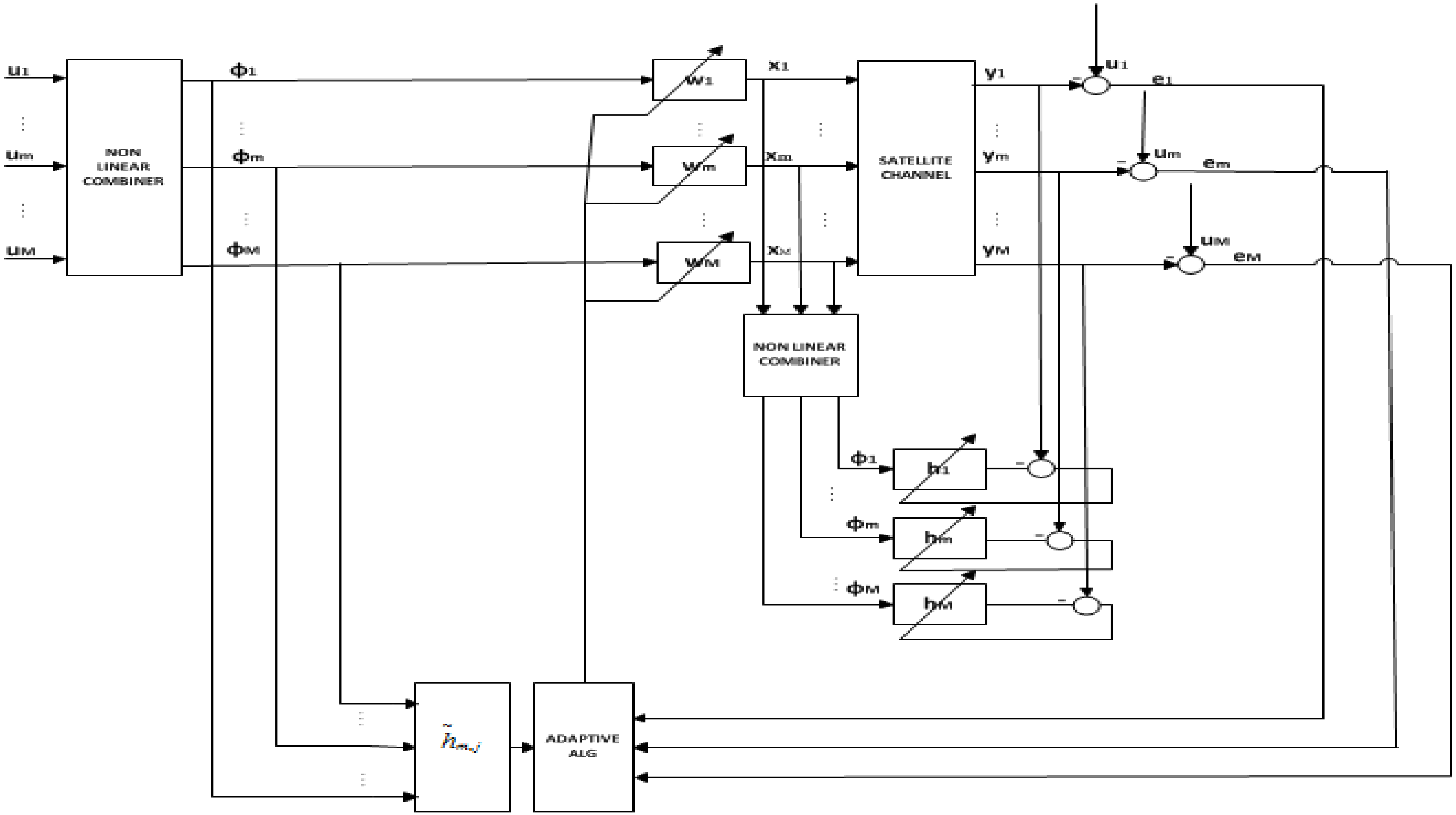
$$C(\mathbf{w}) = \sum_{j=1}^{M} \sum_{i=1}^{n} \lambda^{n-i} |e_j(i)|^2$$

    - where $\boldsymbol{w} = [\boldsymbol{w}_1^T, \ldots, \boldsymbol{w}_M^T]^T$

  - First Order Minimization

$$\frac{\partial C(\mathbf{w})}{\partial \mathbf{w}(n)} = -2 \sum_{j=1}^{M} \sum_{i=1}^{n} \lambda^{n-i} e_j(i)^* \frac{\partial y_j(i)}{\partial \mathbf{w}(n)} = 0$$

Functional Scheme of the Joint Direct Estimation Method



Step by Step Derivation

$$\begin{aligned} \boldsymbol{e}(n) &= [e_1(n), \ldots, e_M(n)]^T \\ \frac{\partial \boldsymbol{y}(i)}{\partial \boldsymbol{w}(n)} &= \left[\boxed{\frac{\partial y_1(i)}{\partial \boldsymbol{w}(n)}}, \ldots, \frac{\partial y_M(i)}{\partial \boldsymbol{w}(n)}\right] \end{aligned}$$

⇒

$$-2\sum_{i=1}^{n} \lambda^{n-i} \frac{\partial \boldsymbol{y}(i)}{\partial \boldsymbol{w}(n)} \boldsymbol{e}^*(i) = \boldsymbol{0}$$

$$\frac{\partial y_m(n)}{\partial \boldsymbol{w}(n)} = \left[\boxed{\frac{\partial y_m(n)}{\partial \boldsymbol{w}_1(n)}}^T \cdots \frac{\partial y_m(n)}{\partial \boldsymbol{w}_M(n)}^T\right]^T$$

$$\frac{\partial y_m(n)}{\partial \boldsymbol{w}_j(n)} = \sum_{l=-K}^{K} \tilde{h}_{m,j}(n,l) \boxed{\frac{\partial x_j(n-l)}{\partial \boldsymbol{w}_j(n)}}$$

$$\tilde{h}_{m,j}(n,l) = \frac{\partial y_m(n)}{\partial x_j(n-l)}$$

⇒

$$\tilde{h}_{m,j}(n,l) = \boldsymbol{h}_m^T \frac{\partial \boldsymbol{\phi}_m(\boldsymbol{x}(n))}{\partial x_j(n-l)}$$

$$\frac{\partial x_j(n-l)}{\partial \boldsymbol{w}_j(n)} \approx \boldsymbol{\phi}_m(\boldsymbol{u}(n-l))$$

⇒

$$\frac{\partial y_m(n)}{\partial \boldsymbol{w}_j(n)} = \sum_{l=-K}^{K} \tilde{h}_{m,j}(n,l)\boldsymbol{\phi}_m(\boldsymbol{u}(n-l))$$

Recursive Algorithm Definition

$$\begin{aligned}
\mathbf{R}(n)\boldsymbol{w}(n) &= \boldsymbol{r}(n), \\
\mathbf{R}(n) &= \sum_{i=1}^{n} \lambda^{n-i} \left[\frac{\partial \boldsymbol{y}(i)}{\partial \boldsymbol{w}(n)}\right]^{*} \left[\frac{\partial \boldsymbol{y}(i)}{\partial \boldsymbol{w}(n)}\right]^{T} \\
\boldsymbol{r}(n) &= \sum_{i=1}^{n} \lambda^{n-i} \left[\frac{\partial \boldsymbol{y}(i)}{\partial \boldsymbol{w}(n)}\right]^{*} \boldsymbol{u}(i)
\end{aligned}$$

$$\boldsymbol{w}(n+1) = \boldsymbol{w}(n) + \mu \mathbf{K}(n)\boldsymbol{e}(n),$$

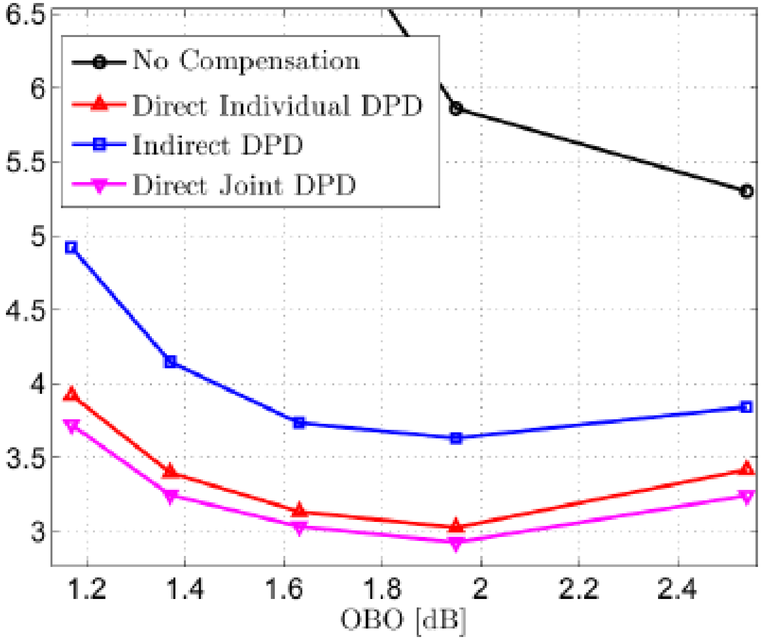
$$\mathbf{K}(n) = \lambda^{-1}\mathbf{P}(n-1)\frac{\partial \boldsymbol{y}(n)}{\partial \boldsymbol{w}(n)} \times$$

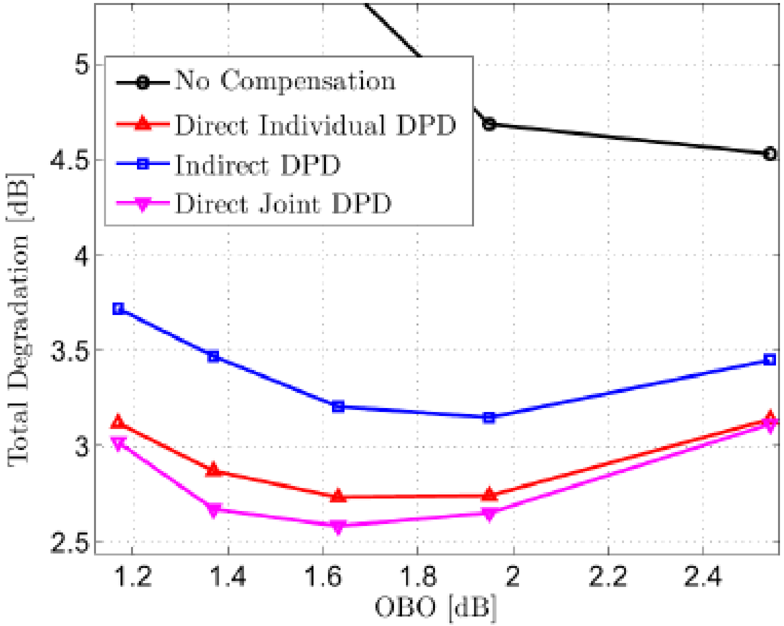
$$(\mathbf{I} + \lambda^{-1}\left[\frac{\partial \boldsymbol{y}(n)}{\partial \boldsymbol{w}(n)}\right]^{H} \mathbf{P}(n-1)\frac{\partial \boldsymbol{y}(n)}{\partial \boldsymbol{w}(n)})^{-1},$$

$$\mathbf{P}(n) = \lambda^{-1}(\mathbf{P}(n-1) - \mathbf{K}(n)\left[\frac{\partial \boldsymbol{y}(n)}{\partial \boldsymbol{w}(n)}\right]^{H} \mathbf{P}(n-1)).$$

Performance Results

- Figure of Merit: $$TD|_{@BER} = \frac{E_s}{N_0}|_{NL} - \frac{E_s}{N_0}|_{AWGN} + OBO$$

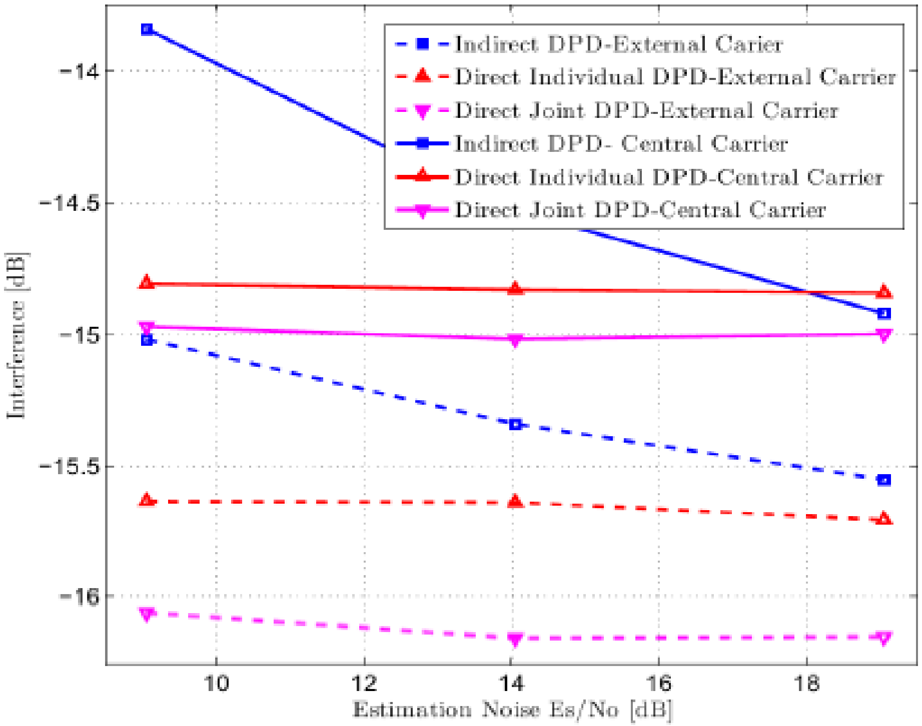




- Internal and External carrier: Three equally spaced carriers, 36 MHz transponder, Rate=8 Mbaud, Mod=16APSK, Code Rate=2/3
- Take away
  - Good Performance Gain
  - Use in future wideband systems

Sensitivity to Noise

- Direct estimation is robust to receiver noise



- Three equally spaced carriers, 36 MHz transponder, Rate=8 Mbaud, Mod=16APSK, Code Rate=2/3, OBO=1.7dB
- Take away
  - Stable adaptive algorithm

Related Works

- Successive Predistortion
  - Successively modifies the transmitted symbols to reduce multicarrier distortion
  - Exploits channel model
  - Refs: [12], [14]
- Extension to distributed predistortion
  - Different carriers uploaded by different Gateway
  - Limited data exchange between Gateways
  - Refs: [16]
- Use of non-linear equalization on the return link
  - Single carrier predistortion for users
  - Multicarrier equalization (+ decoding) at Gateway
  - Refs: [24]
- Use in Time-Frequency packing
  - Faster than Nyquist
  - Refs: [15]

Multicarrier Predistortion in Industry

- Traditional approach : high OBO, high carrier spacing
  - Multicarrier predistortion studies for improving OBO, carrier spacing
- Two European Space Agency projects
- Study Phase project: On-ground multi-carrier digital equalization/pre-distortion techniques for single or multi gateway applications
  - Partners : TZR (Germany), KTH (Sweden), Uni Lu, SES (Luxembourg)
  - Data Predistortion, Equalization
  - Completed: December 2013
  - Conclusions
    - Predistortion/ Equalization provides gains from simulations
    - Next Step: Prototyping, Satellite Demonstration

- Implementation project: Prototyping and Testing of Efficient Multicarrier Transmission for Broadband Satellite Communications
  - Partners : Newtec(Belgium), Airbus D&S (France), Uni Lu, SES (Luxembourg)
  - Over the satellite demonstration
    - Different predistortion algorithms explored
  - Ongoing, planned completion: December 2016

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Contributions by the group

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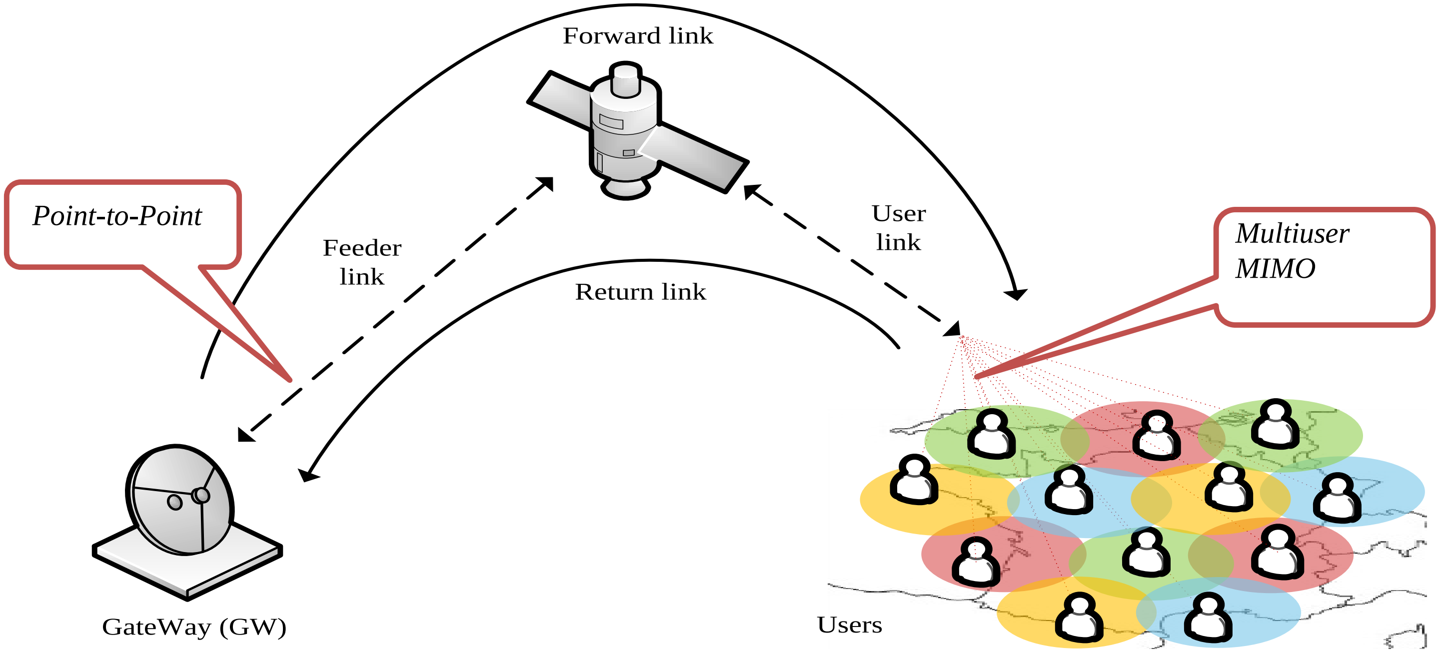
Study Case 2: Linear interference caused by Frequency Reuse

Multibeam Satellite Systems



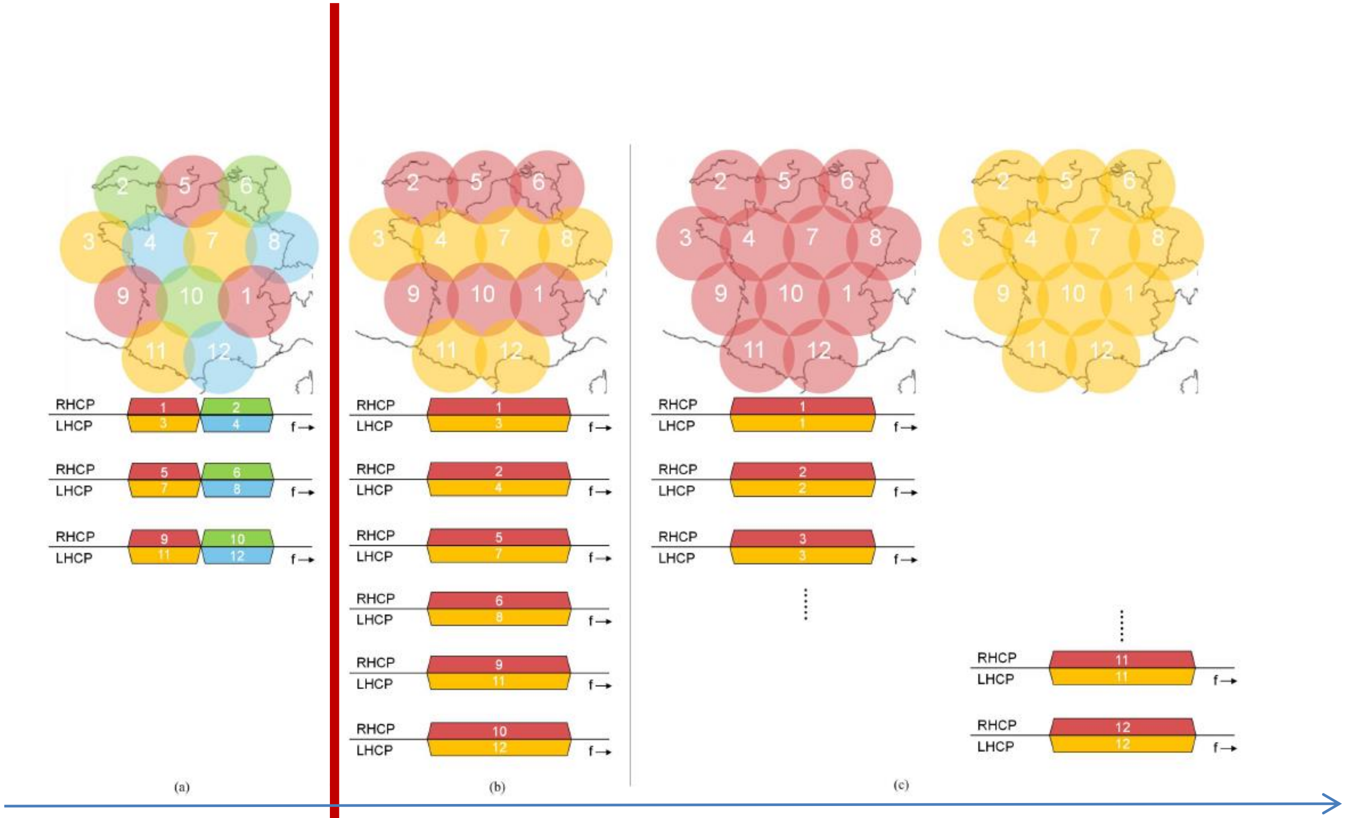
- Multiple antennas (feeds) at the satellite
  - Single antenna receivers
- User downlink : Multiuser-MIMO
  - Similar to cellular?

Multibeam Satellite Systems

- K users and N antennas
  - One antenna per beam
    - Specific radiation pattern on ground
  - Gain reduces with offset from beam centre
- $\boldsymbol{B}$: Beam Gain matrix of dimension $K \times N$
  - $\boldsymbol{B}(i,j)$: Gain from antenna j to user i
    - Dependent on user location
- Channel from antenna j to user i
  - $\boldsymbol{h}(i,j) = \boldsymbol{B}(i,j)\boxed{\hat{\boldsymbol{h}}(i,j)} \longrightarrow$ Propagation effects
  - $\boldsymbol{h}_i$: $1 \times N$ channel vector to user i
  - $\boldsymbol{H} = [\boldsymbol{h}_1^T, \boldsymbol{h}_2^T, \ldots, \boldsymbol{h}_K^T]^T$: $K \times N$ MU-MIMO channel

Aggressive Frequency Reuse

- Shannon formula: $C = f \cdot \log(1 + SINR)$
- Aggressive frequency reuse: $\uparrow f$ per user, but $\downarrow SINR$
- Can SINR be improved by processing?



Today: Viasat1, 110Gbps

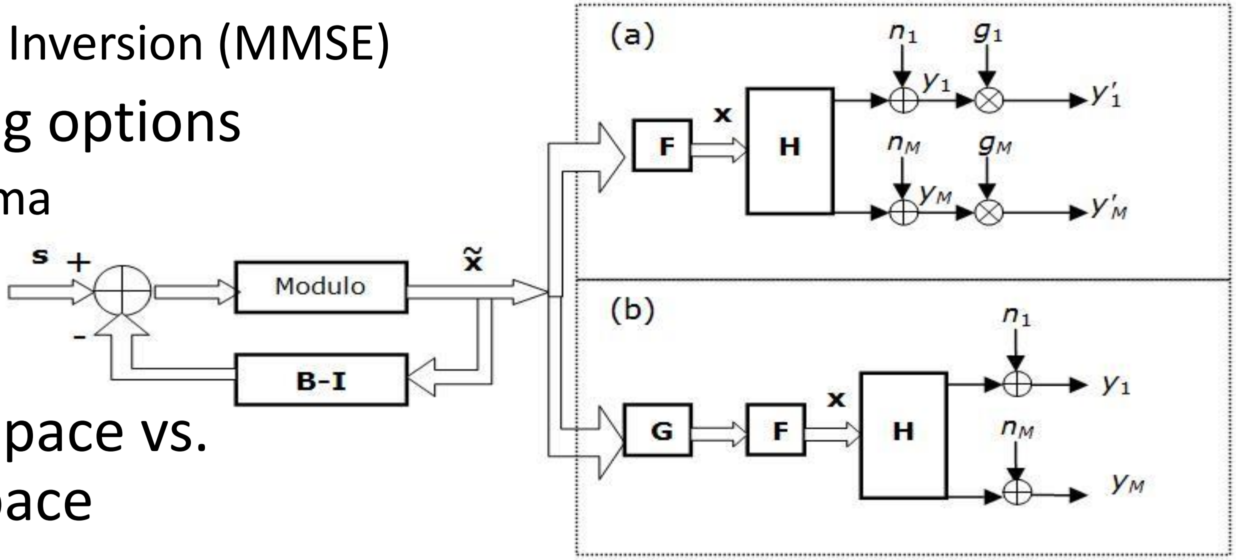
Spectrally efficient, next gen satcoms: "*Terabit Satellite: A myth or reality?*"

Precoding

- Joint encoding of co-frequency signals
  - Minimize the mutual interference between co-channel beams
- Linear Precoding options:
  - Zero-Forcing (ZF)
  - Regularized Channel Inversion (MMSE)
- Non-Linear Precoding options
  - Tomlinshon-Harashima
  - Dirty Paper Coding
- Precoding @ beam space vs. Precoding @ feed space

$$\boldsymbol{y} = \boldsymbol{H}\,\boldsymbol{W}\,\boldsymbol{s} + \boldsymbol{n}$$

$\boldsymbol{W}$: Precoder



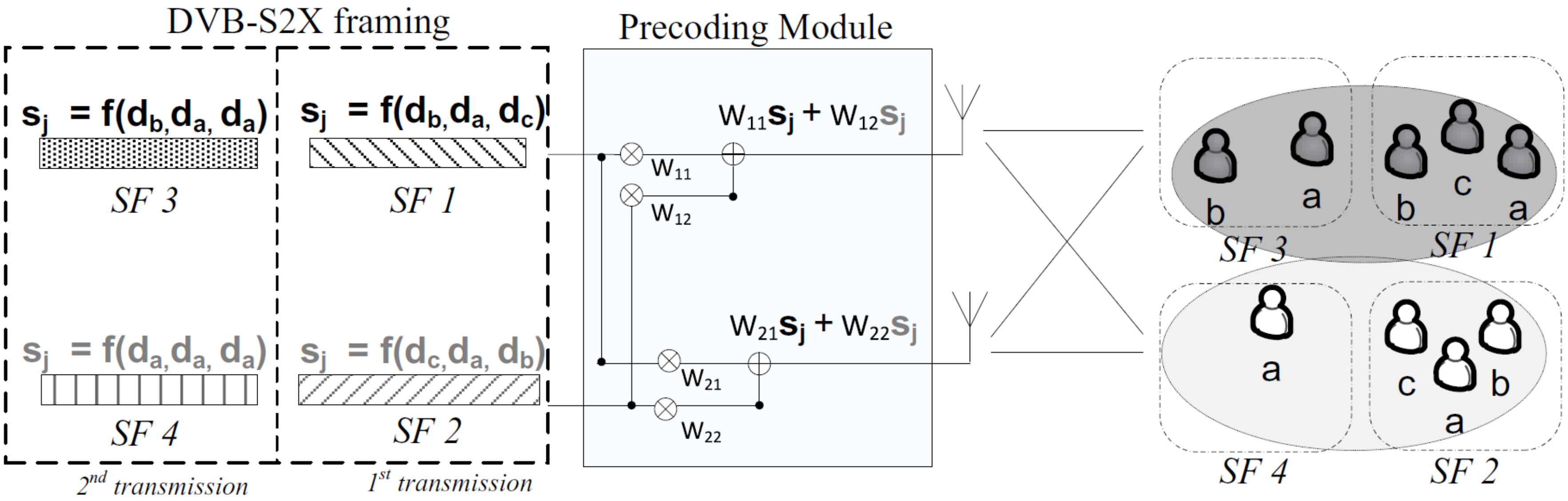
Design of Precoding Matrix

Figure of Merit	Form
SINR of user $i \in [1, K]$	$\gamma_{\mathrm{i}} = \frac{\lvert h_i^H w_i \rvert^2}{\sum_{j \neq i} \lvert h_i^H w_j \rvert^2 + N_0}$
Rate of user $i \in [1, K]$	$R_{\mathrm{i}} = \log(1 + \gamma_{\mathrm{i}})$
Total power	$P = \sum_{i=1}^{K} \lVert w_i \rVert^2$
Power at antenna $i \in [1, \mathrm{N}]$	$\phi_i = \left[\sum_{j=1}^{K} w_j \, w_j{}^H \right]_{i,i}$

Classical optimization problems

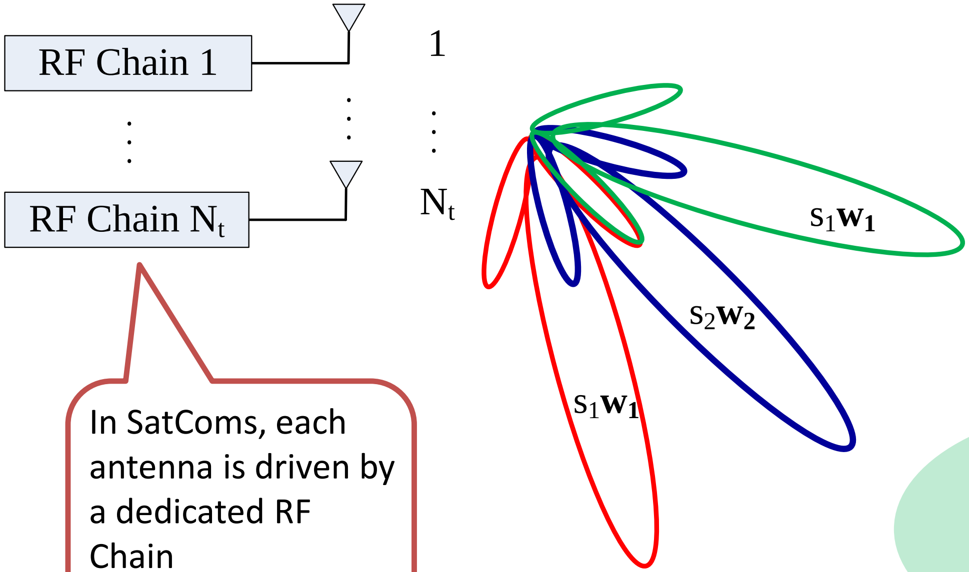
Optimization	Constraint	Remarks
$\max\min \frac{\gamma_\mathrm{i}}{\Gamma_i},$	Sum power constraint Per antenna power constraint	Max min fairness problem Feasibility problem → Bisection
$\max\min \frac{\mathrm{R_i}}{F_i}$	Sum power constraint Per antenna power constraint	Rate Balancing problem
$\min P$	SINR Constraints Per antenna power constraint	Semi-definite relaxation and Gaussian Randomization
$\max \sum R_k$	Per antenna power constraint Sum power constraint	Sum Rate maximization Sub-gradient optimization

Frame-based Precoding



- Data from multiple users multiplexed on a single FEC frame
  - Long lengths of FEC
- Difficult to have multiple precoders per frame
  - Overhead
- How to devise one precoder per frame?
  - [REF 9] posed it as PHY Multigroup, multicast

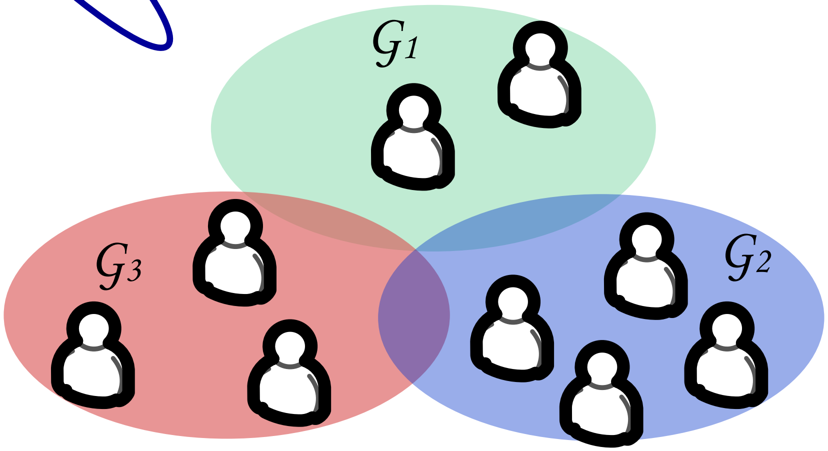
Multigroup Multicasting



In SatComs, each antenna is driven by a dedicated RF Chain

Related Problem

- PHY multicasting to multiple groups
- G groups, each group receives same info
- Formation of such groups → user scheduling



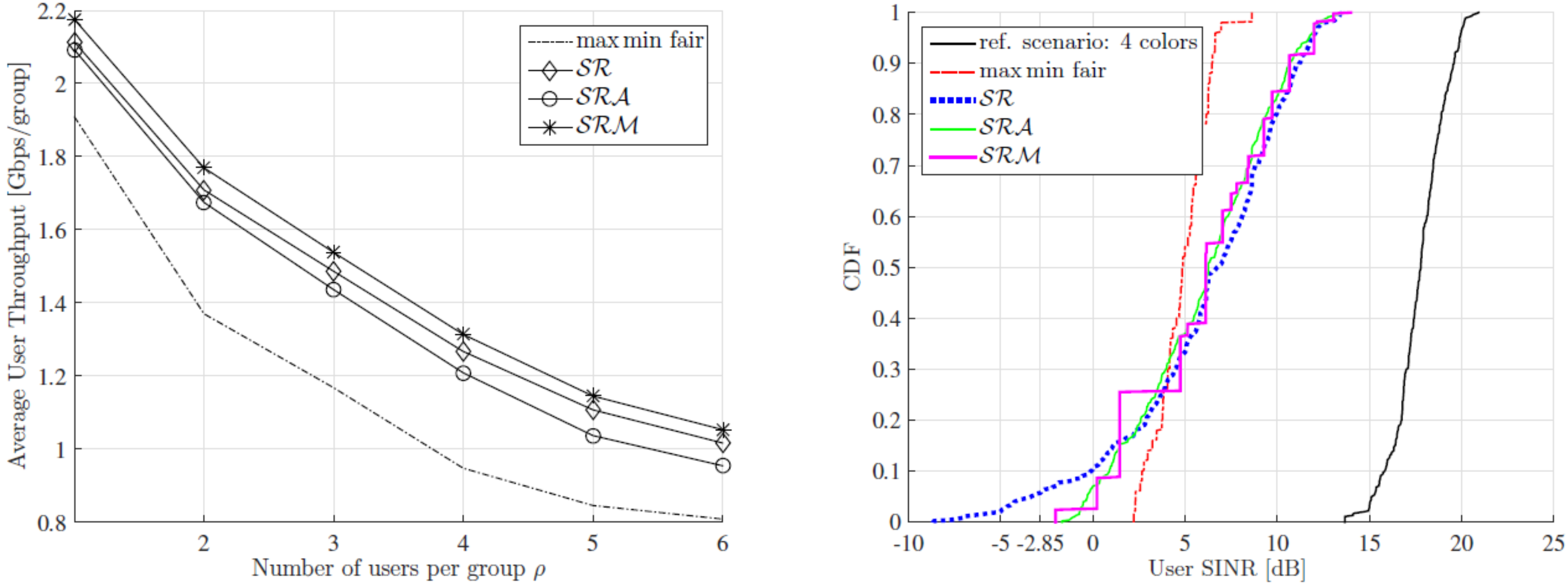
Problem Formulation

- w_l precoder for all users in group G_l
- Less precoders than users
- SINR of user $i \in G_m$

$$\gamma_i = \frac{|h_i^H w_m|^2}{\sum_{j \neq m} |h_i^H w_j|^2 + N_0}$$

- Optimization problems presented earlier can be recast
  - SDR, Gaussian randomization [REFs 7, 9]

Fairness under Per Antenna Constraint



Average user throughput versus the number of users per group(left) and SINR distribution over the coverage (right)

5 Transmit antennas, 4 users [REF 7]

SR: Sum Rate, SRA: Sum Rate with availability constraint, SRM: MODCOD constrained Sum rate with PAC

Non-convex QCQP approach

- Optimization problem

$$\begin{aligned} & min\ \sum_{m=1}^{G} ||w_m||^2 \\ & s.t.\ \ \gamma_i \geq \Gamma_i \end{aligned}$$

- NP-hard
- Recast as non-convex Quadratically Constrained Quadratic Program

$$\begin{aligned} \mathcal{P}:\ \min_{\mathbf{x} \in \mathbb{C}^N} \quad & \mathbf{x}^H \mathbf{A}_0 \mathbf{x} \\ \text{s. t.} \quad & \mathbf{x}^H \mathbf{A}_i \mathbf{x} \leq c_i, \quad \forall i \in [M], \end{aligned}$$

- Sub-optimal solution obtained after penalized reformulation [REF 13]
  - Faster and efficient than SDR

Impact on SatCom Ecosystem

- At least two European Space Agency projects
- Study Phase projects: SatNEx III, Next Generation Waveforms for improved spectral efficiency
  - Partners : Multiple universities from
  - Beamforming and precoding
  - Conclusions
    - Modelling, Identification and Estimation of parameters
    - Significant gain from simulations

- Software Demonstrator project: Precoding Demonstrator for broadband system forward links
  - Partners : DLR (German Aerospace Agency), Fraunhofer, Uni Lu, SES (Luxembourg)
  - Software demonstration of gains from precoding in a system wide environment
  - Ongoing, planned completion: December 2016

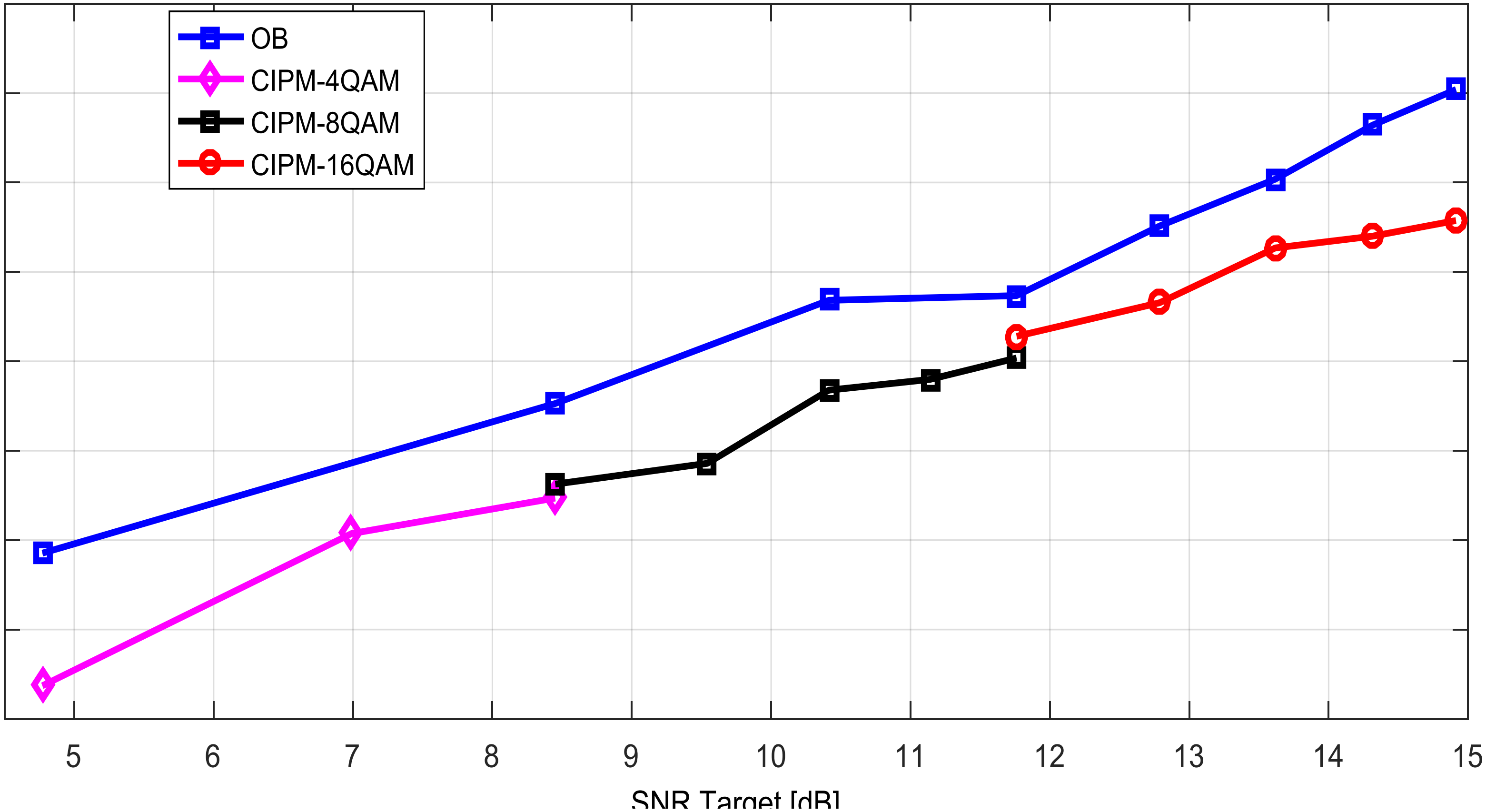
Related Work : Symbol Level Precoding

- Symbol level precoding
  - Precoding dependent on channel as well as symbols
  - [REFS 6, 8, 10, 11, 12]
- Additional degrees of freedom
  - Exploit interference
  - Higher complexity
- Constellation ς comprising symbols d_k

$$\mathbf{w}_k(d_j, \mathbf{H}, \zeta) \quad = \quad \arg \min_{\mathbf{w}_1,\dots,\mathbf{w}_K} \quad \|\sum_{k=1}^{K} \mathbf{w}_k d_k\|^2$$

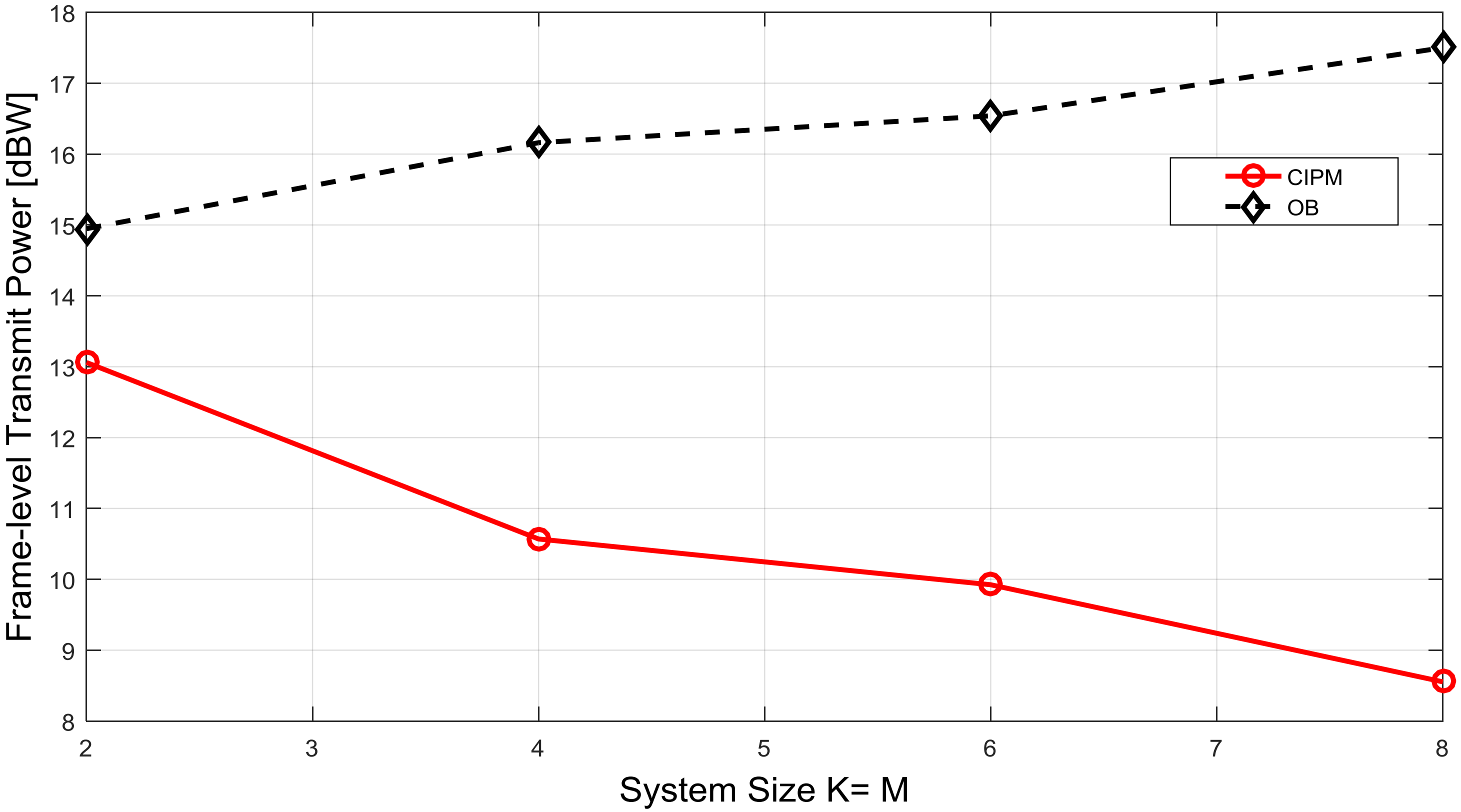
$$s.t. \quad \begin{cases} \mathcal{C}1 : \angle(\mathbf{h}_j \sum_{k=1}^{K} \mathbf{w}_k d_k) = \angle(d_j), \forall j \in K \\ \mathcal{C}2 : \|\mathbf{h}_j \sum_{k=1}^{K} \mathbf{w}_k d_k\|^2 \geq \sigma^2 \zeta_j \quad , \forall j \in K \end{cases}$$

Symbol Level Precoding : Representative Result 2 antennas, 2 users



CIPM: Symbol level precoding
OB: Optimal unicast channel

Symbol Level Precoding : Representative Result (16 QAM, target SNR 11.76 dB)



CIPM: Symbol level precoding
OB: Optimal unicast channel

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Contribution from the group

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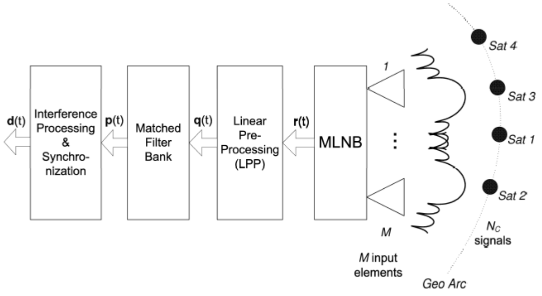
Other Transceiver techniques

Transmission and Reception Technologies

- Interference detection and localization
- Multi-user detection
- Multi-input, multi-output systems
- Precoding + Predistortion



Resource Allocation for Cognitive Satellite Communications

Thanks to SnT Team Members: E. Lagunas, S.K. Sharma, S. Chatzinotas and B. Ottersten

Presenter: Sina Maleki
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Interdisciplinary Centre for Security, Reliability and Trust (SnT)
University of Luxembourg

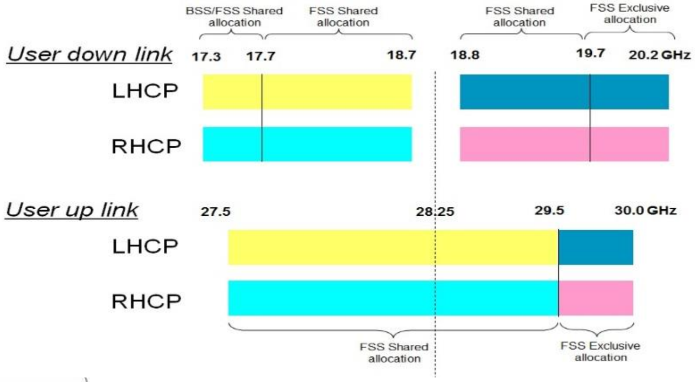
Recap of Motivation

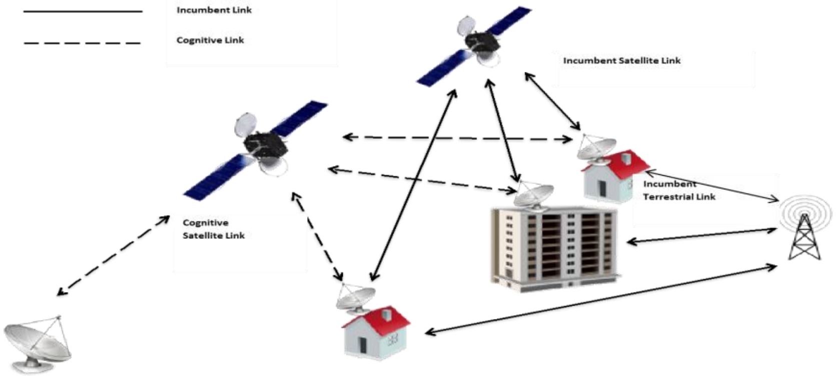
- Why Cognitive Satellite Communication in Ka Band?
  - The satellite communications data traffic is increasing
    - Access to broadband services above 100 Mb/s by 2020, at least 50% of households in Europe.
    - Access to at least 30 Mb/s data rate By 2020, the whole population in Europe.
    - 5 to 10 million households will choose satellite broadband communication by 2020.
  - Ka band is the appropriate spectrum for high data rate services.
  - Challenge: only 500 MHz of exclusive bandwidth for FSS!
  - Possible solution: Cognitive Radio!

An example of satellite broadband systems. Courtesy: SES ASTRA2Connect

Recap of Scenarios

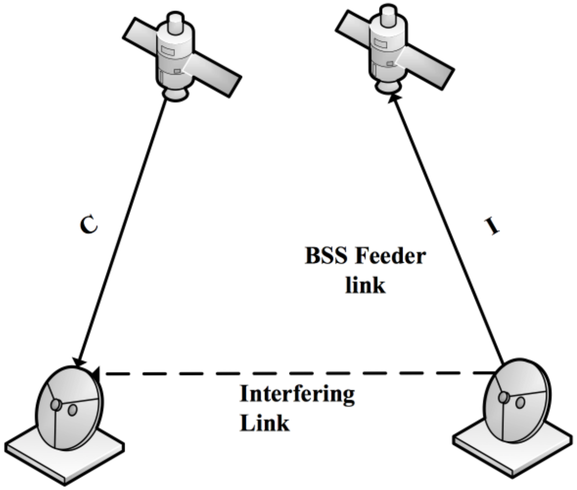
- The most appropriate scenarios in terms of technology, regulations, standardization, and market assessments:
  - Scenario A: cognitive FSS downlink communication in the band 17.3-17.7 GHz where incumbent users are BSS feeder links.
  - Scenario B: cognitive FSS downlink communication in the band 17.7-19.7 GHz where the incumbent users are FS microwave links (terrestrial).
  - Scenario C: Cognitive FSS uplink communication in the band 27.5-19.5 GHz where the incumbent users are FS microwave links (terrestrial).





Scenario A

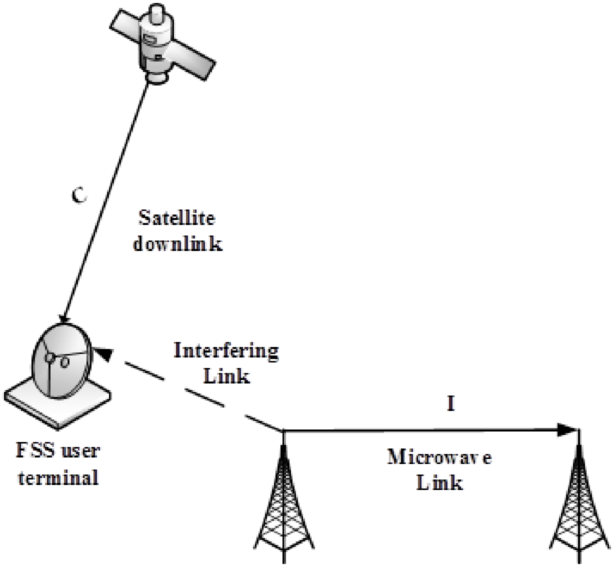
- 17.3-17.7 GHz
- Incumbent users: BSS feeder links



- No interference from the cognitive FSS to the incumbent BSS.
- FSS terminals may receive interference from BSS feeders.
- Cognitive downlink communication is possible provided that the received interference is not harmful.
- Challenge: BSS interference needs to be measured!

Scenario B

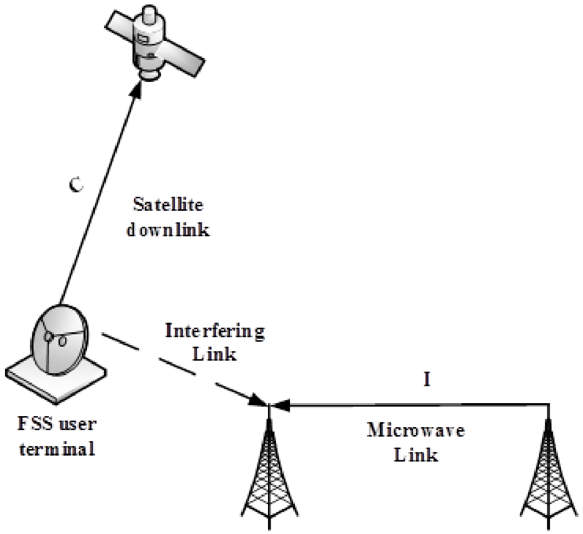
- 17.7-19.7 GHz
- Incumbent users: FS microwave links



- No interference from the cognitive FSS transmitter to the incumbent FS receiver due to power flux density restrictions.
- FSS terminals may receive interference from FS links.
- Cognitive downlink communication is possible provided that the received interference is not harmful.
- Challenge: FS interference needs to be measured!

Scenario C

- 27.5-29.5 GHz
- Incumbent users: FS microwave links



- Cognitive uplink communication is possible provided that the operation of FSS does not interfere with FS.
- FSS terminals may interfere with the FS links: multiple interferers.
- In case of no database, the receivers need to be detected.
- Challenge: FSS interference towards FS links needs to be mitigated by cognitive radio techniques.

Selected Group Outputs

[1] COgnitive Radio for SATellite Communications http://www.ict-corasat.eu/

[2] **E. Lagunas, S.K. Sharma, S. Maleki, S. Chatzinotas**, J. Grotz, J. Krause and **B. Ottersten**, “Resource Allocation for Cognitive Satellite Uplink and Fixed-Service Terrestrial Coexistence in Ka-band,” CROWNCOM, Apr. 2015.

[3] **E. Lagunas, S.K. Sharma, S. Maleki, S. Chatzinotas, and B. Ottersten**, “Power Control for Satellite Uplink and Terrestrial Fixed-Service Coexistence in Ka-band,” IEEE Vehicular Technology Conference (VTCFall), Sep. 2015.

[4] **S. K. Sharma, S. Maleki, S. Chatzinotas**, J. Grotz, J. Krause and **B. Ottersten**, "Joint Carrier Allocation and Beamforming for cognitive SatComs in Ka-band (17.3–18.1 GHz)," 2015 IEEE International Conference on Communications (ICC), London, 2015, pp. 873-878.

[5] **E. Lagunas, S.K. Sharma, S. Maleki, S. Chatzinotas, B. Ottersten**, “Resource Allocation for Cognitive Satellite Communications with Incumbent Terrestrial Networks”, IEEE Transactions on Cognitive Communications and Networking, 2015.

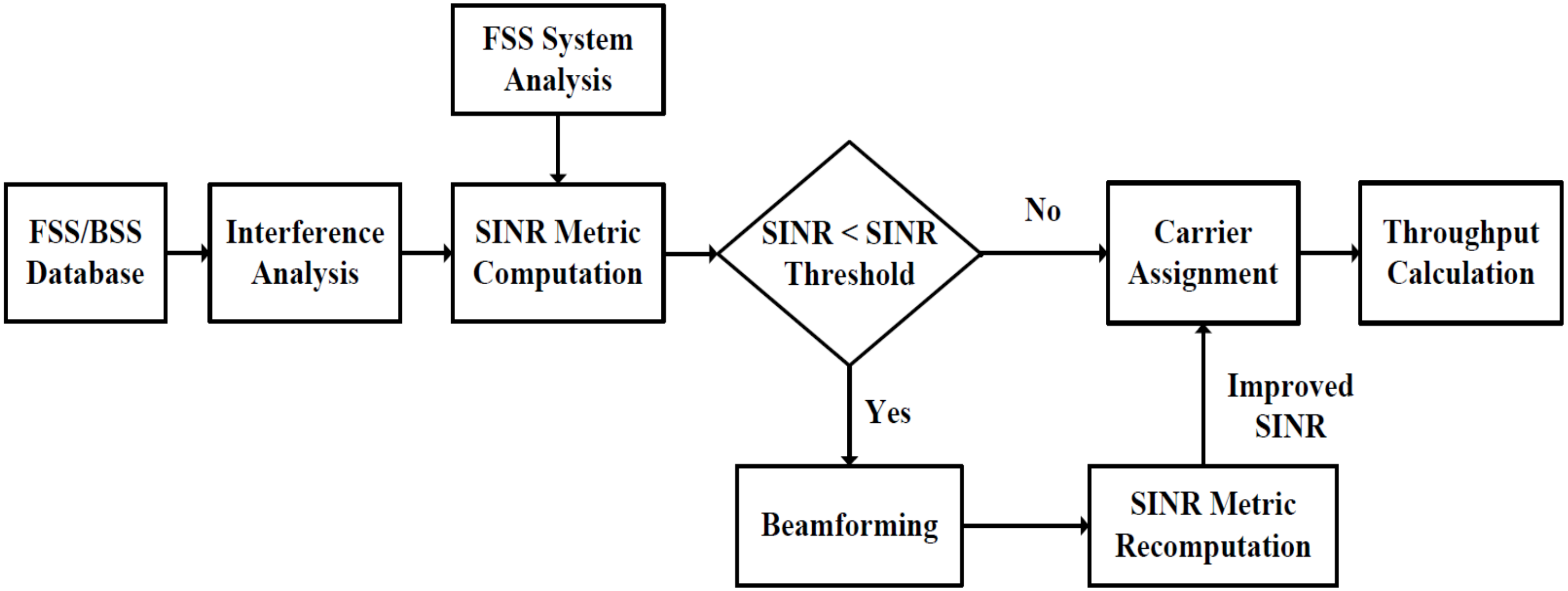
[6] **S. K. Sharma, E. Lagunas, S. Maleki, S. Chatzinotas**, J. Grotz, J. Krause and **B. Ottersten,** “Resource allocation for cognitive Satellite Communications in Ka-band (17.7–19.7 GHz)”, ICC Workshops 2015.

[7] **S. Maleki, S. Chatzinotas, B. Evans, K. Liolis, J. Grotz, A. Vanelli-Coralli, N. Chuberre**, “Cognitive spectrum utilization in Ka band multibeam satellite communications”, IEEE Communications Magazine 2015.

Joint Carrier Allocation and Beamforming for Cognitive SatComs in Ka-band: Scenario A

Reference: ICC 2015

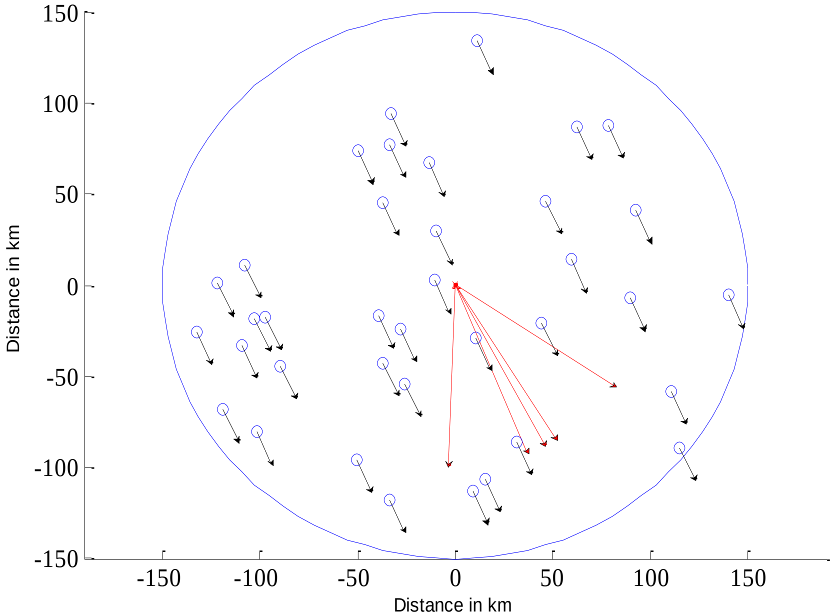
Proposed Cognitive Exploitation Framework



- ❑ Underlay CR approach
  - Carrier Assignment (**CA**) and Beamforming (**BF**)

Representative Beam

- ☐ 150 Km radius with its center located in **Betzdorf, Luxembourg** (49.6833° N and 6.35° E)



- **Black** lines: **azimuthal directions of the FSS terminals** with respect to the GEO FSS satellite located at 25 ° E
- **Red** lines: **azimuthal directions of the BSS feeder links** from Betzdorf, Luxembourg (49.6833° N and 6.35° E)
- **21 BSS feeder links** (carriers) towards **five different satellites** (Thanks to SES, Luxembourg)

Interference Analysis

- Received signal level at the *m*th FSS terminal from link analysis of the FSS system

$$P_{r,m} = P_{\text{tfss}} G_{\text{ter}}(0) F L_{\text{fss}}(m) B(m,k)$$

$$B(m,k) = G_{\max}\left(\frac{J_1(u(m,k))}{2u(m,k)} + 36\frac{J_3(u(m,k))}{u(m,k)^3}\right)^2$$

- Interference level received at the *m*th FSS terminal

$$I_{r,m}(m) = P_{\text{tbss}} G_{\text{tbss}}(\theta_{\text{off1}}) G_T(\theta_{\text{off2}}) F L_{\text{bss-fss}}(m)$$

- SINR at the FSS terminal due to a single BSS interfering feeder link (carrier)

$$SINR = \frac{P_{\text{tfss}} G_{\text{ter}}(0) B(m,k) (\frac{c}{4\pi D(m) f_c})^2}{P_{\text{tbss}} G_{\text{tbss}}(\theta_{\text{off1}}) G_{\text{ter}}(\theta_{\text{off2}}) \left(\frac{c}{4\pi d(m) f_c}\right)^2 + I_{\text{co}} + N_0}$$

- **Carrier bandwidth** for both victim FSS and interfering BSS links are assumed to be **36 MHz**.
- **Aggregate interference** calculation: summing all the contributions from interfering BSS carriers

Applied Techniques: Beamforming

- ❑ A **receive beamformer** at the FSS terminal in order to mitigate interference coming from BSS feeder links
  - **DoA** information calculated from available database
- ❑ Important aspects of **beamforming design**
  - Array geometry or antenna structure
  - Weight design
- ❑ **Antenna Structure**
  - A terminal reflector based feed array (**Multiple Input LNB (MLNB)** set up) system with 75 cm reflector diameter (f/D=0.6)
  - 3 feeds that are aligned along the feed array horizontal line
    - Out of these 3 LNBs, two side feeds are offset at 2 degrees (1.91 cm) from the centered beam and are symmetrical.
  - **Array response vector** calculated using **GRASP** software
- ❑ **BF Weight Design**
  - LCMV beamformer $\mathbf{w} = \mathbf{R}_y^{-1}\mathbf{C}(\mathbf{C}^H\mathbf{R}_y^{-1}\mathbf{C})^{-1}\mathbf{g}$
    - BF applied **only in the FSS terminals which receive harmful interference** (below a certain threshold defined based on **modcod adaptation** of the terminal)

Applied Techniques: Carrier Allocation

- ☐ **Carrier assignment** matrix

$$\mathbf{A} = \begin{bmatrix} a_{11} & \dots & a_{1N} \\ \vdots & \ddots & \vdots \\ a_{M1} & \dots & a_{MN} \end{bmatrix} \qquad \begin{array}{c} a_{ij} \in \{0,1\} \\ \sum_{i=1}^{M} a_{ij} = 1 \end{array}$$

- ☐ **SINR** matrix

$$\mathbf{SINR} = \begin{bmatrix} \mathrm{SINR}_{11} & \dots & \mathrm{SINR}_{1N} \\ \vdots & \ddots & \vdots \\ \mathrm{SINR}_{M1} & \dots & \mathrm{SINR}_{MN} \end{bmatrix}$$

- ☐ **CA problem** to maximize the overall throughput of the system

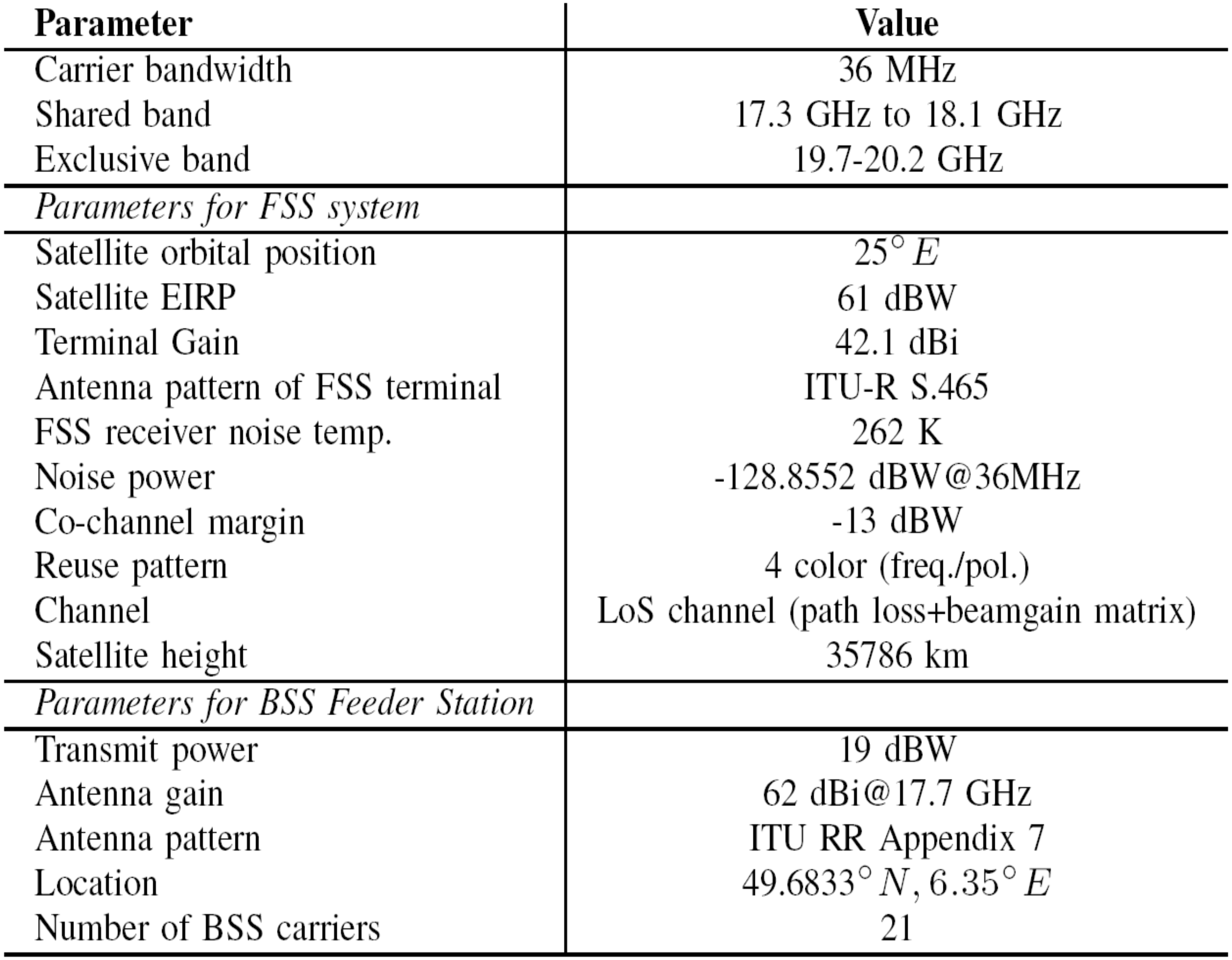
$$\max_{\mathbf{A}} ||\,\mathrm{vec}(\mathbf{A} \odot \mathbf{R}(\mathbf{SINR}))||_1$$
$$\text{subject to} \;\; ||\mathbf{A}_j||_1 = 1,$$

- ☐ Hungarian Method

☐ H. W. Kuhn, “**The Hungarian method for the assignment problem**,” *Naval Research Logistics Quarterly*, vol. 2, pp. 83–97, 1955.

Numerical Results

Simulation and link budget parameters

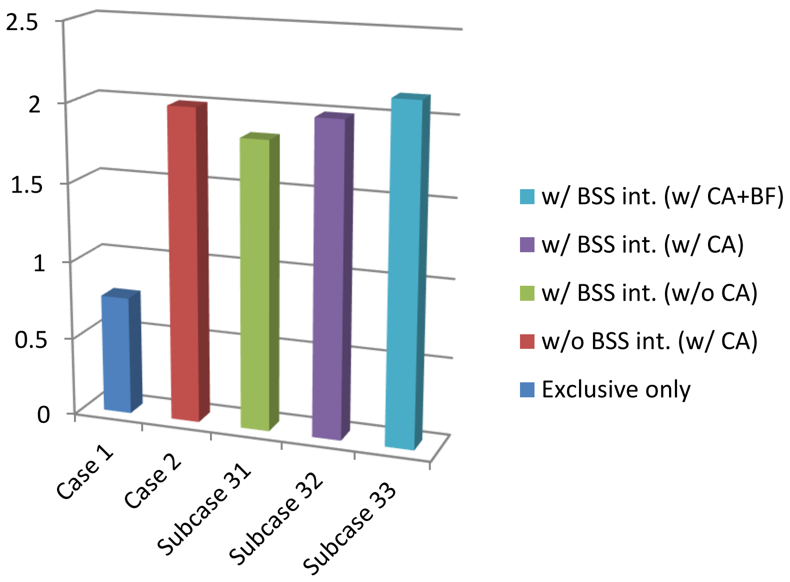


Parameter	**Value**
Carrier bandwidth	36 MHz
Shared band	17.3 GHz to 18.1 GHz
Exclusive band	19.7-20.2 GHz
Parameters for FSS system	
Satellite orbital position	$25^\circ E$
Satellite EIRP	61 dBW
Terminal Gain	42.1 dBi
Antenna pattern of FSS terminal	ITU-R S.465
FSS receiver noise temp.	262 K
Noise power	-128.8552 dBW@36MHz
Co-channel margin	-13 dBW
Reuse pattern	4 color (freq./pol.)
Channel	LoS channel (path loss+beamgain matrix)
Satellite height	35786 km
Parameters for BSS Feeder Station	
Transmit power	19 dBW
Antenna gain	62 dBi@17.7 GHz
Antenna pattern	ITU RR Appendix 7
Location	$49.6833^\circ N, 6.35^\circ E$
Number of BSS carriers	21

Numerical Results

Per beam throughput comparison of various cases

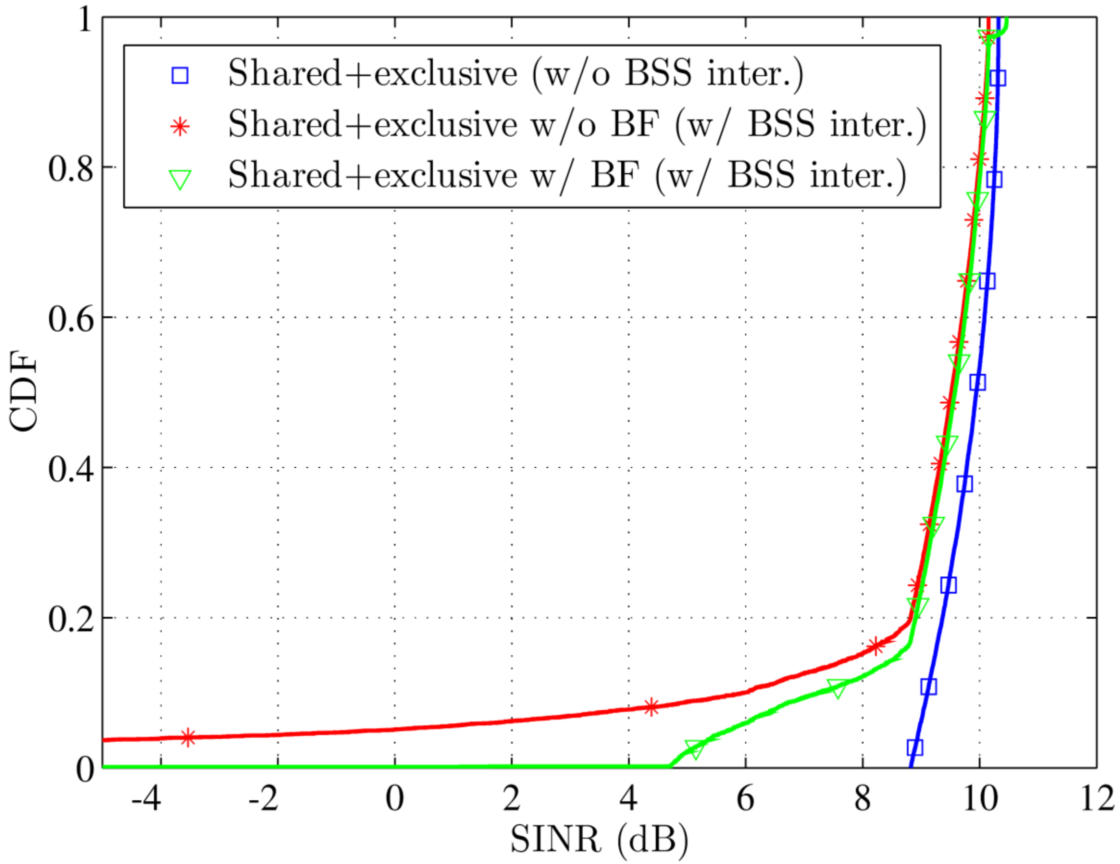
Cases	Value (Gbps)
Exclusive only w/ CA (**Case 1**)	0.761
Shared plus Exclusive w/o BSS int. w/ CA (**Case 2**)	2.0006
Shared plus Exclusive w/ BSS int. w/o CA (**Subcase 31**)	1.8357
Shared plus Exclusive w/ BSS int. w/ CA (**Subcase 32**)	1.9916
Shared plus Exclusive w/ BSS int. w/ CA+BF (**Subcase 33**)	2.1388
Comparison of cases	**Improvement (%)**
Improvement of **Subcase 32** over **Subcase 31**	8.49 %
Improvement of **Subcase 32** over **Case 1**	161.70 %
Improvement of **Subcase 33** over **Case 1**	181.05 %
Improvement due to **BF** w. r. t. **Case 1**	19.35 %



- ❑ Case 1: **exclusive only**
  - Conventional system without the use of shared carriers.
- ❑ Case 2: **shared plus exclusive** without BSS interference
  - This case does not exist in practice but considered for the comparison purpose.
- ❑ Case 3: Shared plus Exclusive with BSS interference
  - FSS systems share 17.3 – 18.1 GHz band, primarily allocated to the BSS system.

Numerical Results

CDF plots of SINR distribution with and without beamforming

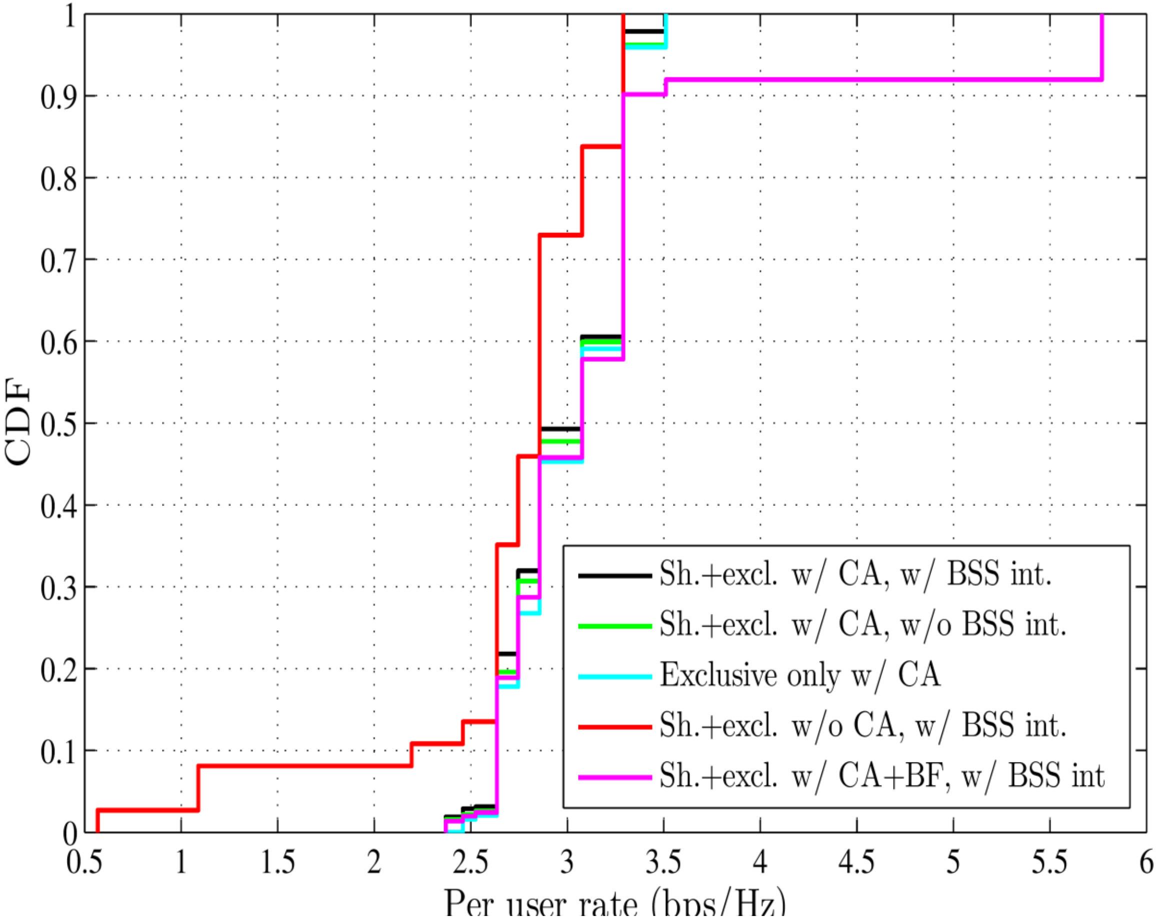


❑ Main Observations

- **SINR distribution degrades** in the presence of the BSS interference.
- In the presence of BSS interference, **almost 10 % users have SINR less than 6 dB** and about **5 % users have SINR less than 0 dB.**
- Beam availability **significantly improves** while employing the BF.

Numerical Results

CDF plots of per user rate for different cases



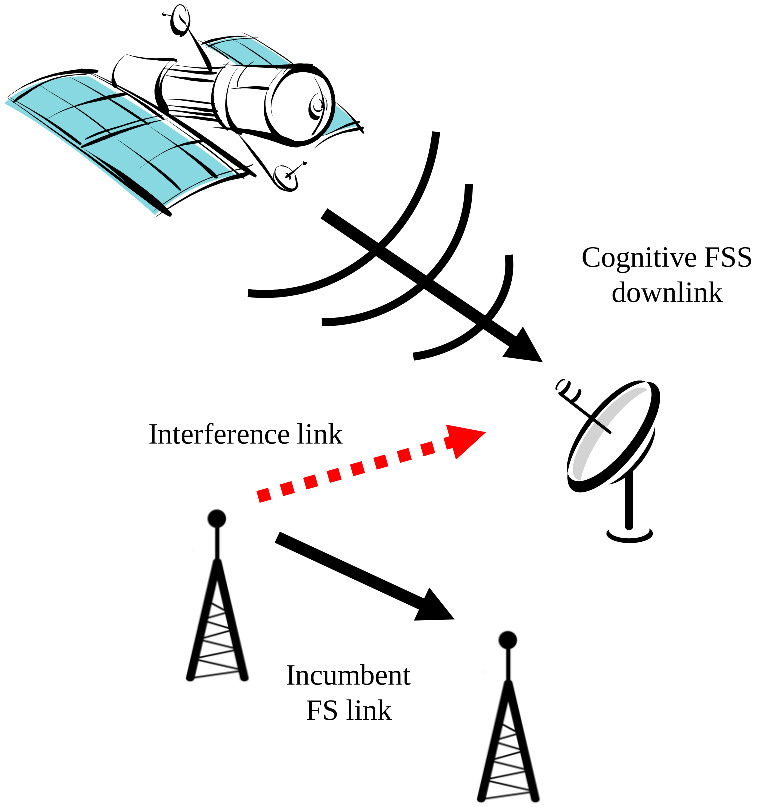
❑ Main Observations

- By employing CA, **beam availability w/ BSS interference approaches the availability** that would be obtained **w/o BSS interference**.
- The **minimum rate** increases from **0.567 to 2.37 bps/Hz** while employing CA scheme.
- BF approach provides **more than 3.5 bps/Hz to almost 8 % users** i.e., it allows these users to use **higher modcod** than in the other cases.

Resource Allocation for Cognitive Satellite Communications in Ka-band: Scenario B

References: ICC 2015, TCCN 2015.

Scenario and Problem Description (Recap)



- ☐ **Spectral coexistence** of FSS downlink with FS microwave links in **17.7–19.7 GHz**
  - FS microwave link (incumbent)
  - GEO FSS downlink (cognitive)
- ☐ Interference **from cognitive satellite to FS receivers is negligible** due to the limitation in the maximum EIRP density of current Ka band satellite systems
- ☐ **Main interfering link**: from FS Tx to the cognitive FSS terminal

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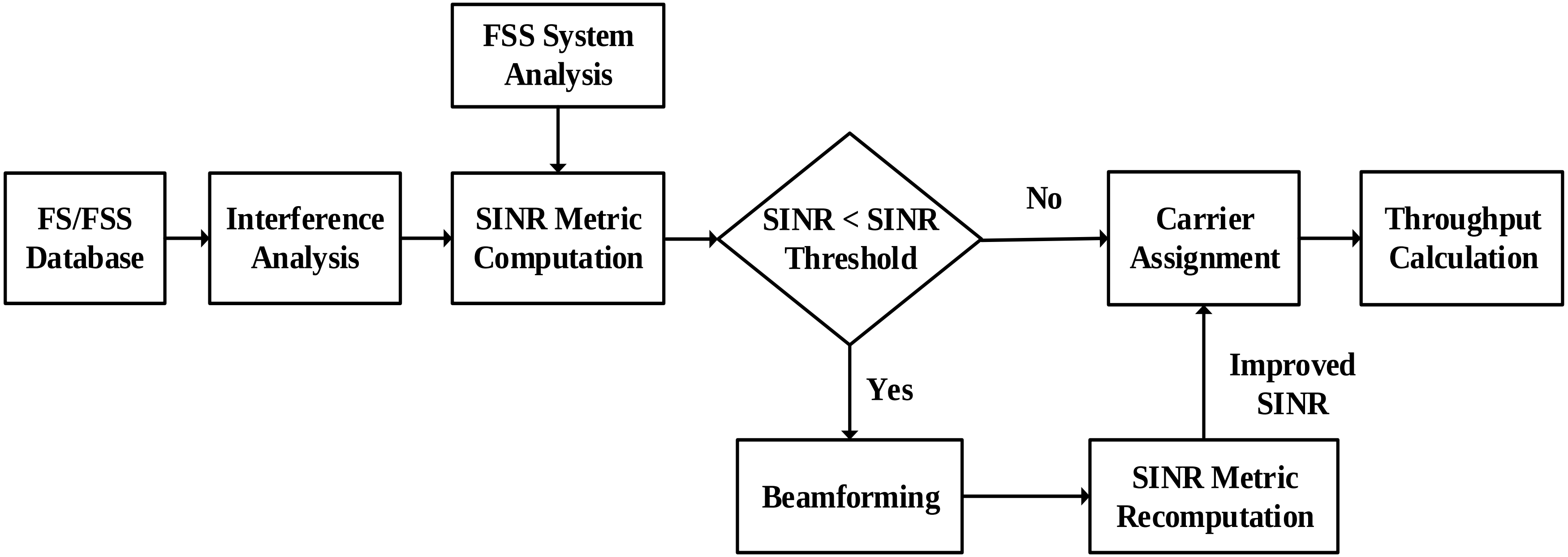
- ☐ K. Liolis, *et al.*, "**Cognitive radio scenarios for satellite communications: The CoRaSat approach**," in Proc. FUNMS, July 2013, pp.1-10.
- ☐ ITU, "Radio Regulations", ITU-R, Article 21, 2004.

Cognitive Exploitation Framework



- ☐ Underlay CR approach
  - Carrier Assignment (**CA**) and Beamforming (**BF**)

Interference Analysis

- *L* FSS terminals and *N* FS stations

$$P_{r,m} = P_{\text{tfss}} G_{\text{ter}}(0) F L_{\text{fss}}(m) B(m,k)$$

- **Aggregate interference** from *N* FS microwave stations received at the *l*th FSS terminal at the frequency of f_m

$$I_l(m) = \sum_{n=1}^{N} I_l(n,m)$$

$$I_l(n,m) = P_{\text{Tx}}^{FS}(n) \cdot G_{\text{Tx}}^{FS}(n, \theta_{n,l}) \cdot G_{\text{Rx}}^{\text{FSS}}(\theta_{l,n}) \cdot L(d_{n,l}, f_m)$$

- Free space propagation model: **worst case** scenario
- Received signal level at the *l*th FSS terminal from **link analysis** of the FSS system

$$P_{\text{Rx}}(l) = P_{\text{Tx}}^{\text{SAT}} \cdot G_{\text{Tx}}^{\text{SAT}}(l) \cdot G_{\text{Rx}}^{\text{FSS}}(0) \cdot L(D, f_m)$$

- **SINR** at the FSS terminal

$$\text{SINR}(m,l) = \frac{P_{\text{Rx}}(l)}{I_l(m) + I_{\text{co}} + N_0}$$

- In case of asymmetry of **carrier bandwidths of FS and FSS systems**, compensation factor

$$B_{\text{overlap}} / B^{\text{FSS}}$$

Applied Techniques: Beamforming

- A **receive beamformer** at the FSS terminal in order to mitigate interference coming from FS links
  - **DoA** information calculated from available database
- Important aspects of **beamforming design**
  - Array geometry or antenna structure
  - Weight design
- **Antenna Structure**
  - A terminal reflector based feed array (**Multiple Input LNB (MLNB)** set up) system with 75 cm reflector diameter (f/D=0.6)
  - 3 feeds that are aligned along the feed array horizontal line
    - Out of these 3 LNBs, two side feeds are offset at 2 degrees (1.91 cm) from the centered beam and are symmetrical.
  - **Array response vector** calculated using **GRASP** software
- **BF Weight Design**
  - LCMV beamformer

$$\mathbf{w} = \mathbf{R}_y^{-1}\mathbf{C}(\mathbf{C}^H\mathbf{R}_y^{-1}\mathbf{C})^{-1}\mathbf{g}$$

    - BF applied **only in the FSS terminals which receive receive harmful interference** (below a certain threshold defined based on **modcod adaptation** of the terminal)

Applied Techniques: Carrier Allocation

- ☐ Carrier assignment matrix

$$\mathbf{A} = \begin{bmatrix} a_{11} & \dots & a_{1N} \\ \vdots & \ddots & \vdots \\ a_{M1} & \dots & a_{MN} \end{bmatrix} \qquad a_{ij} \in \{0,1\} \qquad \sum_{i=1}^{M} a_{ij} = 1$$

- ☐ SINR matrix

$$\mathbf{SINR} = \begin{bmatrix} \mathrm{SINR}_{11} & \dots & \mathrm{SINR}_{1N} \\ \vdots & \ddots & \vdots \\ \mathrm{SINR}_{M1} & \dots & \mathrm{SINR}_{MN} \end{bmatrix}$$

- ☐ CA problem to maximize the overall throughput of the system

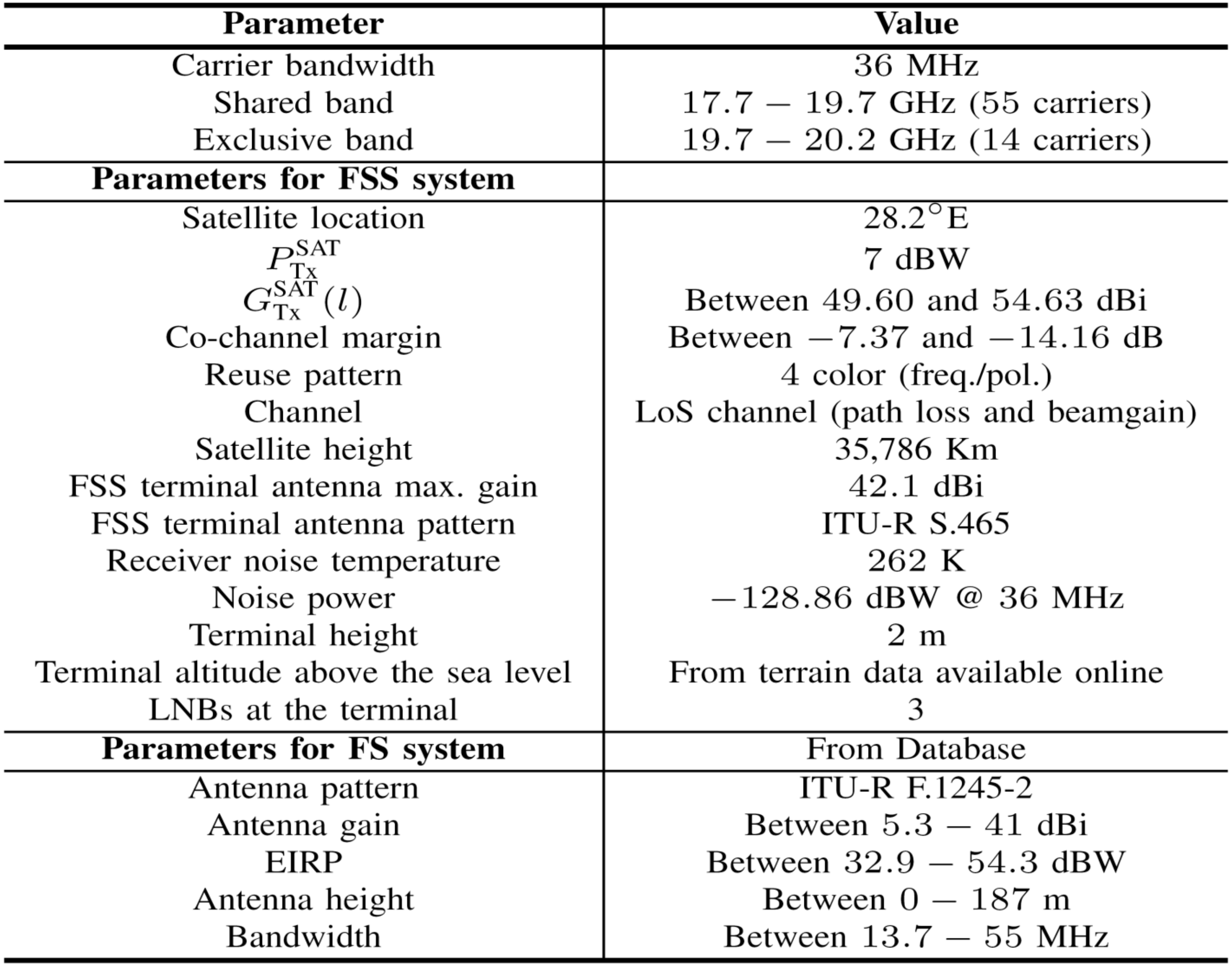
$$\max_{\mathbf{A}} ||\,\mathrm{vec}(\mathbf{A} \odot \mathbf{R}(\mathbf{SINR}))||_1$$
$$\text{subject to } \; ||\mathbf{A}_j||_1 = 1,$$

- ☐ Hungarian Method

☐ H. W. Kuhn, “**The Hungarian method for the assignment problem**,” *Naval Research Logistics Quarterly*, vol. 2, pp. 83–97, 1955.

Numerical Results

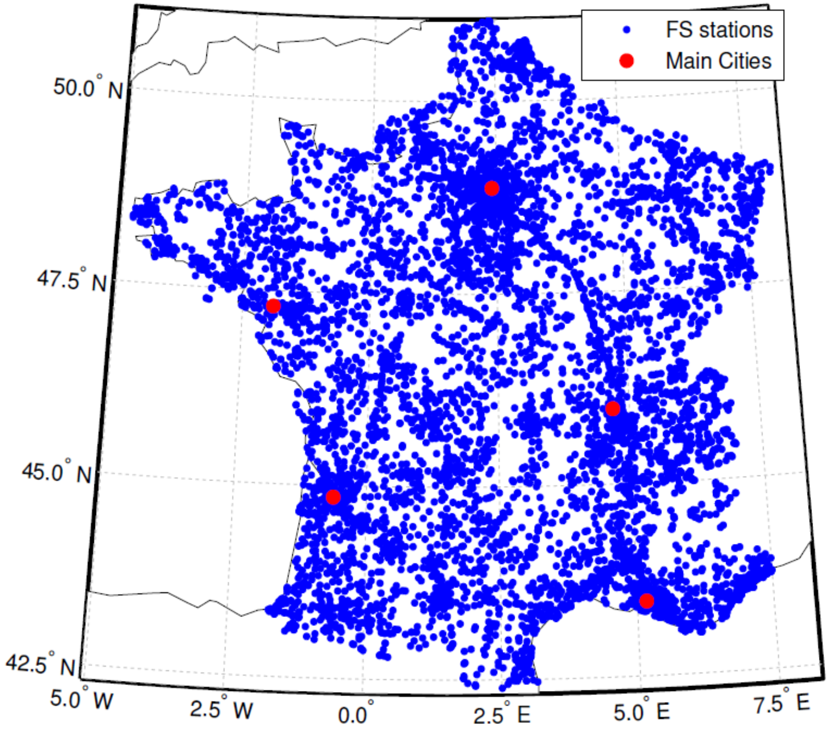
☐ Simulation parameters

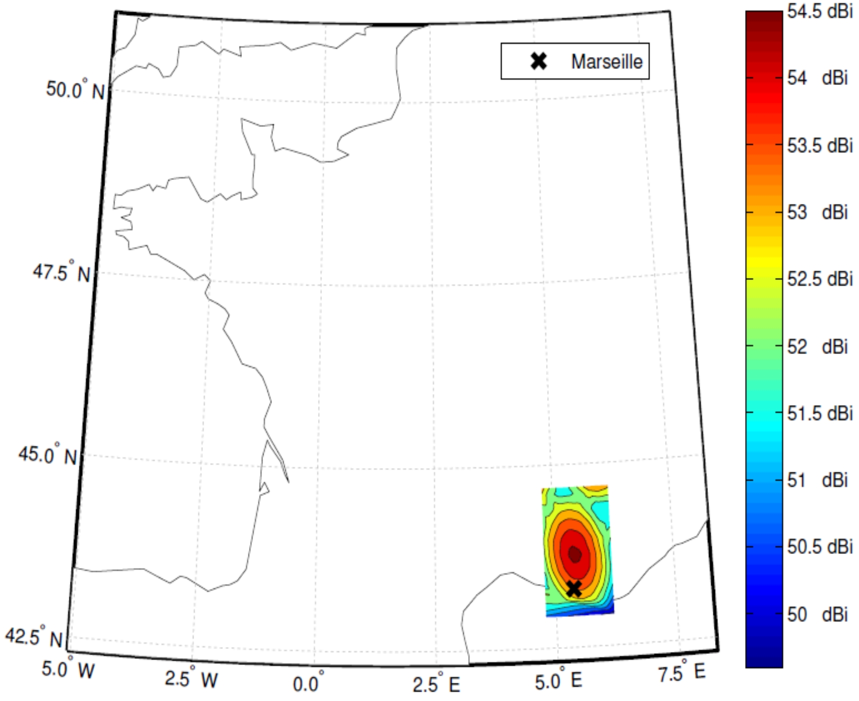


Parameter	Value
Carrier bandwidth	36 MHz
Shared band	17.7 – 19.7 GHz (55 carriers)
Exclusive band	19.7 – 20.2 GHz (14 carriers)
Parameters for FSS system	
Satellite location	28.2°E
$P_{\mathrm{Tx}}^{\mathrm{SAT}}$	7 dBW
$G_{\mathrm{Tx}}^{\mathrm{SAT}}(l)$	Between 49.60 and 54.63 dBi
Co-channel margin	Between −7.37 and −14.16 dB
Reuse pattern	4 color (freq./pol.)
Channel	LoS channel (path loss and beamgain)
Satellite height	35,786 Km
FSS terminal antenna max. gain	42.1 dBi
FSS terminal antenna pattern	ITU-R S.465
Receiver noise temperature	262 K
Noise power	−128.86 dBW @ 36 MHz
Terminal height	2 m
Terminal altitude above the sea level	From terrain data available online
LNBs at the terminal	3
Parameters for FS system	From Database
Antenna pattern	ITU-R F.1245-2
Antenna gain	Between 5.3 – 41 dBi
EIRP	Between 32.9 – 54.3 dBW
Antenna height	Between 0 – 187 m
Bandwidth	Between 13.7 – 55 MHz

Numerical Results

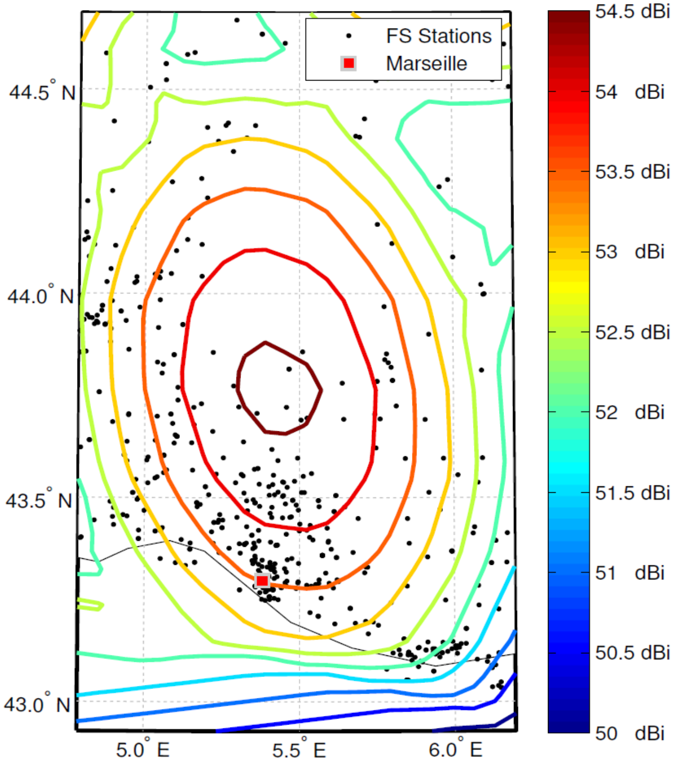
- Parameters about FS links are obtained via **ITU-R BR IFIC database**.
- Population density database from **NASA SEDAC**.
- <u>FS distribution over France</u>



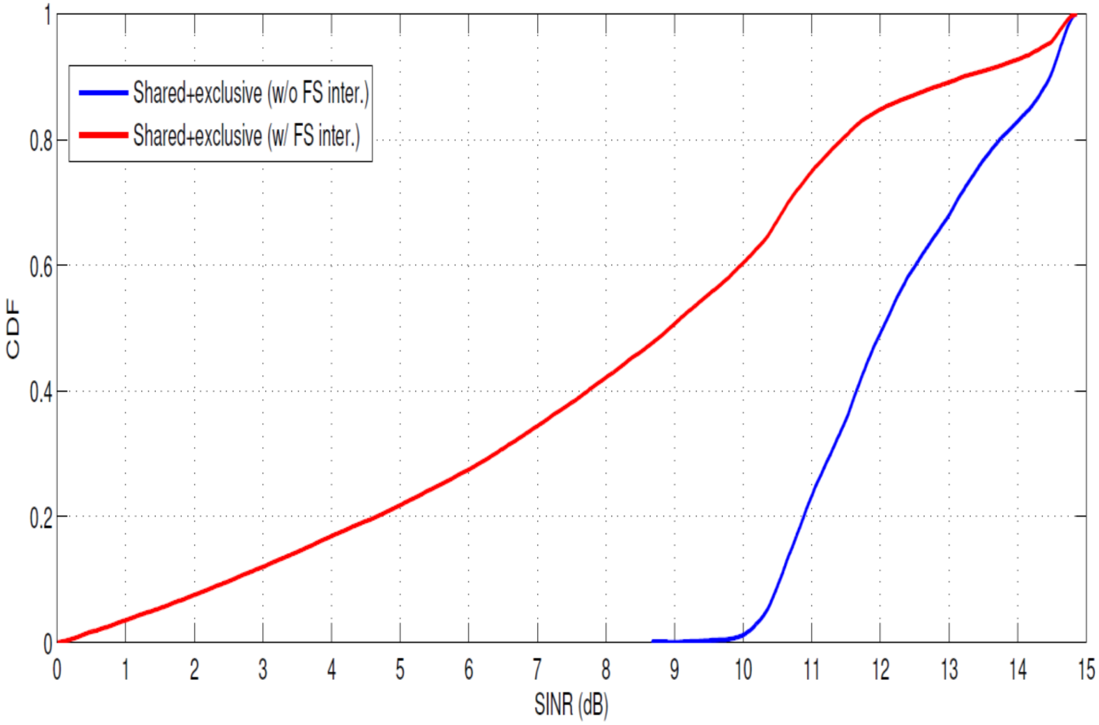


Numerical Results

Beam pattern of FSS satellite over Marseille



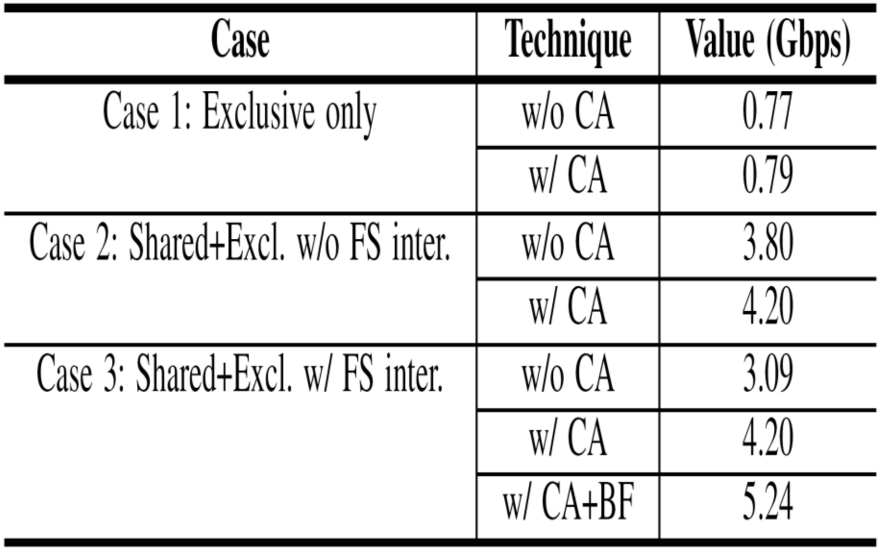
CDF of SINR distribution



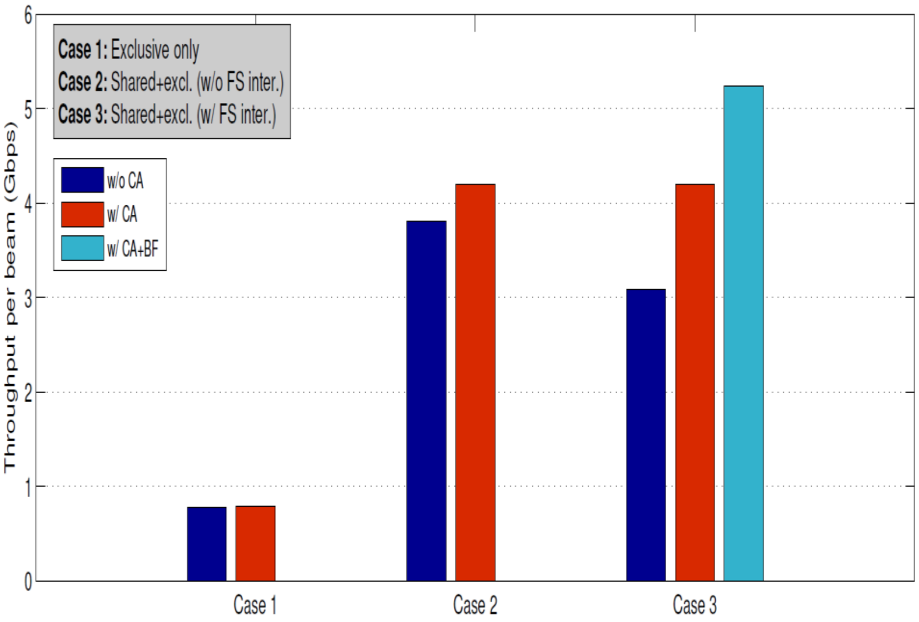
- **SINR distribution degrades** in the presence of FS interference
- Only **1.2% of FSS terminals** experience **SINR below 10dB** in an interference-free scenario, which increases **up to 60%** in the FSS-FS coexistence case.

Numerical Results

Per beam throughput comparison of various cases



Case	Technique	Value (Gbps)
Case 1: Exclusive only	w/o CA	0.77
	w/ CA	0.79
Case 2: Shared+Excl. w/o FS inter.	w/o CA	3.80
	w/ CA	4.20
Case 3: Shared+Excl. w/ FS inter.	w/o CA	3.09
	w/ CA	4.20
	w/ CA+BF	5.24

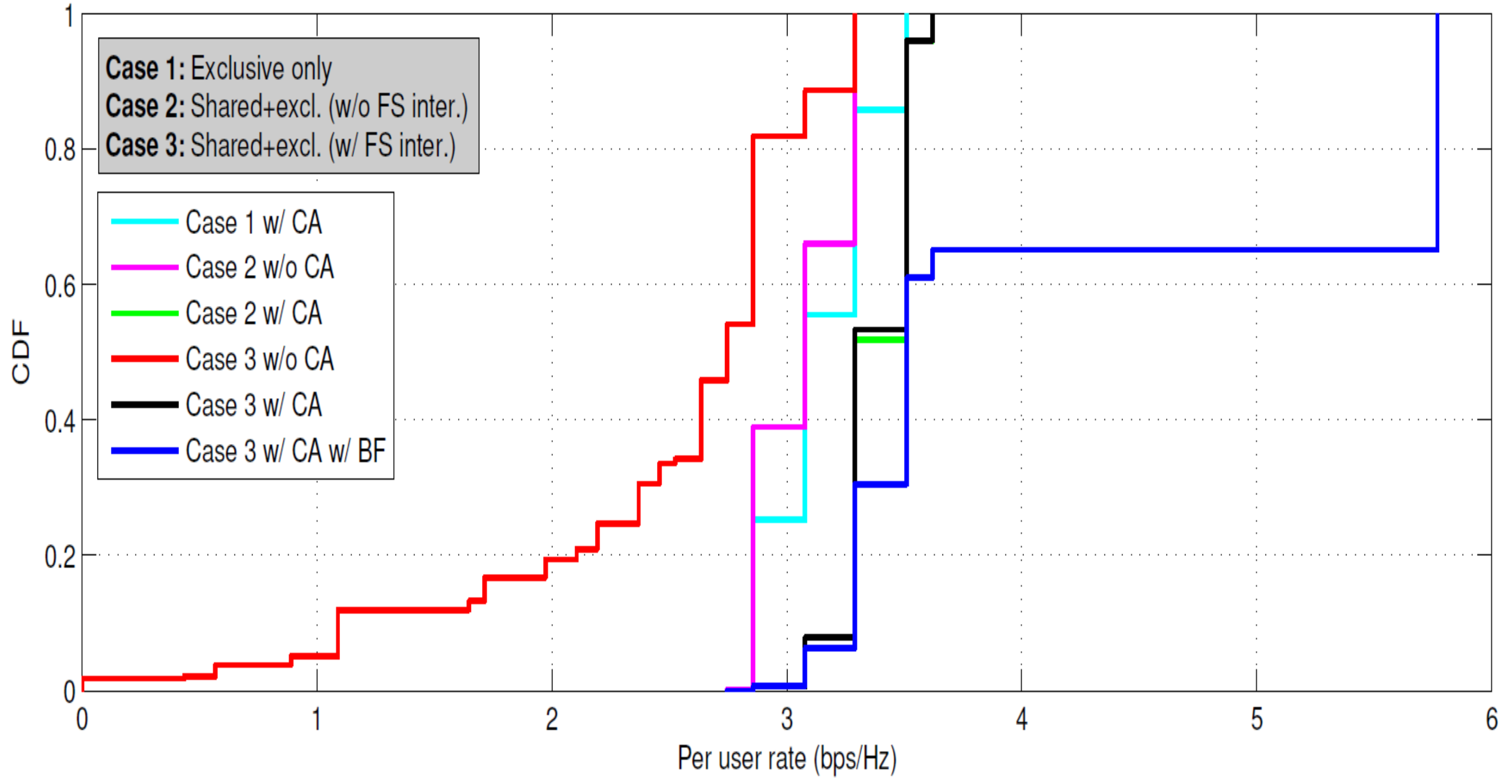


- ☐ Case 1: **exclusive only**
- ☐ Case 2: **shared plus exclusive** without FS interference
- ☐ Case 3: shared plus exclusive with FS interference

- **445.45 %** throughput improvement with **shared+exclusive (CA)** w.r.t. the exclusive only case
- **580.5% throughput improvement with shared+exclusive (CA+BF)** w.r.t. the exclusive only case

Numerical Results

CDF plots of per user rate for different cases



❑ Main Observations

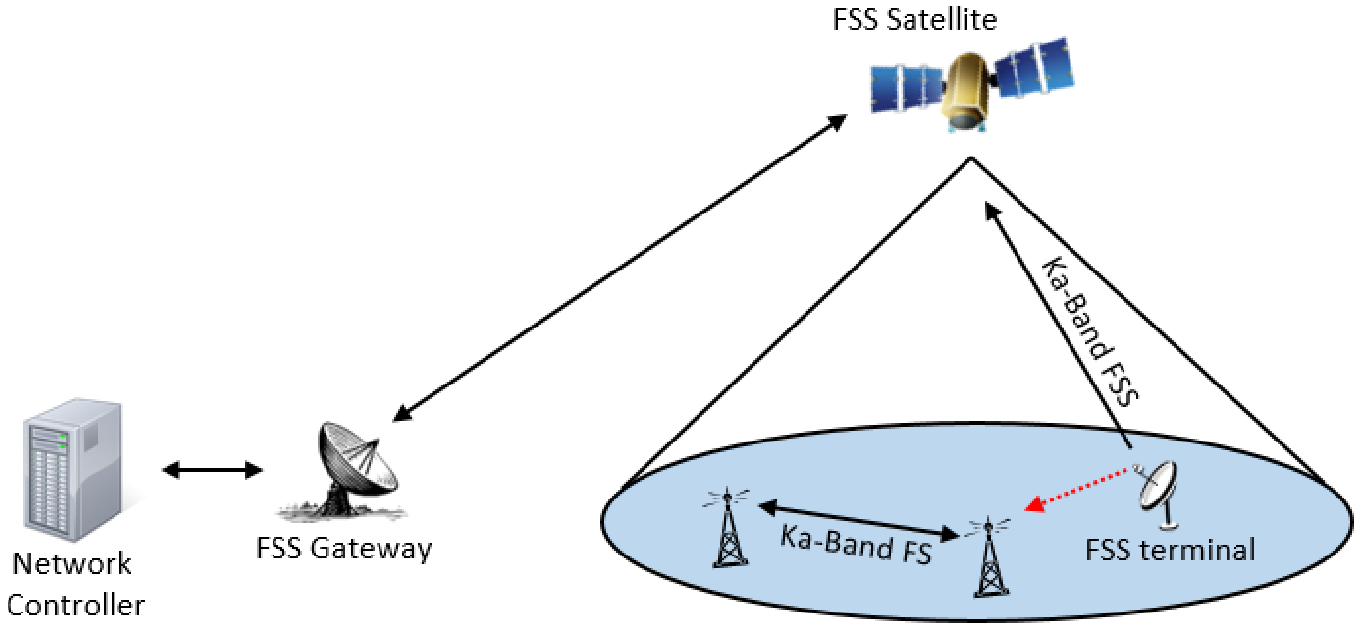
- **Beam availability in the presence of the FS interference improves** while employing the proposed schemes
- **Minimum user rate** in the cognitive scenario (Case 3) increases **from 0 to 2.75 bps/Hz** while employing the CA

Resource Allocation for Cognitive Satellite Uplink Communications in Ka-band: Scenario C

Reference: CROWNCOM 2015, TCCN 2015.

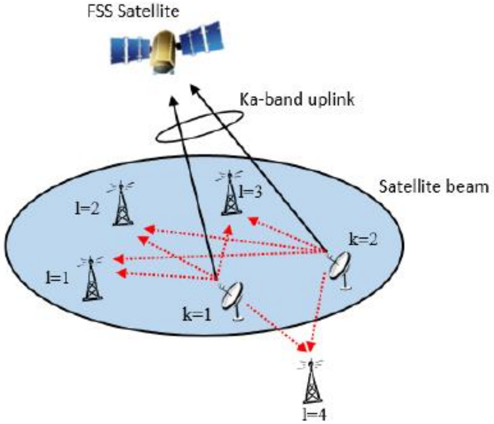
Considered Scenario:

Band: 27.5 – 29.5 GHz
Incumbent User: FS links



Related works and contribution

- Cognitive Satellite Uplink is one of the three promising scenarios
- This scenario falls within the underlay CR paradigm
    - Many works on general interference channels
    - Satellite-terrestrial co-existence, in contrast, have not received much attention in the literature.
    - No interference at the Satellite!



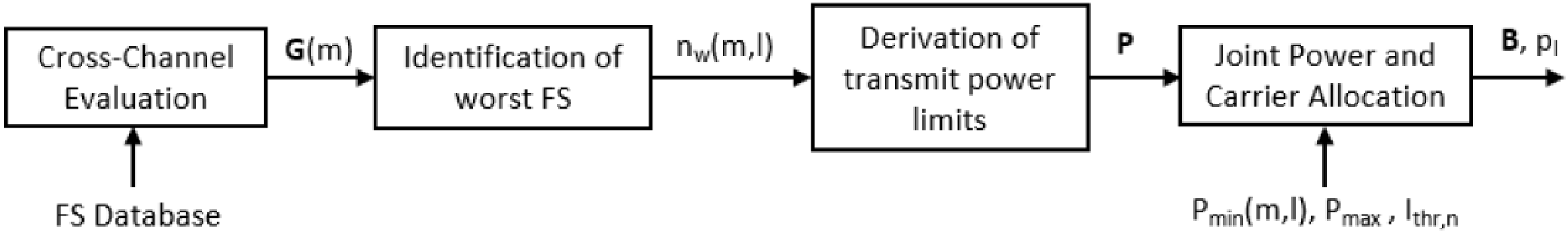
- The applicability of CR in the aforementioned scenario was discussed in [2-3]
- Here, we go a step further, and consider **designing efficient resource allocation** algorithms for this scenario.

[1] COgnitive Radio for SATellite Communications http://www.ict-corasat.eu/

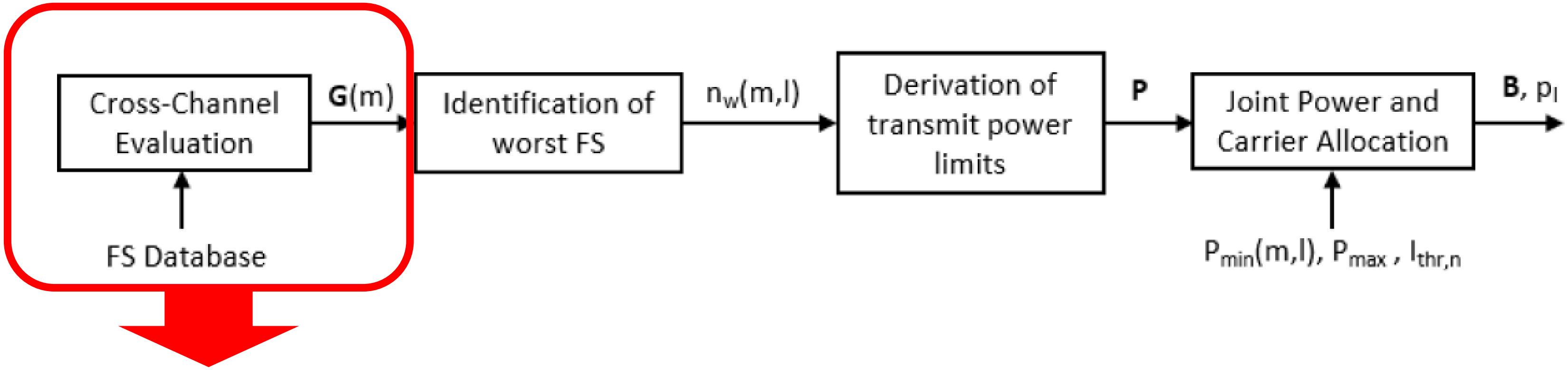
[2] A. Mohamed, M. Lopez-Benitez, and B. Evans, \Ka Band Satellite Terrestrial Co-Existence: A Statistical Modelling Approach," Ka and Broadband Communications, Navigation and Earth Observation Conf., Salerno, Italy, Oct, 2014.

[3] S. Maleki, S. Chatzinotas, B. Evans, K. Liolis, J. Grotz, A. Vanelli-Coralli, and N. Chuberre, Cognitive Spectrum Utilization in Ka Band Multibeam Satellite Communications," to appear in IEEE Communication Magazine.

Joint Power and Carrier Allocation (JPCA)



Joint Power and Carrier Allocation (JPCA)



Cross-Channel Evaluation

FS Database

$\mathbf{G}(m)$

Identification of worst FS

$n_w(m,l)$

Derivation of transmit power limits

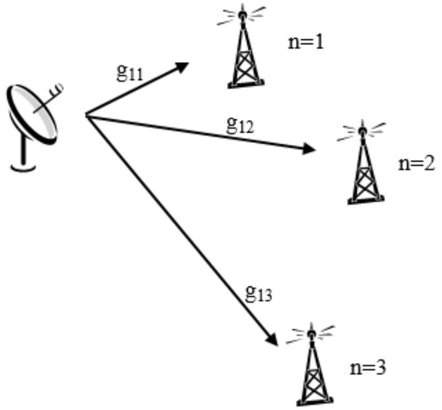
$\mathbf{P}$

Joint Power and Carrier Allocation

$P_{min}(m,l)$, P_{max}, $I_{thr,n}$

$\mathbf{B}$, p_l

The cross-channel gain matrix is obtained from the DATABASE



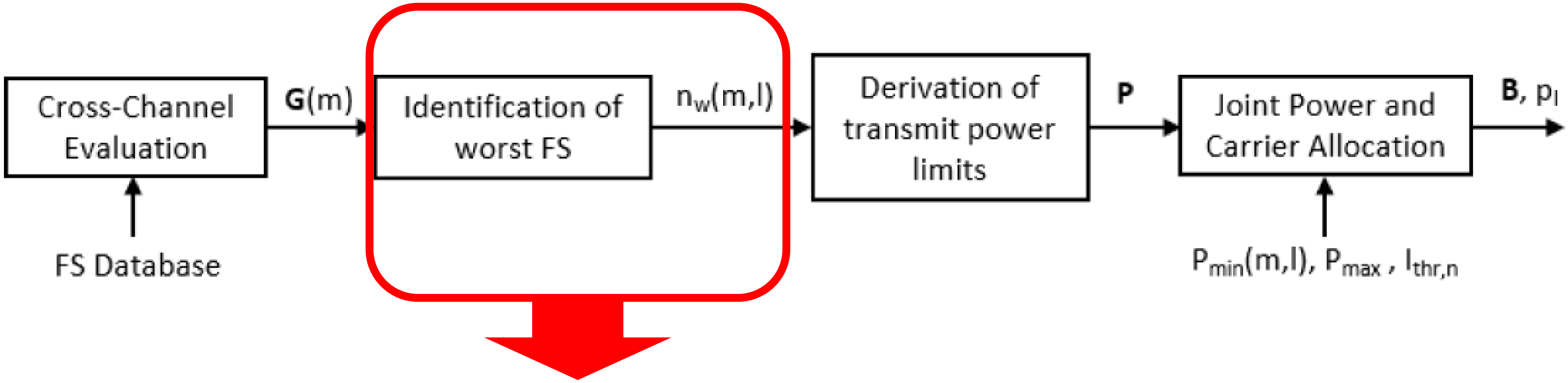
$$\mathbf{G}(m) = \begin{bmatrix} g_{1,1}(m) & \cdots & g_{1,N}(m) \\ \vdots & \ddots & \vdots \\ g_{L,1}(m) & \cdots & g_{L,N}(m) \end{bmatrix}$$

$$g_{l,n}(m) = G_{\text{Tx}}^{FSS}(\theta_{l,n}) \cdot G_{\text{Rx}}^{\text{FS}}(n, \theta_{n,l}) \cdot L(d_{l,n}, f_m)$$

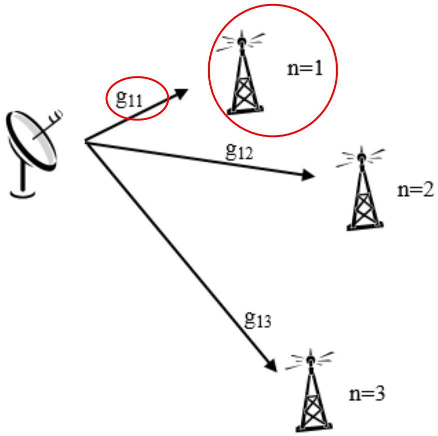
where,

- $G_{\text{Tx}}^{FSS}(\theta)$: Gain of the FSS transmitting antenna at offset angle θ.
- $\theta_{i,j}$: Offset angle (from the boresight direction) of the i-th station in the direction of the j-th station.
- $G_{\text{Rx}}^{\text{FS}}(n, \theta)$: Gain of the n-th FS station antenna at offset angle θ.
- $L(d, f) = \left(\frac{c}{4\pi df}\right)^2$: Free space path loss with d being the transmitter-receiver distance and f being the carrier frequency.
- $d_{i,j}$: Distance between the i-th transmitter and the j-th receiver.

Joint Power and Carrier Allocation (JPCA)



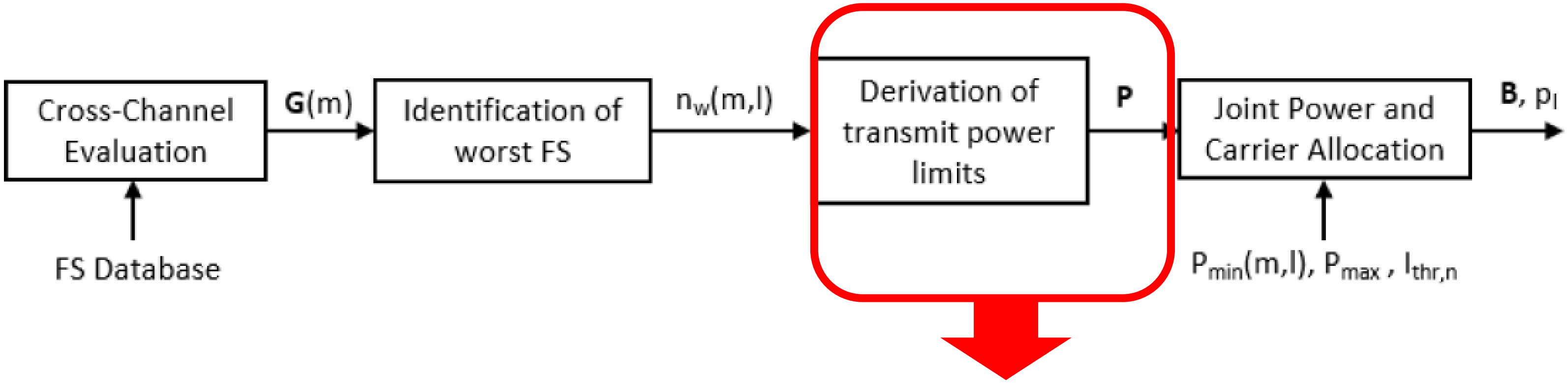
Identication of the worst FS station in terms of interference consists in determining the one with maximum cross-channel gain



$$n_{\mathrm{w}}(m,l) = \max_n \left[\mathbf{G}(m)\right]_l$$

l-th row of matrix $\mathbf{G}(m)$

Joint Power and Carrier Allocation (JPCA)



Cross-Channel Evaluation

FS Database

$G(m)$

Identification of worst FS

$n_w(m,l)$

Derivation of transmit power limits

P

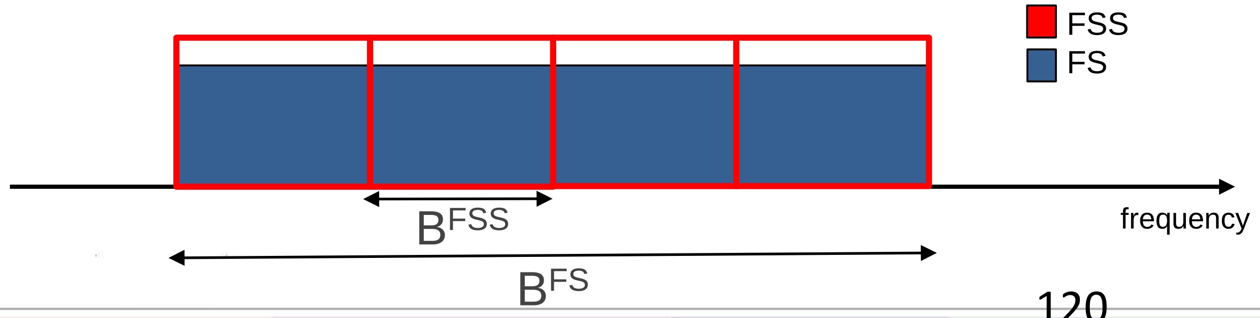
Joint Power and Carrier Allocation

$P_{min}(m,l)$, P_{max} , $I_{thr,n}$

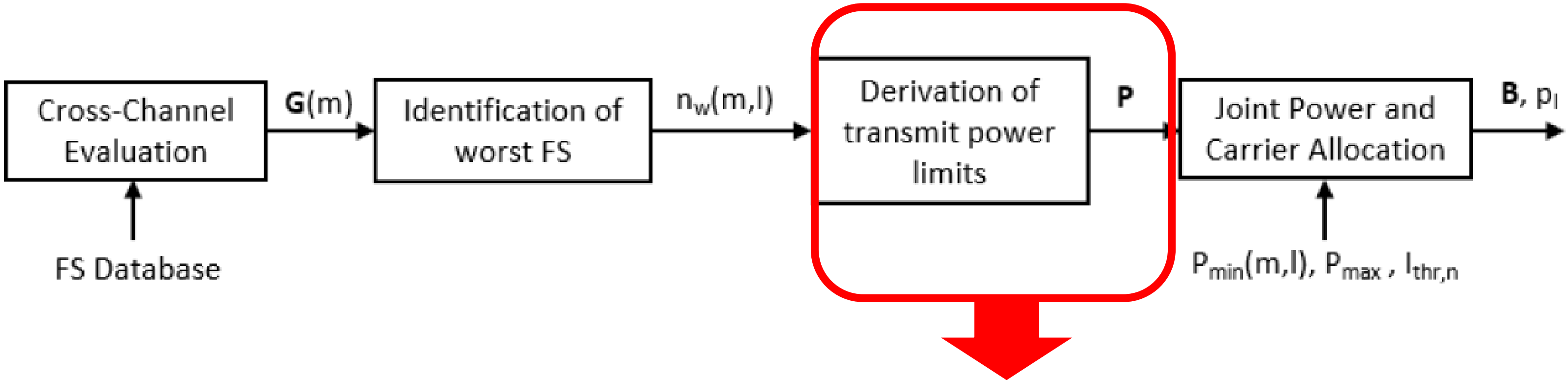
B, p_l

The interference limit of the worst FS receiver, namely $I_{\mathrm{thr},n_{\mathrm{w}}(m,l)}$ $[\mathrm{W}]$, is divided into different portions according to the maximum number of FSS users that can potentially interfere with it:

$$I_{\mathrm{w}}(m,l) = I_{\mathrm{thr},n_{\mathrm{w}}(m,l)} \left(\frac{B^{\mathrm{FS}}}{B^{\mathrm{FSS}}} \right)^{-1}$$



Joint Power and Carrier Allocation (JPCA)



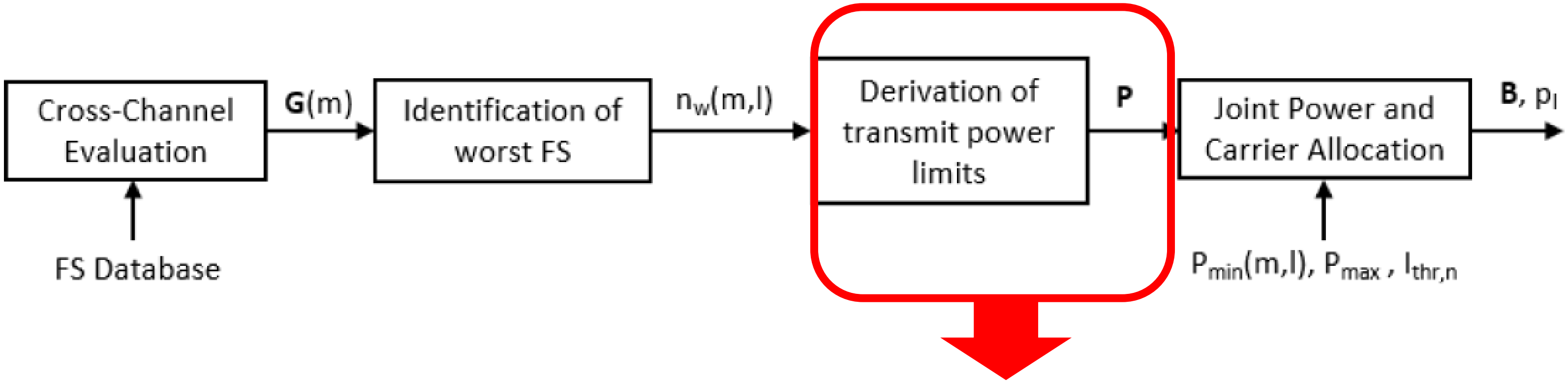
Therefore, the transmit power limit is established to ensure that the following individual interference constraint is satisfied,

$$I_{\mathrm{w}}(m,l) \leq p_l \cdot G_{\mathrm{Tx}}^{FSS}(\theta_{l,n}) \cdot G_{\mathrm{Rx}}^{\mathrm{FS}}(n,\theta_{n,l}) \cdot L(d_{l,n}, f_m)$$

$$\Big\Downarrow$$

$$p_{\max}(m,l) = \frac{I_{\mathrm{w}}(m,l)}{G_{\mathrm{Tx}}^{FSS}(\theta_{l,n}) \cdot G_{\mathrm{Rx}}^{\mathrm{FS}}(n,\theta_{n,l}) \cdot L(d_{l,n}, f_m)}$$

Joint Power and Carrier Allocation (JPCA)



Cross-Channel Evaluation

FS Database

$G(m)$

Identification of worst FS

$n_w(m,l)$

Derivation of transmit power limits

P

Joint Power and Carrier Allocation

$P_{min}(m,l)$, P_{max}, $I_{thr,n}$

B, p_l

At the end we have,

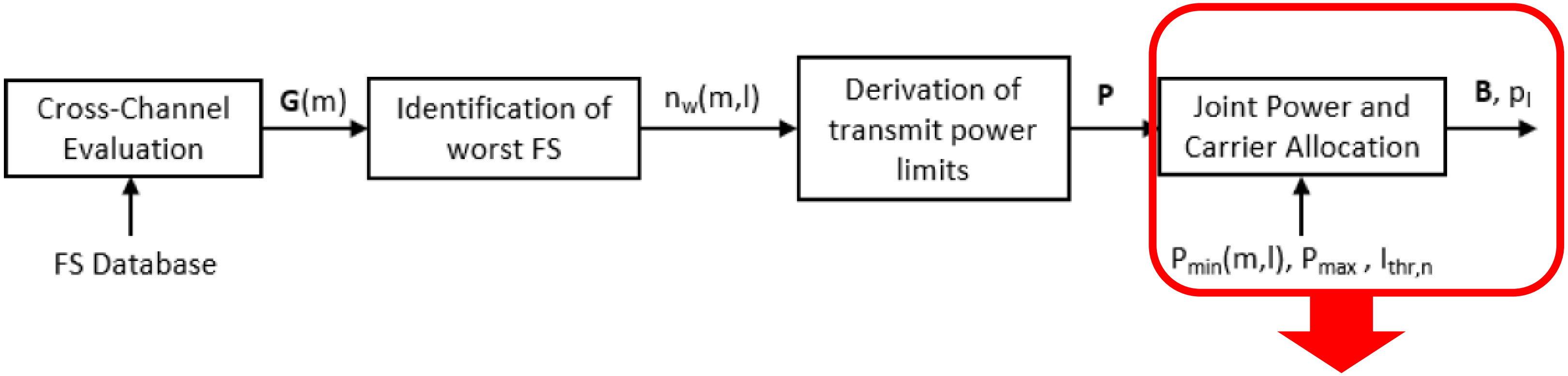
$$\mathbf{P} = \begin{bmatrix} p(1,1) & \cdots & p(1,L) \\ \vdots & \ddots & \vdots \\ p(M,1) & \cdots & p(M,L) \end{bmatrix}$$

Frequency

FSS terminal

Any combination of the powers contained in P never results in an aggregate interference above the acceptable threshold

Joint Power and Carrier Allocation (JPCA)



Cross-Channel Evaluation

FS Database

G(m)

Identification of worst FS

$n_w(m,l)$

Derivation of transmit power limits

P

Joint Power and Carrier Allocation

$P_{min}(m,l)$, P_{max}, $I_{thr,n}$

B, p_l

Find the optimal power allocation by maximizing the sumrate of the FSS system, which gives you the carrier allocation,

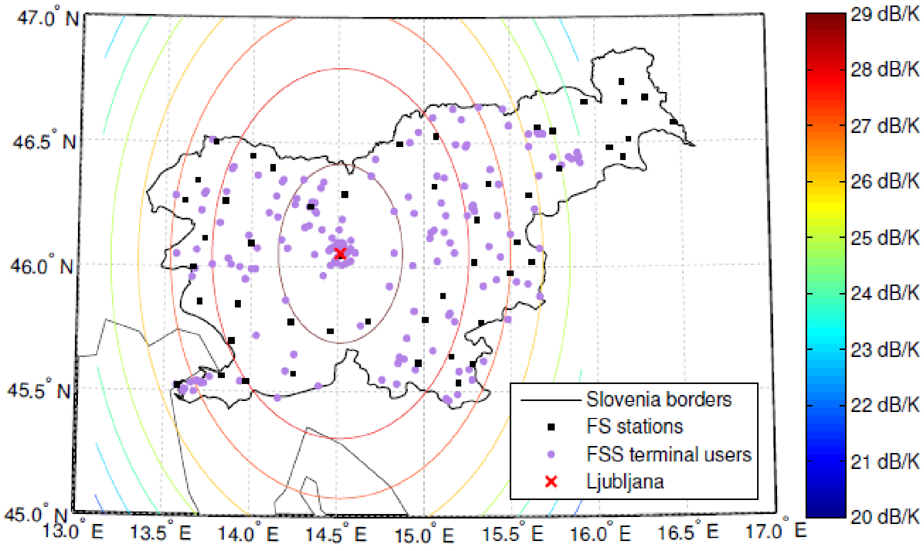
$$\begin{aligned} \max_{\mathbf{B}} \quad & \left\| \mathrm{vec}(\mathbf{B} \odot \mathbf{R}(\mathbf{SINR})) \right\|_{l_1} \\ \text{s.t.} \quad & \sum_{l=1}^{L} b(m,l) = 1, \end{aligned}$$

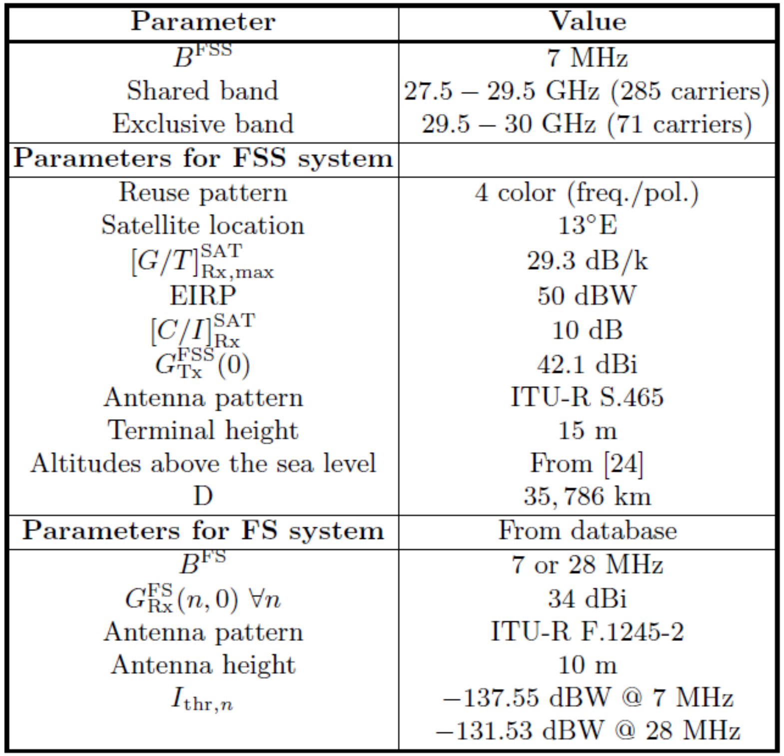
where $\mathbf{B} = [\mathbf{b}_1 \quad \cdots \quad \mathbf{b}_L]$ and $\mathbf{b}_l$ is the carrier assignment of l-th FSS user.

$$\mathbf{b}_l(m) = \begin{cases} 1 & \text{if } m\text{-th carrier is assigned to the } l\text{-th user} \\ 0 & \text{otherwise} \end{cases}$$

Numerical Evaluation

Simulation Setup

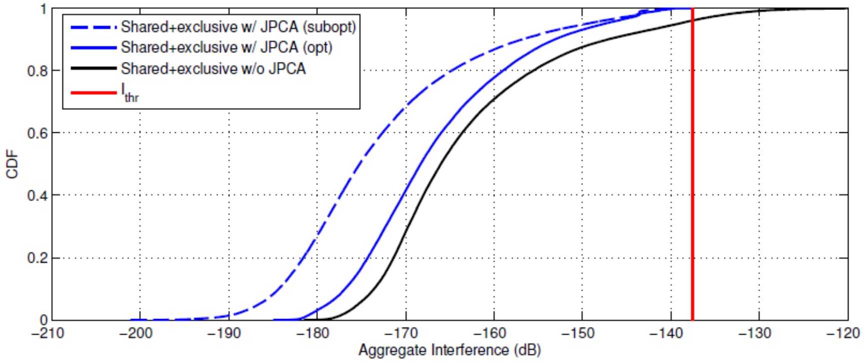




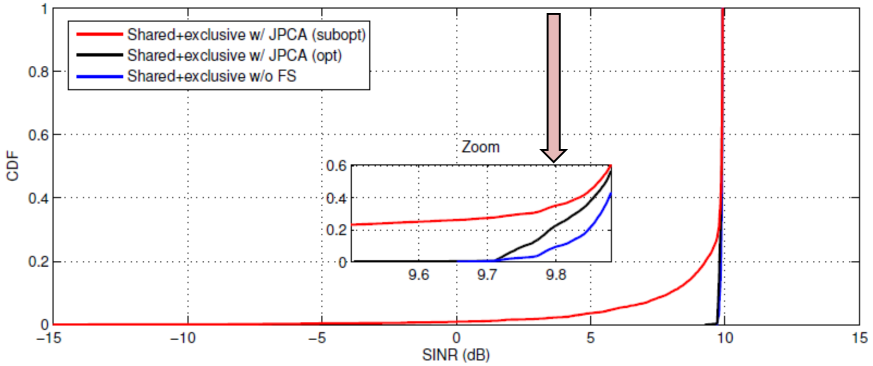
Parameter	Value
B^{FSS}	7 MHz
Shared band	27.5 – 29.5 GHz (285 carriers)
Exclusive band	29.5 – 30 GHz (71 carriers)
Parameters for FSS system	
Reuse pattern	4 color (freq./pol.)
Satellite location	13°E
$[G/T]^{\text{SAT}}_{\text{Rx,max}}$	29.3 dB/k
EIRP	50 dBW
$[C/I]^{\text{SAT}}_{\text{Rx}}$	10 dB
$G^{\text{FSS}}_{\text{Tx}}(0)$	42.1 dBi
Antenna pattern	ITU-R S.465
Terminal height	15 m
Altitudes above the sea level	From [24]
D	35, 786 km
Parameters for FS system	From database
B^{FS}	7 or 28 MHz
$G^{\text{FS}}_{\text{Rx}}(n, 0)\ \forall n$	34 dBi
Antenna pattern	ITU-R F.1245-2
Antenna height	10 m
$I_{\text{thr},n}$	-137.55 dBW @ 7 MHz -131.53 dBW @ 28 MHz

Numerical Evaluation

Simulation Results



- If they use Pmax → interference exceeds the acceptable threshold
- With JPCA → the interference is kept always below the threshold



SINR < 9.8 dB

•Sub opt JPCA → 35% of FSS

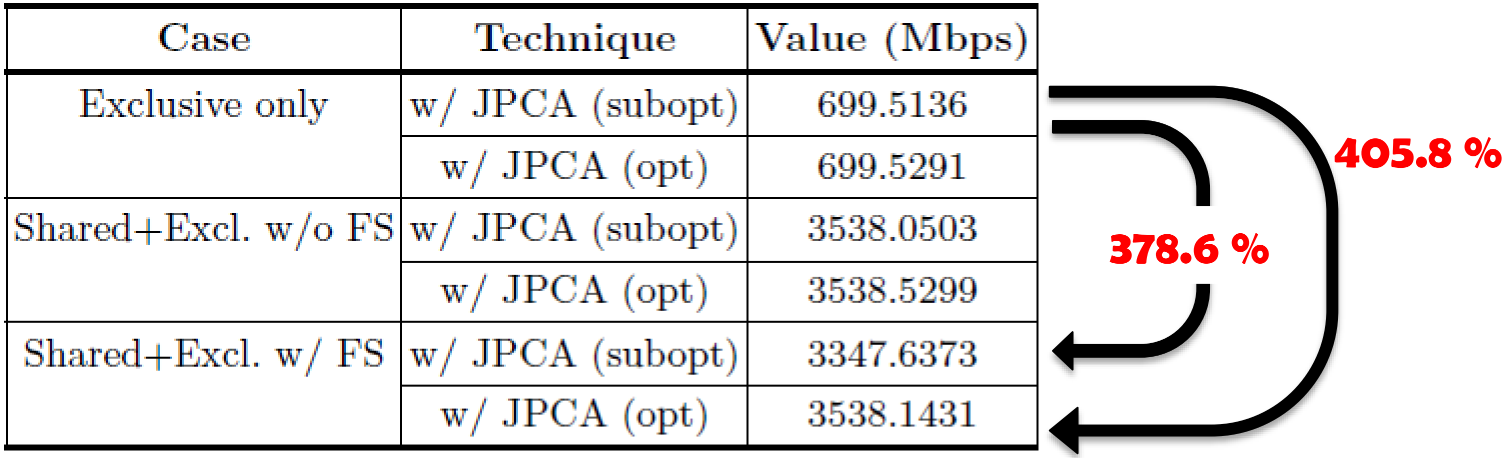
•Optimal JPCA → 22.5% of FSS

•w/o FS → 9.3%

Numerical Evaluation

Simulation Results

Total throughput per beam:



Case	Technique	Value (Mbps)
Exclusive only	w/ JPCA (subopt)	699.5136
	w/ JPCA (opt)	699.5291
Shared+Excl. w/o FS	w/ JPCA (subopt)	3538.0503
	w/ JPCA (opt)	3538.5299
Shared+Excl. w/ FS	w/ JPCA (subopt)	3347.6373
	w/ JPCA (opt)	3538.1431

405.8 %

378.6 %

Power and Rate Allocation in Cognitive Satellite Uplink Networks: Scenario C

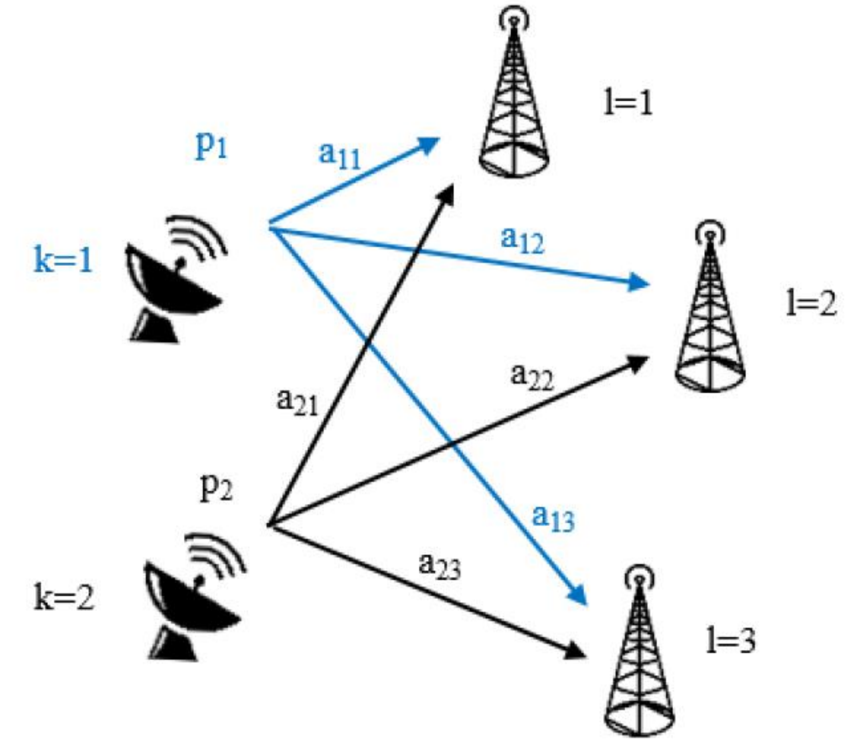
Reference: VTC 2015, ICC 2016.

Some notes

- ☐ Question: What is the optimal power allocation strategy for overlapping carriers in satellite uplink?
- ☐ Note that the satellite uplink works in an MF-TDMA mode.
- ☐ A good future direction: inclusion of bandwidth optimization.

System Model

- K satellite terminals
- L FS microwave stations
- p_k transmit power of the k-th satellite terminal
- $p^{\max}$ Maximum transmit power of a satellite terminal
- $a_{k,l}$ Channel power gain of the interference link between the k-th satellite terminal and the l-th FS station.



The achievable rate by the k-th RCST is:

$$r_k = \log_2\left(1 + \frac{d_k p_k}{\sigma_k^2}\right)$$

where

d_k denotes the channel power gain of the link from the k-th RCST to the satellite

denotes the noise power level of the k-th σ_k^2ellite link.

Optimization problem

- ☐ **Maximizing the user transmit rate** and **keeping the imposed interference to the FS system below a given limit.**

$$\boxed{\begin{array}{lll} \max\limits_{\mathbf{p}} & \mathbf{r} & \\ \text{s.t.} & \mathbf{A}\mathbf{p} \leq I_{\text{thr}}\mathbf{1} & \\ & 0 \leq p_k \leq p^{\max}, & k = 1, \ldots, K \end{array}}$$

where

$$\mathbf{p} = [p_1 \quad p_2 \quad \ldots \quad p_K]^{\mathrm{T}}$$

$$\mathbf{A} = \begin{bmatrix} a_{1,1} & \cdots & a_{K,1} \\ \vdots & \ddots & \vdots \\ a_{1,L} & \cdots & a_{K,L} \end{bmatrix}$$

- Is a multi-objective optimization problem, since $\mathbf{r} = [r_1 \quad \ldots \quad r_K]^{\mathrm{T}}$
- $\mathbf{A}\mathbf{p} \leq I_{\text{thr}}\mathbf{1}$ includes the L interference constraints required to guarantee the protection of the incumbent FS system.
  - Such limitations are defined by the regulatory authorities.
  - Typical reference limitations are given by ITU such as ITU-R F.758, where the interference level is recommended to be -10 dB below the receiver noise.

Optimization problem (cont'd)

- From the previous Multi-objective Optimization Problems it is clear that…

$$\begin{aligned} \max_{\mathbf{p}} \quad & \mathbf{r} \\ \text{s.t.} \quad & \mathbf{A}\mathbf{p} \le I_{\text{thr}}\mathbf{1} \\ & 0 \le p_k \le p^{\max}, \ k = 1, \dots, K \end{aligned}$$

Each FSS terminal user aims at selfishly maximizing its own rate and …

altruistically consume the interference limit of the FS receivers.

- The $\{r_k\}$ are monotonically increasing functions of the corresponding $\{p_k\}$ then the multi-objective problem is equivalent to

$$\begin{aligned} \max_{\mathbf{p}} \quad & \mathbf{p} \\ \text{s.t.} \quad & \mathbf{p} \in \Omega \end{aligned}$$

where Ω denotes the set of feasible vectors $\mathbf{p}$ satisfying the two previous constraints and is convex.

Pareto feasible $\mathcal{P} = \{\mathbf{p} : \mathbf{p} \in \Omega\}$, i.e., the set that contains all the combinations of possible values $\mathbf{p}$ that are simultaneously attainable with the available resources.

Example

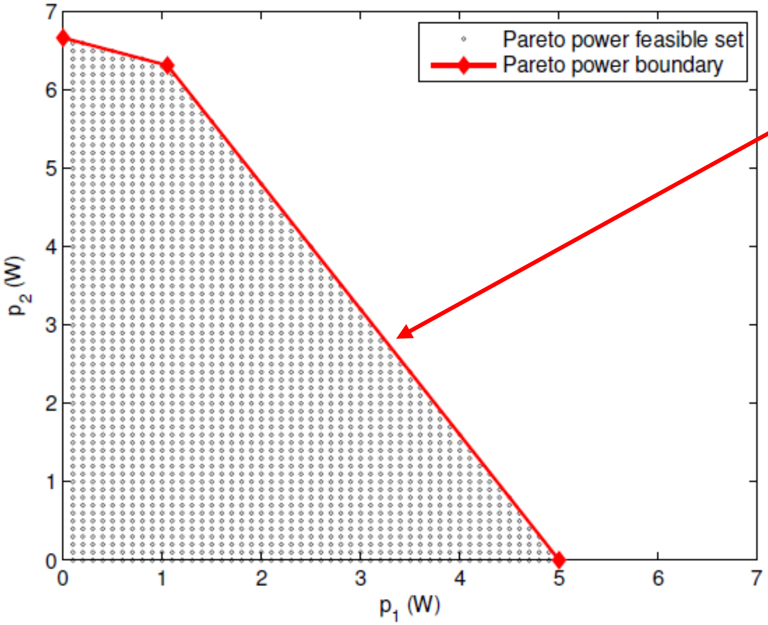
- ☐ Problem:

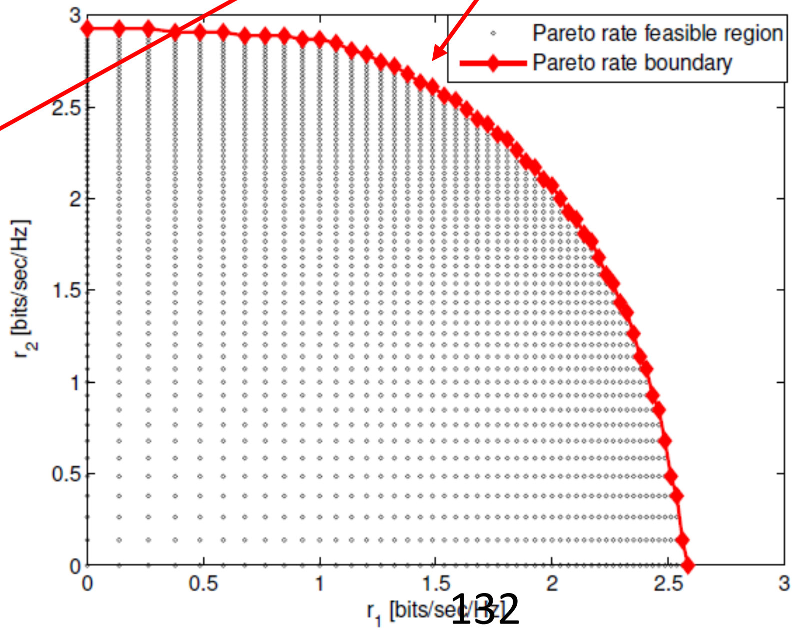
$$\begin{aligned} \max_{\mathbf{p}} \quad & \mathbf{r} \\ \text{s.t.} \quad & \mathbf{A}\mathbf{p} \leq I_{\text{thr}}\mathbf{1} \\ & 0 \leq p_k \leq p^{\max}, \; k = 1, \ldots, K \end{aligned}$$

- ☐ **Example: K=2, L=3**

$$\mathbf{A} = \begin{bmatrix} 0.4 & 0.25 \\ 0.1 & 0.3 \\ 0.2 & 0.1 \end{bmatrix}, \;\; I_{\text{thr}} = 2, \;\; p^{\max} = 10, \;\; d_k = 1, \sigma_k^2 = 1, \;\; \forall k$$

Any point in the Pareto boundary is an optimal point





General Iterative Framework for Pareto-Optimization

- ☐ Considering:

$$\begin{array}{lll} \max\limits_{\mathbf{x}} & \operatorname{all}\limits_{\mathbf{y}} & \mathbf{f}(\mathbf{x},\mathbf{y}) \\ \text{s.t.} & & \mathbf{x} \in \Gamma \end{array}$$

- ☐ A Pareto-Optimal solution is given by the following iterative approach*:

Given $\mathbf{x}^{(t)} \in \Gamma$btain $\mathbf{x}^{(t+1)}$e solution to:

(*) Proof given in the manuscript.

$$\begin{array}{lll} \max\limits_{\mathbf{x}^{(t+1)}} & \min\limits_{\mathbf{y}} & \left\{ \dfrac{\mathbf{f}\left(\mathbf{x}^{(t+1)},\mathbf{y}\right)}{\mathbf{f}\left(\mathbf{x}^{(t)},\mathbf{y}\right)} \right\} \\ \text{s.t.} & & \mathbf{x}^{(t+1)} \in \Gamma \end{array}$$

This always provide a solution in the Pareto boundary. The only constraint is that the initial point should be within the Pareto region.

- ☐ **Application to cognitive satellite uplink:**

$$\boxed{\begin{array}{ll} \max\limits_{\mathbf{p}} & \mathbf{p} \\ \text{s.t.} & \mathbf{p} \in \Omega \end{array}} \Longrightarrow \begin{array}{lll} \max\limits_{p_k^{(t+1)}} & \min\limits_{k} & \left\{ p_k^{(t+1)} / p_k^{(t)} \right\} \\ \text{s.t.} & & \mathbf{p}^{(t+1)} \in \Omega \end{array}$$

Multi-Objective to Single-Objective transformation

- ❑ The solution of a multi-objective optimization problem consists of a set (the Pareto boundary).
- ❑ However, we need a single solution for operation.
- ❑ Picking a desirable point out of the set of the Pareto boundary requires the incorporation of preferences or priorities into the problem.

Multi-Objective to Single-Objective transformations considered here:

- Weighted sum
  - It is the simplest multi-criteria decision making method.
  - It is a compensatory method ("poor" user rates can be compensated by "good" ones.
  - The relation between weights and user rate requirements remains unsolved
- Fairness
  - The rate of all users will be degraded to match the rate of the user with the lowest quality channel
  - We study: Max-Min Fairness and Proportional Fairness.

Maximization of weighted sum-rate

- Maximization of a weighted sum of user rates is one of the most popular figures of merit for measuring the performance of a communication system

$$\boxed{\begin{aligned} \max_{\mathbf{p}} \quad & \sum_{k=1}^{K} w_k \log_2\left(1 + \frac{d_k p_k}{\sigma^2}\right) \\ \text{s.t.} \quad & \mathbf{p} \in \Omega \end{aligned}}$$

Where $\{w_k\}$re non-negative weights assigned to the RCSTs, with $\sum_{k=1}^{K} w_i = 1$

- Note that the objective function is concave with respect to the power values, so it can be solved numerically using convex solvers, e.g. CVX.

Max-Min Fairness

- Max-Min fairness is a type of resource allocation problem to make sure weakest users are not penalized.

- In other words, it maximizes the user with the minimum rate:

$$\boxed{\max_{\mathbf{p}\in\Omega} \quad \min_{k} \{r_k\}}$$

- The most widely used algorithm for obtaining max-min fairness is the water-filling algorithm (WF) [6]
  - Intuitively, WF satisfies users with a poor conditions first, and distributes evenly the remaining resource to the remaining users enjoying a good condition.

In our case, we focus first on assigning the power of the RCST transmitters (the bottleneck RCSTs) affecting the worst FS station, i.e., the FS station which receives the highest level of aggregate interference.

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[6] T. Lan, D. Kao, M. Chiang, and A. Sabharwal, “An Axiomatic Theory of Fairness in Network Resource Allocation,” IEEE Conf. on Computer Communications (INFOCOM), San Diego, CA, USA, Mar. 2010

Proportional Fairness

- Max-Min fairness does not perform well in the presence of bottleneck users: if one user imposes strong interference constraints it may prevent the others from improving.
- **Proportional fairness (PF)**: a transfer of resources between two users is accepted if the percentage increase in rate of one user is larger than the percentage decrease in rate of the other user.

In [7], it is proved that a proportionally fair allocation of rates is given by maximizing the sum of logarithmic utility functions.

$$\begin{aligned} \max_{\mathbf{p}} \quad & \sum_{k=1}^{K} \log_{10}(p_k) \\ \text{s.t.} \quad & \mathbf{p} \in \Omega \end{aligned}$$

- This is a concave problem, and thus can be solved by convex solvers, e.g. CVX.

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[7] F. Kelly, “Charging and Rate Control for Elastic Traffic,” European Transactions on Telecommunications, vol. 8, pp. 33–37, 1997.

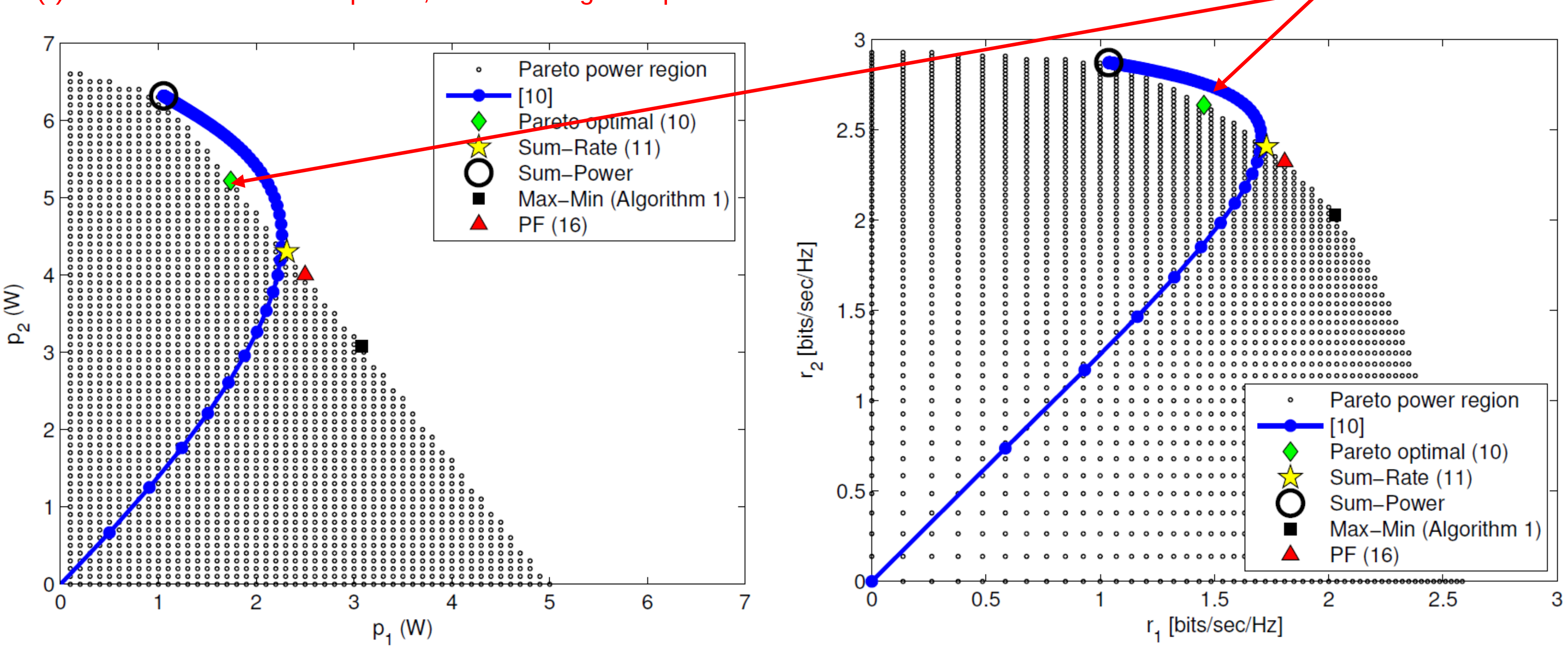
Numerical Evaluation

- **K=2, L=3**

$$\mathbf{A} = \begin{bmatrix} 0.4 & 0.25 \\ 0.1 & 0.3 \\ 0.2 & 0.1 \end{bmatrix}, \ I_{\text{thr}} = 2, \ p^{\max} = 10, \ d_k = 1, \sigma_k^2 = 1, \ \forall k$$

For the proposed Pareto-Optimal algorithm, the initial point is chosen at random

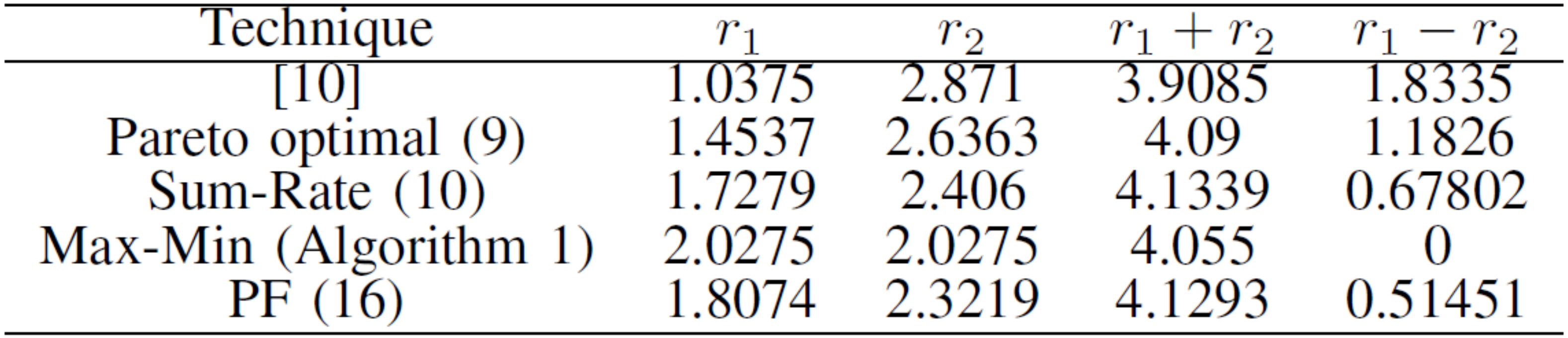
(*) For sum-rate and sum-power, we take weights equal to 1.



[10] E. Lagunas, S.K. Sharma, S. Maleki, S. Chatzinotas, and B. Ottersten, “Power Control for Satellite Uplink and Terrestrial Fixed-Service Coexistence in Ka-band,” IEEE VTC-Fall, Boston, USA, Sep. 2015.

Numerical Evaluation

- **Summary of results**



Technique	r_1	r_2	$r_1 + r_2$	$r_1 - r_2$
[10]	1.0375	2.871	3.9085	1.8335
Pareto optimal (9)	1.4537	2.6363	4.09	1.1826
Sum-Rate (10)	1.7279	2.406	4.1339	0.67802
Max-Min (Algorithm 1)	2.0275	2.0275	4.055	0
PF (16)	1.8074	2.3219	4.1293	0.51451

- The technique presented in [10] perfectly matches with the solution of the maximization of the sum-powers.
- The Max-Min fairness gives the same rate to both users.
- The PF allows a small difference between individual rates to achieve higher sum-rate compared to the max-min.
- The Pareto optimal solution lies in the Pareto boundary, but its value strongly depends on the initial power assignment.

According to the achieved results, PF seems to be the best solution since it provides a good trade-off between fairness and overall satellite throughput. Even so, the choice of appropriate algorithm depends on the design criteria we want to follow.

Some current and future directions:

- Integrated satellite-terrestrial backhauling inspired by scenarios B and C, European project SANSA: http://sansa-h2020.eu/

- Carrier, bandwidth and power allocation for multiple cognitive satellite systems.

- Coexistence of multiple antenna satellite systems with terrestrial and satellite networks

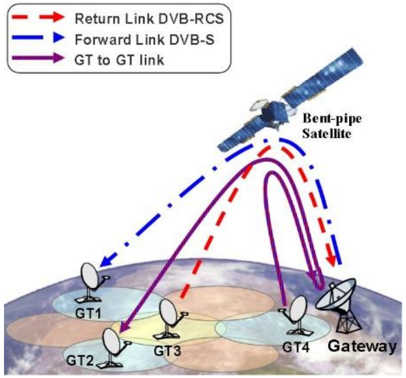
- Spectrum cartography of Ka band incumbent systems, National Project SATSENT: http://wwwen.uni.lu/snt/research/research_projects2/satsent_satellite_sensor_networks_for_spectrum_monitoring

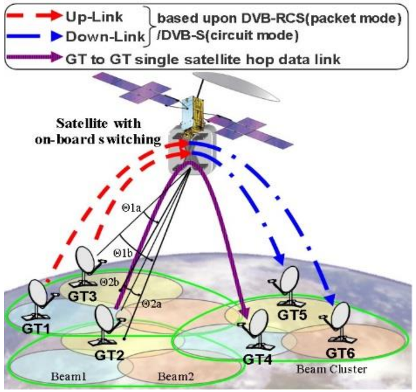
- Other related projects:
  - National project SeMIGod: http://wwwen.uni.lu/snt/research/research_projects2/semigod_spectrum_management_and_interference_mitigation_in_cognitive_radio_satellite_networks
  - ESA Project ASPIM:

Future Topics : On-Board Signal Processing

On-Ground Techniques

- Work horse for enhancing performance
- Allows use of well established bent-pipe design
  - Saves on-board power, mass
  - Payload design can be agnostic to
    - Service and traffic
    - Waveform
    - Techniques used
- Incorporates Flexibility
  - Use of new techniques
  - Upgrade algorithm/ parameters
  - Implementation platform
- Imposes Academic Challenges
  - Differentiates with terrestrial communication design





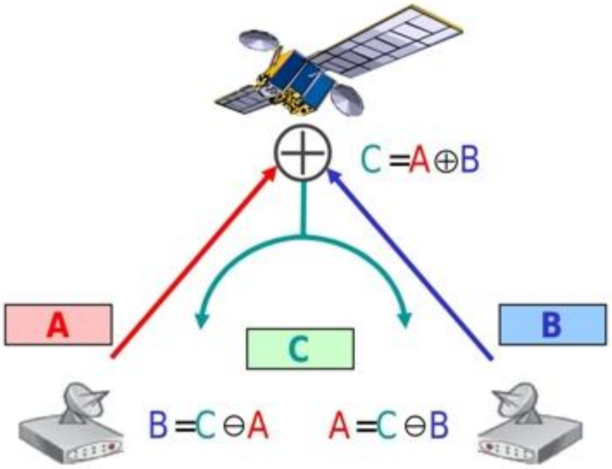
Courtesy: DLR

On-Ground Processing Limitations

- High throughput → New techniques
- New techniques bring new challenges
  - Can overload the workhorse
- Complex on-ground processing cannot be implemented at UT
- Stronger impairments and poorer efficiency
  - Propagation effects
- Inefficient Feeder Link Utilization
  - E.g., on-ground beamforming
- Higher Latency
  - Large round trip delays affect MSS applications (typically 250 ms)

On-Ground Processing Limitations

- Inadequacy of information
  - Loss of useful information after multiplexing (e.g., angles of arrivals)
- Inadequacy of support
  - Full-duplex relaying
  - Network coding
  - Anti-jamming
  - Multiple interference tracking over one carrier
  - Inter-satellite communications



Courtesy: DLR Institute for Communication and Navigation

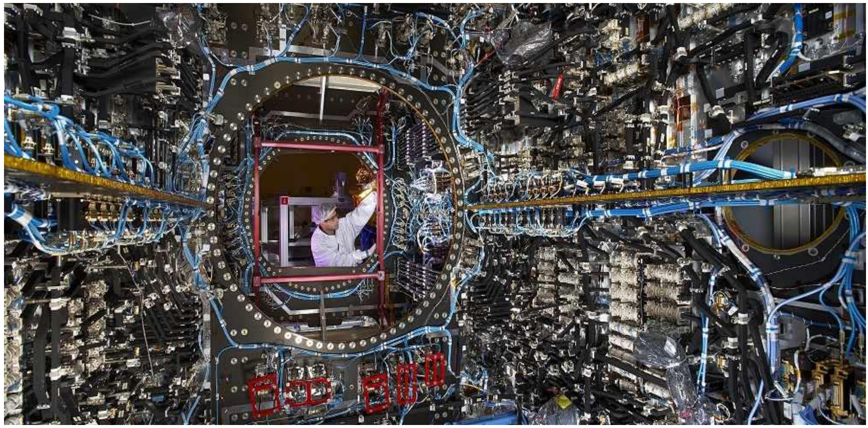
Benefits of OBP

- **Increasesd flexibility creating more networking capability in the sky**
  - Routing, mesh connectivity
  - Lower latency
  - Resource management

- Relieving the burden of on-ground processing

- Less complex ground equipment
  - Spectrum monitoring units
  - Uplink gateways
  - User equipment
  - Uplink Energy-efficiency

- Feeder link BW reduction, fewer GWs

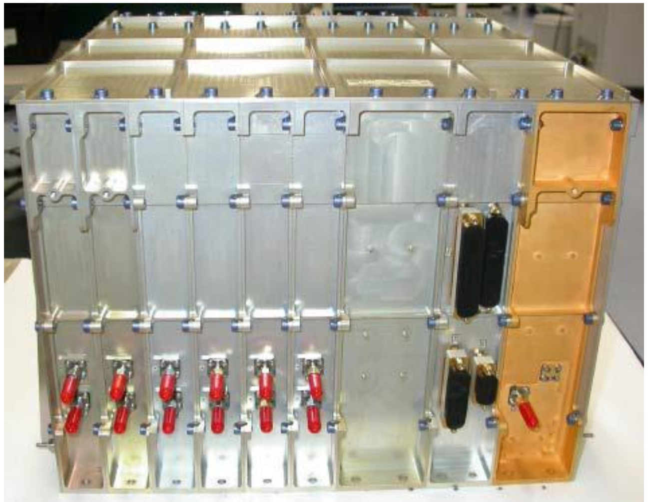


Courtesy: Thales Alenia Space

Benefits of OBP

- Higher user and system throughput, link spectral efficiency
  - Predistortion and interference mitigation improve SINR
  - Newer Waveforms
  - Full Duplexing

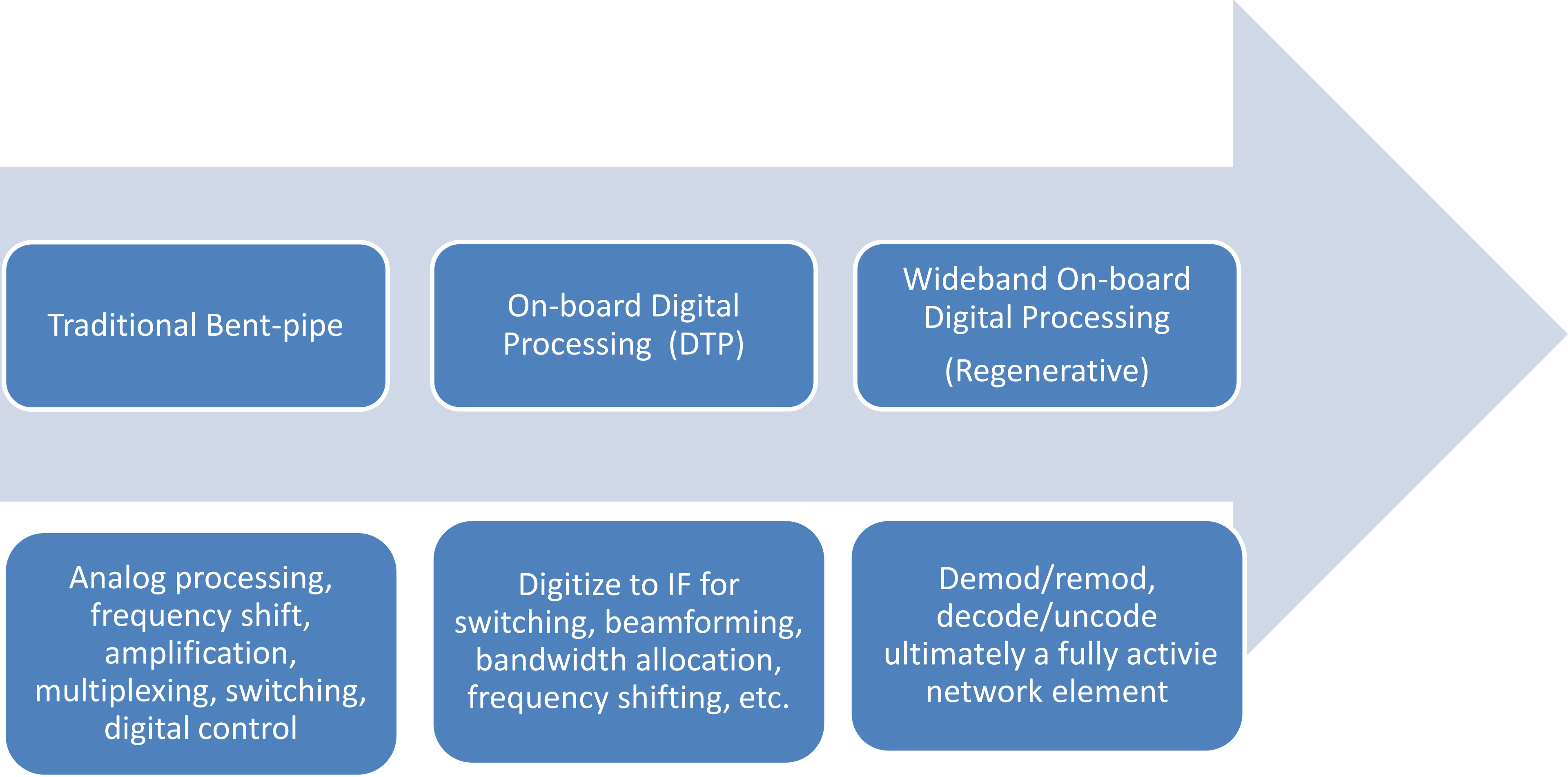
- System Robustness
  - Anti-jamming
  - Higher resilience to the interference



TAS designed Digital Transparent Processor

On-board processing is an important component in the next generation of satellites to keep SatCom competitive in the market.

Evolution of On-Board Processing



Traditional Bent-pipe

Analog processing, frequency shift, amplification, multiplexing, switching, digital control

On-board Digital Processing (DTP)

Digitize to IF for switching, beamforming, bandwidth allocation, frequency shifting, etc.

Wideband On-board Digital Processing

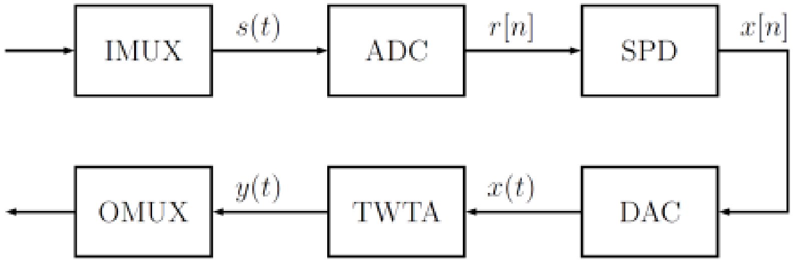
(Regenerative)

Demod/remod, decode/uncode ultimately a fully activie network element

Current On-Board Processing Technology

SATELLITE, BAND	PROCESSOR	FUNCTIONALITIES	APPLICATIONS & BENEFITS
Hotbird6 (Ka, K-band)	Regenerative Skyplex	Multiplexing streams with audio, video and data content, Turbo decoding. Flexibility in (i) channel gains, (ii) uplink-downlink channel mapping, (iii) BW allocation on uplink.	Internet and TV • Reduced latency
SPACEWAY 3 (Ka band)	Regenerative	Switching, Routing, user-user connectivity, Dynamic Beamforming. Flexibility in (i) channel to beam assignment, (ii) Bandwidth and power allocation, (iii) uplink-downlink channel mapping.	Broadband IP services • Reduced latency
Amazonas 1, 2 (Ku-band) HISPASAT-AG1 (Ku-band)	Regenerative AmerHis REDSAT	Routing (DVB-S/S2/RCS support), Multiplexing, Mesh networking, Digital filtering, turbo decoding. user-user connectivity, Flexibility in (i) channel to beam assignment, (ii) Bandwidth allocation, (iii) uplink-downlink channel mapping.	Multibeam broadband multimedia services • Reduced latency
Thuraya (L band)	DTP (Processing in IF)	Digital Beam forming; Flexibility in (i) channel to beam assignment, (ii) Bandwidth allocation, (iii) channel gains, (iv) uplink-downlink mapping.	Interactive services, GSM Real-time adaptation
Inmarsat-4 (L band)	DTP (Processing in IF)	Digital Beam forming; Flexibility in (i) channel to beam assignment, (ii) Bandwidth allocation, (iii) channel gains, (iv) uplink-downlink mapping.	Global 3G Mobile Communications • Enhanced rate, flexibility, capacity

Challenges with OBP



- **Additional payload/hardware is required**
  - Higher mass and power consumption
  - Manage processor heating
- **Reliability**
  - Backup DSP chains is required in case of component failure
- **Adaptivity**
  - Reconfiguring HW chains
- Limited **sampling capability** (ADC dynamics and power requirements)
- A key question to be answered: **How much OBP?**

Low cost but reliable processing techniques are required

Conclusions

- Driving applications for SatCom are changing:
    - Absolute need to take advantage of new & advanced DSP solutions overcoming conservative approach of the satellite industry
    - New paradigms are emerging, large-LEO networks, small/cheap/redundant satellites
- From link to communication network design
- Applicability of different DSP solutions
    - Important differences between Sat/Terr: Not straightforward extension of terrestrial solutions
    - Long channel coherence time favors many advance DSP solutions
- High Throughput Satellites
    - Interference mitigation required – MUD, pre-coding, interference cancellation, resource management, etc.
    - Cognitive radio techniques have great potential to exploit spectrum more efficiently
- On-board Processing
    - Networking functionality on-board
    - Increased flexibility adapting to traffic demand
    - Numerous challenges remain

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