Satellite radio-frequency payloads and instruments - Overview and challenges

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Agenda

- 16:30-17.15 Satcom tutorial:
  - Overview of satellite Communications Payloads
  - The need for Flexibility
  - Flexible Payload Architectures
  - Enabling Technologies
  - GEO vs non-GEO systems
  - Challenges Ahead
  - Digital processors
  - DBF quantitative scenarios
  - Efficient DBF algorithms
- 17.15-18:00 RF digital equipment:
  - RF Digital Equipment Components
    - Active Arrays
    - Processors
    - Routers
  - Annex on UDSM
    - IPs for RF payloads
  - Annex on 5G:
    - Intro
    - System aspects
    - 5G Payloads
    - 5G Components
    - EEE

Satellite Communication Applications

Satellite communication classical applications include:

- *Broadcast services*
- *High speed Broadband Services*
- *Mobile connectivity*
- *In flight connectivity*
- *Secure Communications*
- *IoT Services*

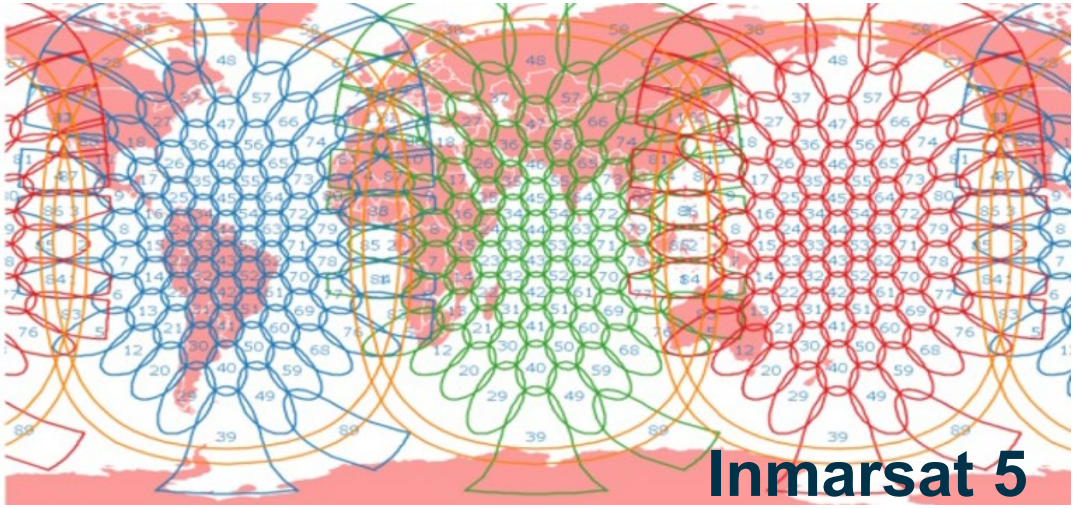
Requirements on: latency, coverage, availability, high rates, low power

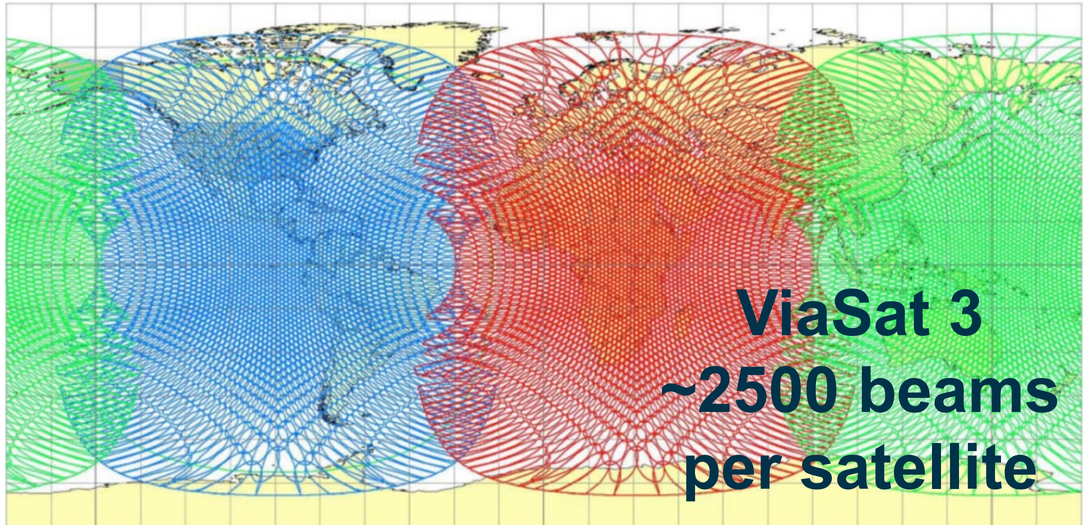
…and possibility to contribute/extend 5G networks with the 5G NTN component…

… but many challenges ahead!

The Challenge until now … Terabit(ps) GEOs

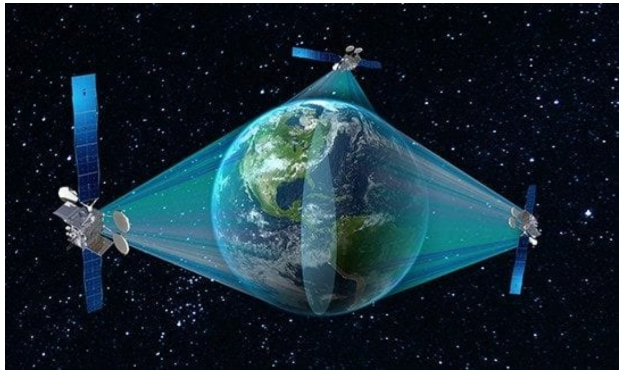
- Trend until approx. 2017-2018 to target VHTS per single GEO satellite (~1Tbps per satellite)
- Targeting maximum capacity is often not able to offer full payload flexibility (e.g. coverage/beamforming flexibility with digital processors)
- Digital beamforming at element level is currently not yet feasible for supporting the full capacity (too high power consumption)

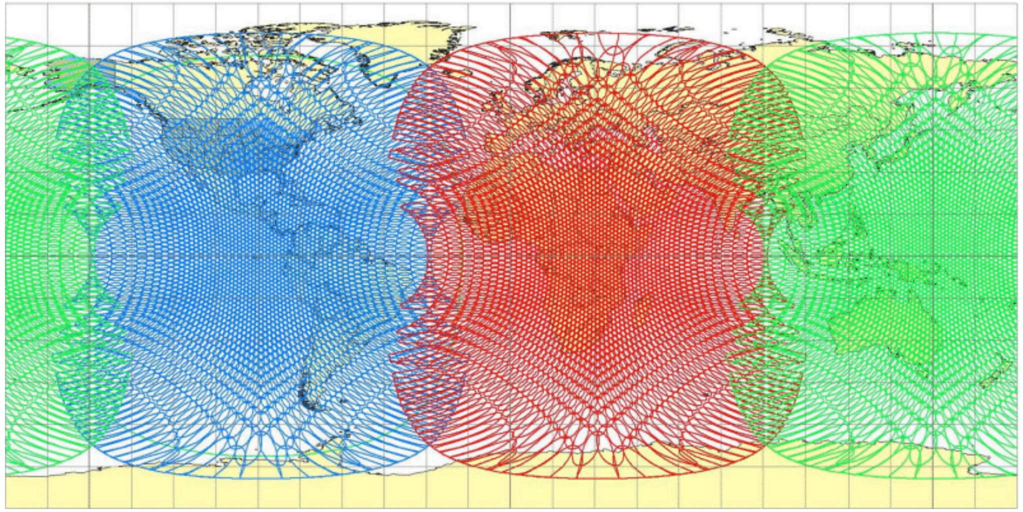




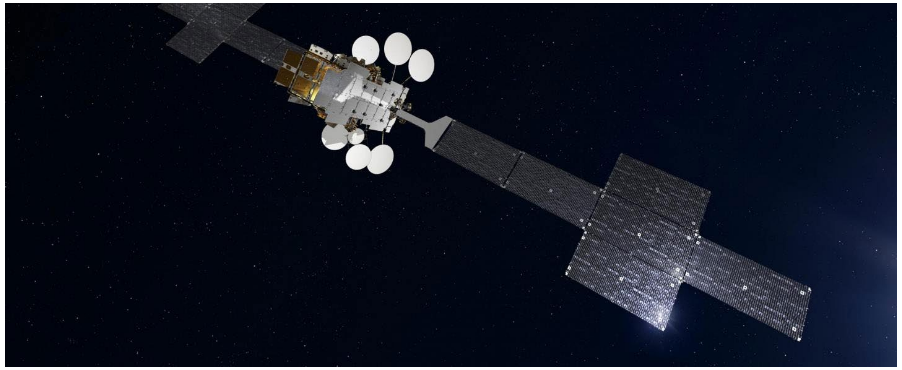
HTS systems - Bent-pipe Single feed per beam

-Viasat-1/2 (VHTS)

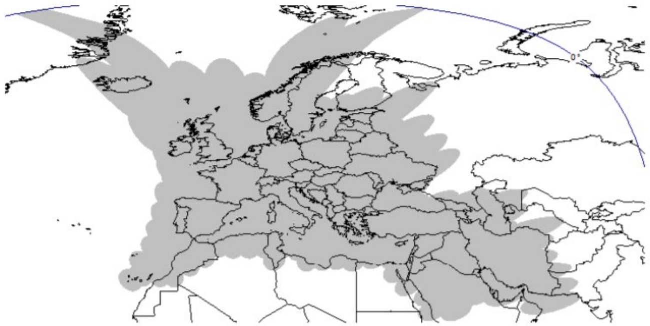




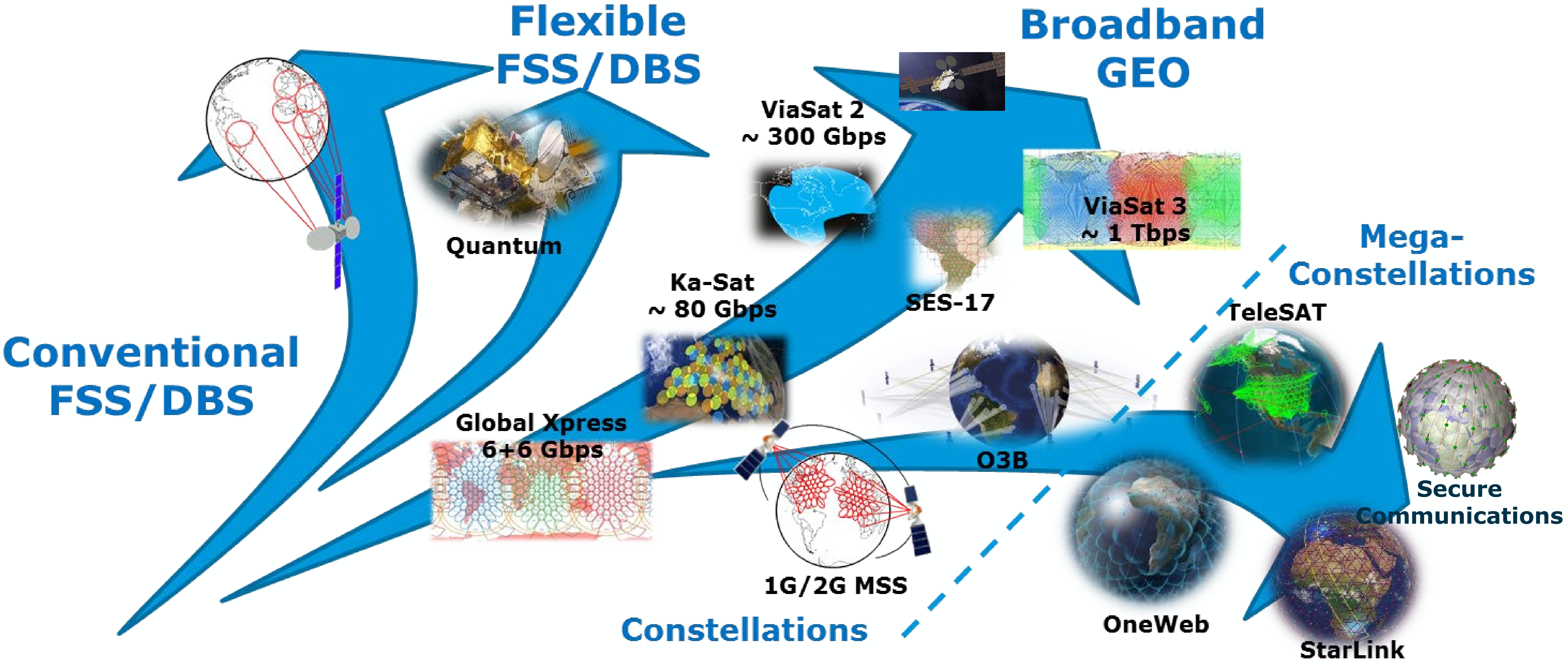
- SES-17 (VHTS)



- EUTELSAT KONNECT (VHTS)



Satellite Communication Systems – Trends (Excluding New Space)



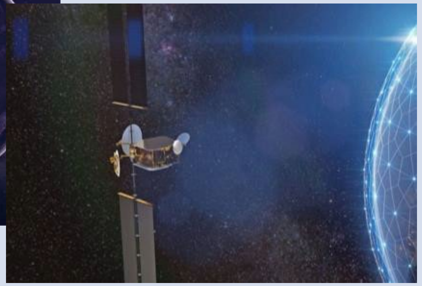
Recent Satellite Systems – *a very non-exhaustive overview*

GEO

Spaceinspire (TAS)

Source/Credit: TAS

Onesat (ADS)



Source/Credit: ADS

MicroGEO/Hummingsat (Swissto12)

Source/Credit: Swissto12

MEO

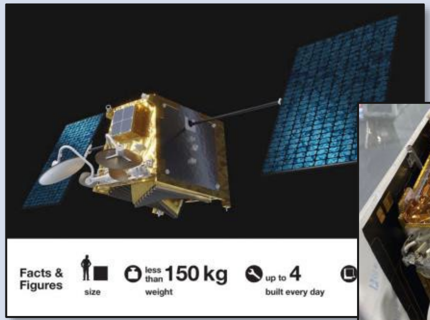
O3b - mpower

Source/Credit: Boeing

LEO

SpaceX - Starlink

Oneweb



Credit: Oneweb, ADS

Joeysat

Lightspeed - Telesat

Source/Credit: Telesat, MDA

Aurora

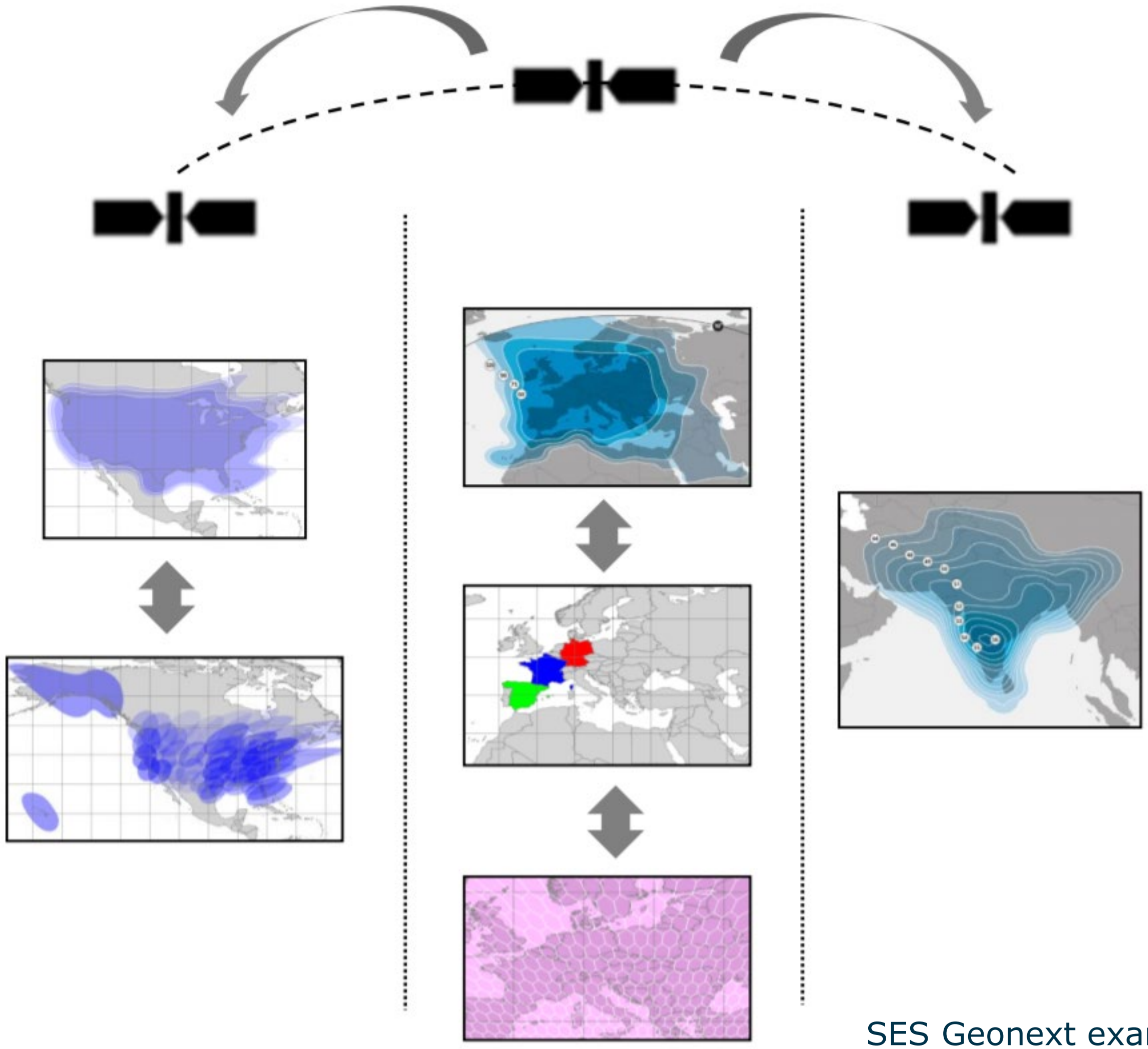
Source/Credit: MDA

and D2H/D2D…

Recent GEO Trend – Flexible Medium Capacity

Since 2017/2018, for GEO the attention has also moved toward the capability to achieve flexible, medium capacity, short time-to-market satellite solutions

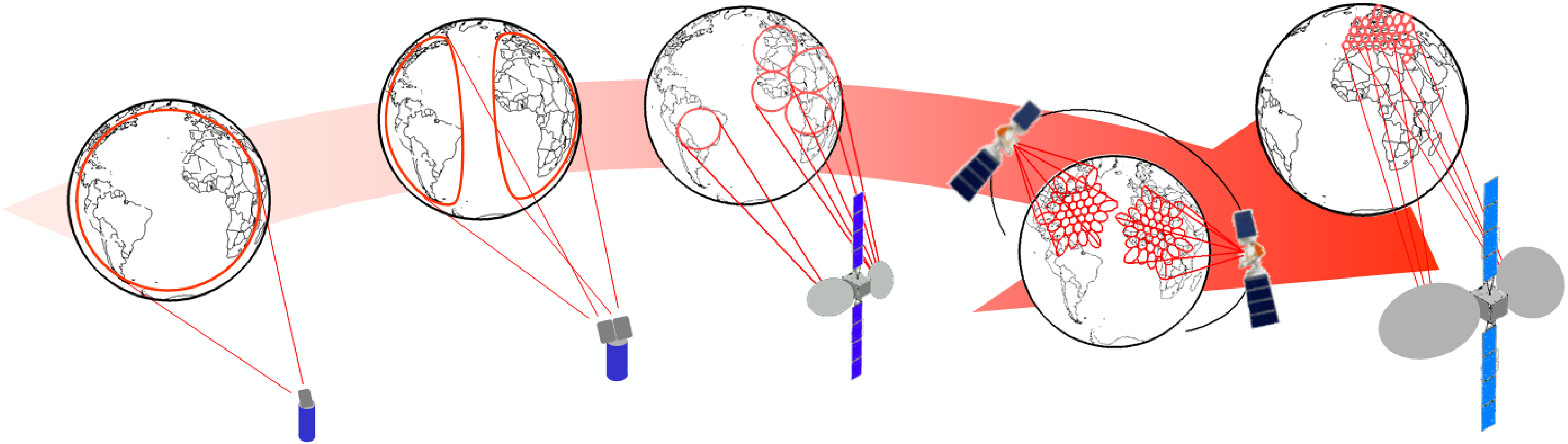
- Targeting mainly Ku/Ka-band services on continental coverage for both broadband and TV broadcast
- Throughput Range 50-100Gbps), with beams of moderate size (about 0.5 degs).
- Payloads based on digital processors and array-fed reflectors with about ~100-200 radiating elements.
- Payload Power Consumption expected in the range 10-15kW
- Coverage flexibility is a key requirement (shaped beam and spot beam capability-reconfigurability)



SES Geonext example, *source www.ses.com*

SATCOM System Needs for Flexibility

- High degree of coverage and mission re-configurability during lifetime to cope with time variant commercial requirements
- Simultaneous support of multiple beams (global and regional) or large number of spot beams with high level of frequency reuse with in-flight re-configurability
- Increased request for flexibility (coverage, power, signal)



Call for Flexibility

Operators' Expectation

- Flexibility to adapt to evolving business conditions
  - Market evolution (services and/or users)
  - Satellite Operator Competition
  - Terrestrial Network Competition
  - Evolution of Terminal Technology (Transparency)
- Early entry into new markets
- Rationalization of the procurement process (schedule, less customization)
- Efficient operations (Payload Resources, in-orbit redundancy, different orbital slots)

Manufactures' Expectation

- Increase of generic equipment volumes
  - Less customization
  - Decrease of equipment types
  - Increased production runs, Wider range of usage
  - Effective buying/stocking policy for parts
- Reduced Non Recurring Engineering (NRE)
- Late definition/modification of the missions
- Industrial competitive advantages
  - Differentiator wrt competition
  - At regime lower costs and shorter schedule

KEY TECH

Active Antennas

- Power / coverage / orbit flexibility

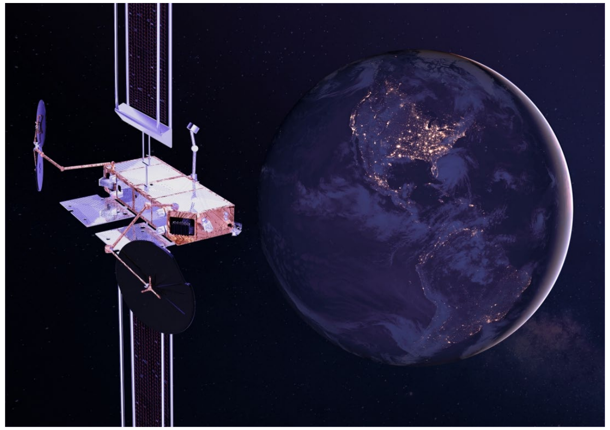
On-Board Digital Processors

- Routing / switching / beamforming / hopping flexibility

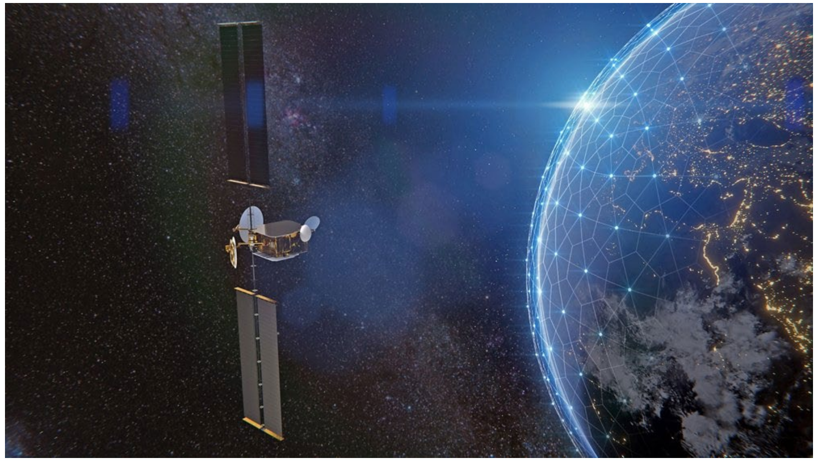
Flexibility, modularity, scalability, genericity

Recent European Mid-Class Flexible Payloads

- Recent European platform and payload developments (e.g. ADS Onesat and TAS SpaceInspire) target indeed mid-class fully reconfigurable payloads, based on digital transparent processor, distributed amplification and active antennas.
- These payloads will be equipped with latest digital processors developments with also digital beamforming capability
- Software defined, moderate/high capacity, agility, in-orbit reconfiguration, flexible coverage, proven serial production
- Obviously flexibility comes at a cost, they are not able to achieve (yet) very high throughput capacity per satellite (e.g. about 200-300Gbps in FW link)



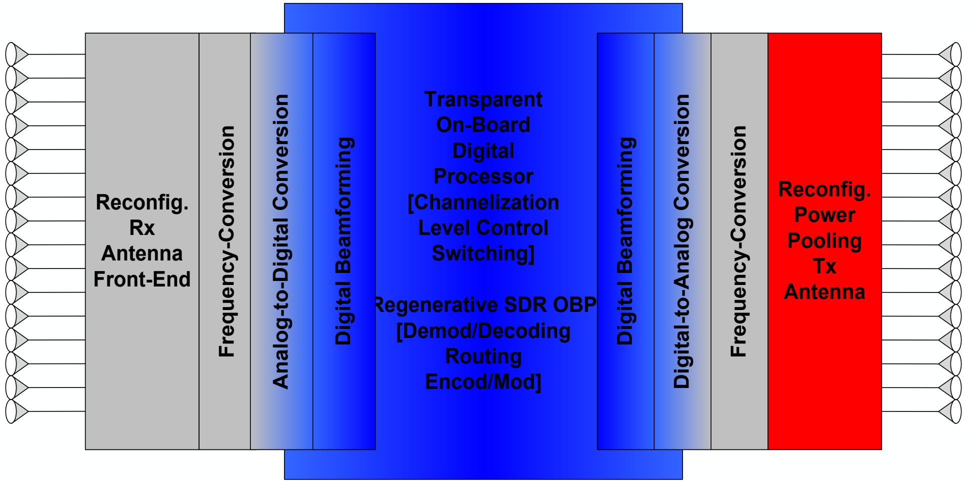
SpaceInspire artistic impression (Thales website)



Onesat artistic impression (ADS website)

The Ideal SATCOM Payload

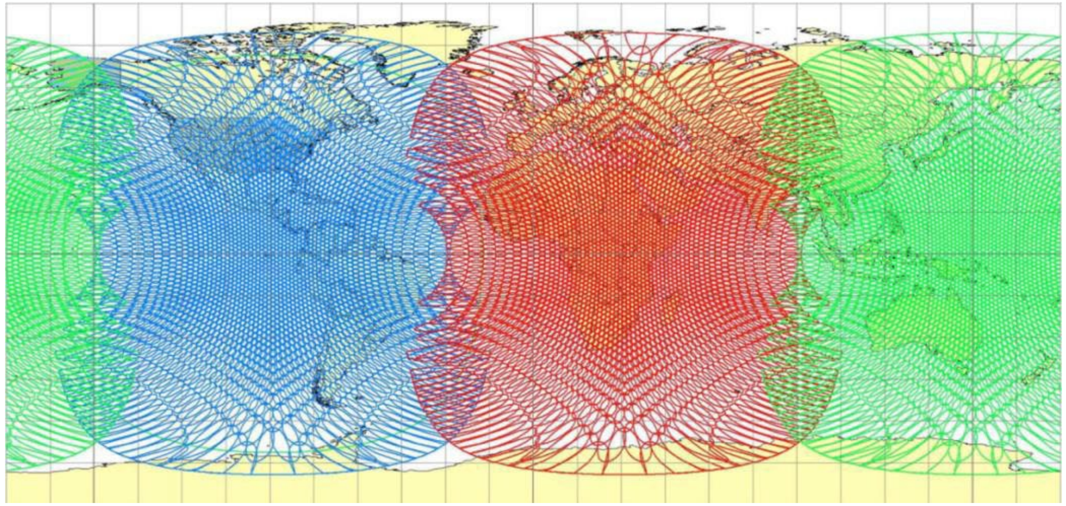
- **Modular (active) antenna** able to cope with different type of missions with flexibility in power allocation
- Compact low-mass/low-power modular **RF Frequency Conversion Chains** (one per antenna feed)
- **Core common digital processor, reprogrammable and reconfigurable** providing the required flexibility in terms of:
  - Satellite coverage
  - Beam shape
  - Beam frequency allocation / Beam Hopping
  - Regenerative Functions: MOD/DEMOD, COD/DECOD
  - Frequency Channelisation
  - Routing and Switching (also to Inter-Satellite Links)
  - Sharing between bent-pipe and meshed capabilities
  - Payload self-calibration
  - Geolocation and Spectrum Monitoring Functions
  - Future “ready” (e.g. 5G compatible)



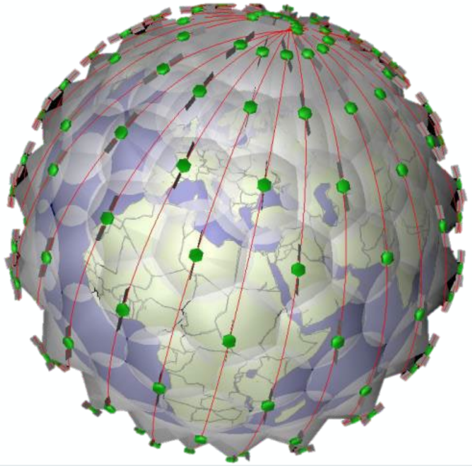
GEO vs MEO vs LEO - Constellations

Recent years have seen the re-proposing of the well-known trade-off between GEO and non-GEO:

- GEO: 3 GEOs provide global coverage except polar regions
- MEO: Provides global coverage except polar regions with 4-20 satellites
- LEO: Provides global coverage with hundreds to thousands satellites with:
    - + Limited latency (30-50ms wrt 600-800ms for GEO orbit)
    - + Smaller satellites / series production
    - + Larger # satellites
    - + Possible polar areas coverage
    - - Shorter lifetime, high (total) launch cost
    - - User terminal tracking antenna
    - - More complex infrastructure deployment and management
    - - More difficult spectrum sharing



VS

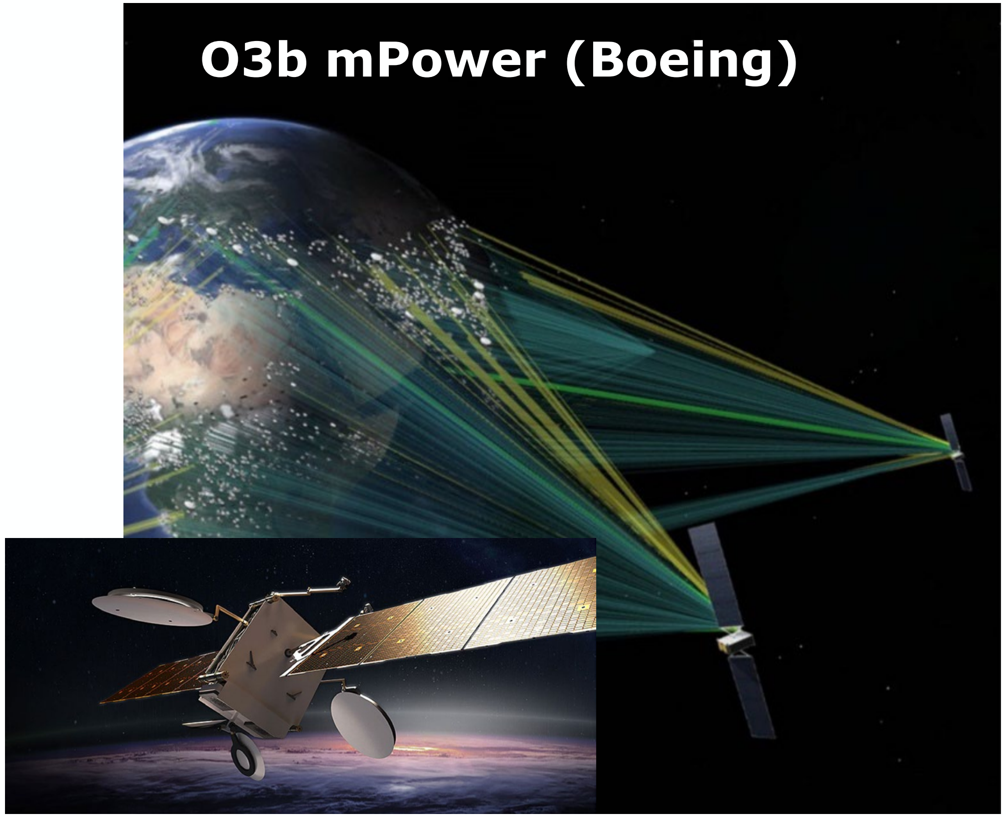


The Challenge until now … Constellations

Recent Broadband systems are emerging in LEO and MEO

Operator	Satellite system (deployed)	Spectrum	Technology	Operational	Services
Space X (Starlink)	12000+ (3580)	Ku-band	Proprietary	Yes	Broadband
OneWeb	648 (542)	Ku-band	Proprietary	TBD	Broadband
Kuiper	3236 (0)	Ka band	Proprietary	Estimated 2024	Broadband
Galaxy Space	1000 (7)	Q/V spetrum	Proprietary	TBD	Broadband
Boeing	147 NGSO (1)	V band	Proprietary	TBD	TBD
Inmarsat	14 GEO (14)	TBD	Proprietary	TBD	Broadband to IoT
Telesat	188 (2)	C, Ku, Ka bands	Proprietary	TBD	Broadband
Echostar	10 GEO (10)	Ku, Ka, S bands	Proprietary	Yes	Broadband
HughesNet	3 GEO (2)	Ka band	Proprietary	Yes	Broadband
Viasat	4 GEO (4)	Ka band	Proprietary	Yes	Broadband

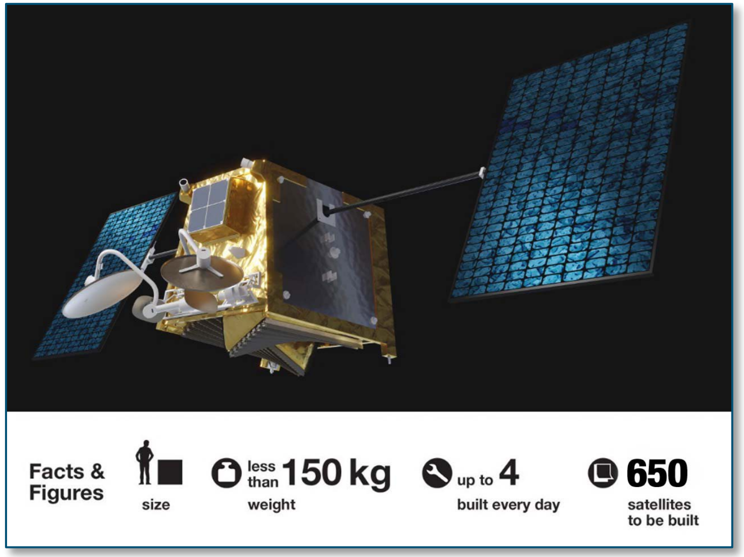
Source/Credit: 5G Americas



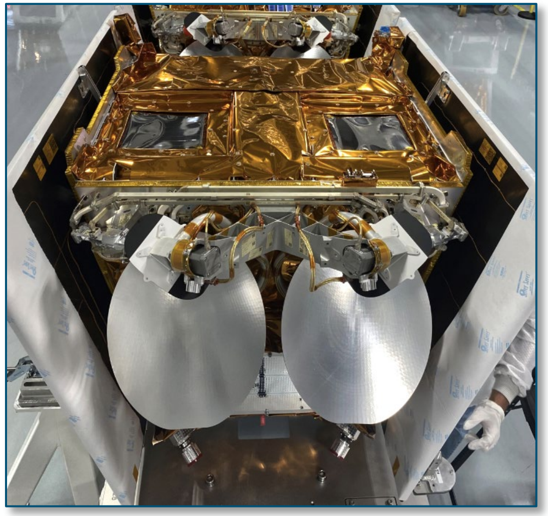
- MEO System
- Supported by Software Defined Radio Boeing 702X satellites
- Digital beamforming performed (claimed up to 5000 beams per satellite)

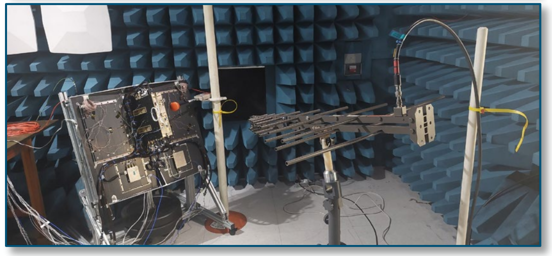
The Challenge now and Ahead … Mega Constellations

Oneweb



- >618 satellite launched to date
- Sat: 150kg, 1kW
- Ku-band non-active antennas
- Next generation Oneweb 2nd gen will likely increase satellite size (~500kg) and upgrade payload capabilities based on active antennas and digital processors





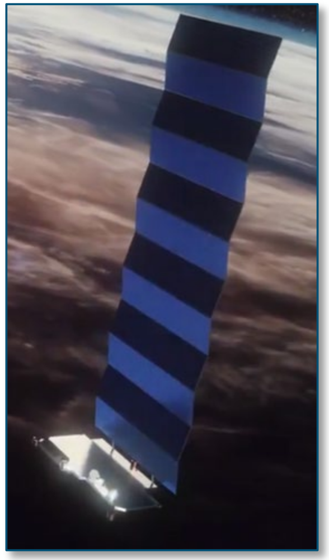
Credit: JoeySat satellite, (demonstrator for 2nd gen)

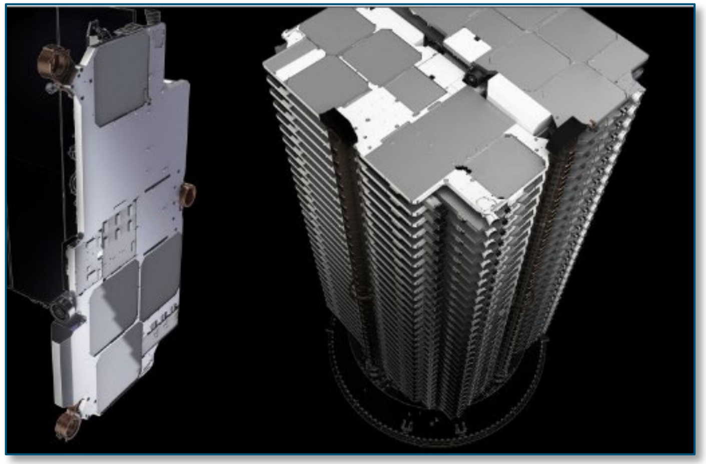
Lightspeed - Telesat

Main Facts:

- 198 satellites on polar orbit
- payload based on:
  - Ka-band active phased array antennas
  - Digital processor,
  - Digital beamforming, and beam hopping
  - Sat Class: ~750kg, ~2-3kW

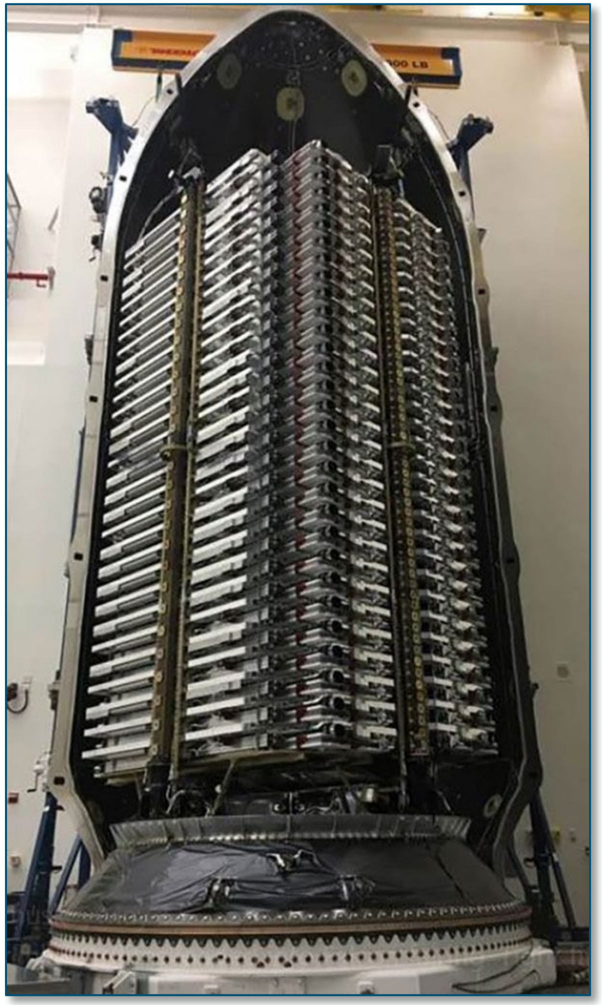
The Challenge now and Ahead … Mega Constellations





Starlink

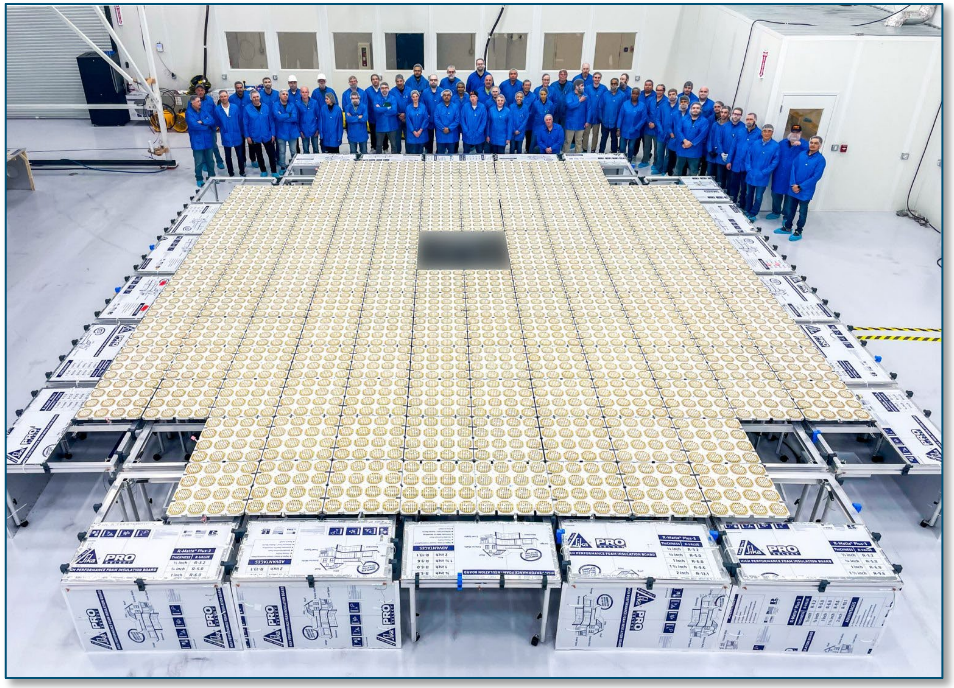
Starlink high level facts		
Mass	260kg	
Payload	Phased Array Antenna based Ku-band, ~600W	
Dimensions	Stowed	2.8m x 1.5 m x 0.23m
	Deployed	P/F:3.7m x 1.5m x 0.1 m SA: 2.8 m x 8.1 m
Launch	Falcon 9; 60 sats/launch	



- About 4000 satellites launched so far!
- Starlink 2nd gen will feature much larger satellites. V2 mini satellites have been recently launched

Direct to Handheld and NB-IoT - Status

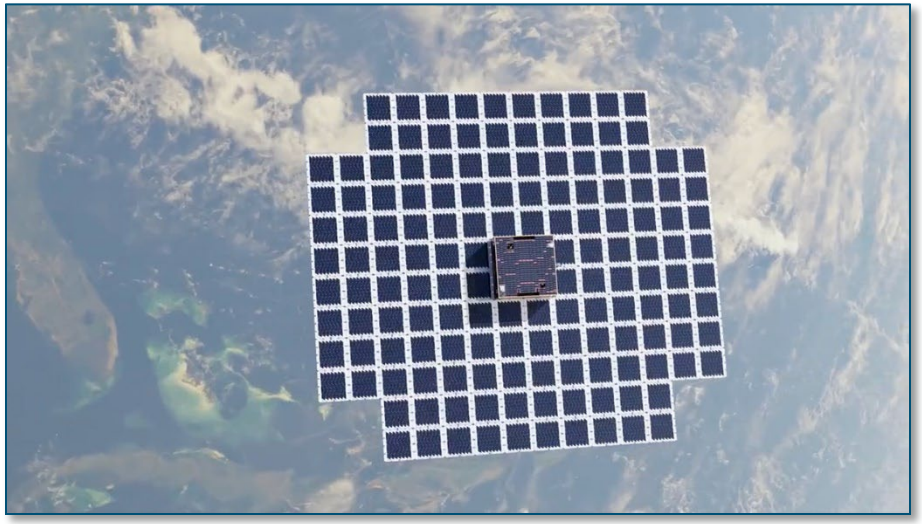
Broadband Applications



Source: AST-Science Spacemobile, BlueWalker 3 prototype satellite

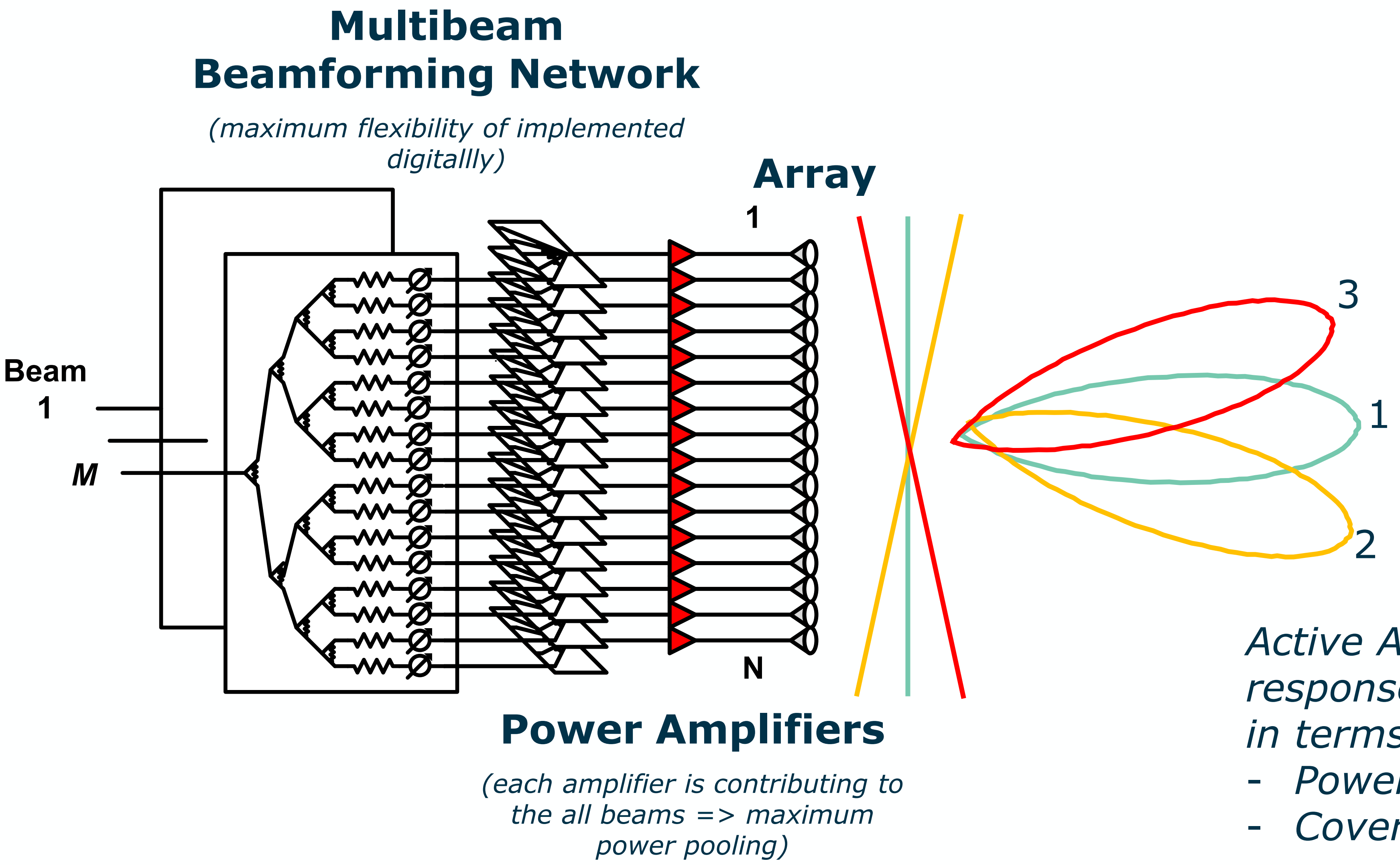
Main Facts:

- 64m^2 aperture
- 3GPP Frequency: 750-850MHz
- Enables data-rates ~10Mbps



On April 25 2023, made the world's first space-based two-way telephone call with unmodified smartphones (a Samsung Galaxy S22 and an Apple iPhone) using the satellite.

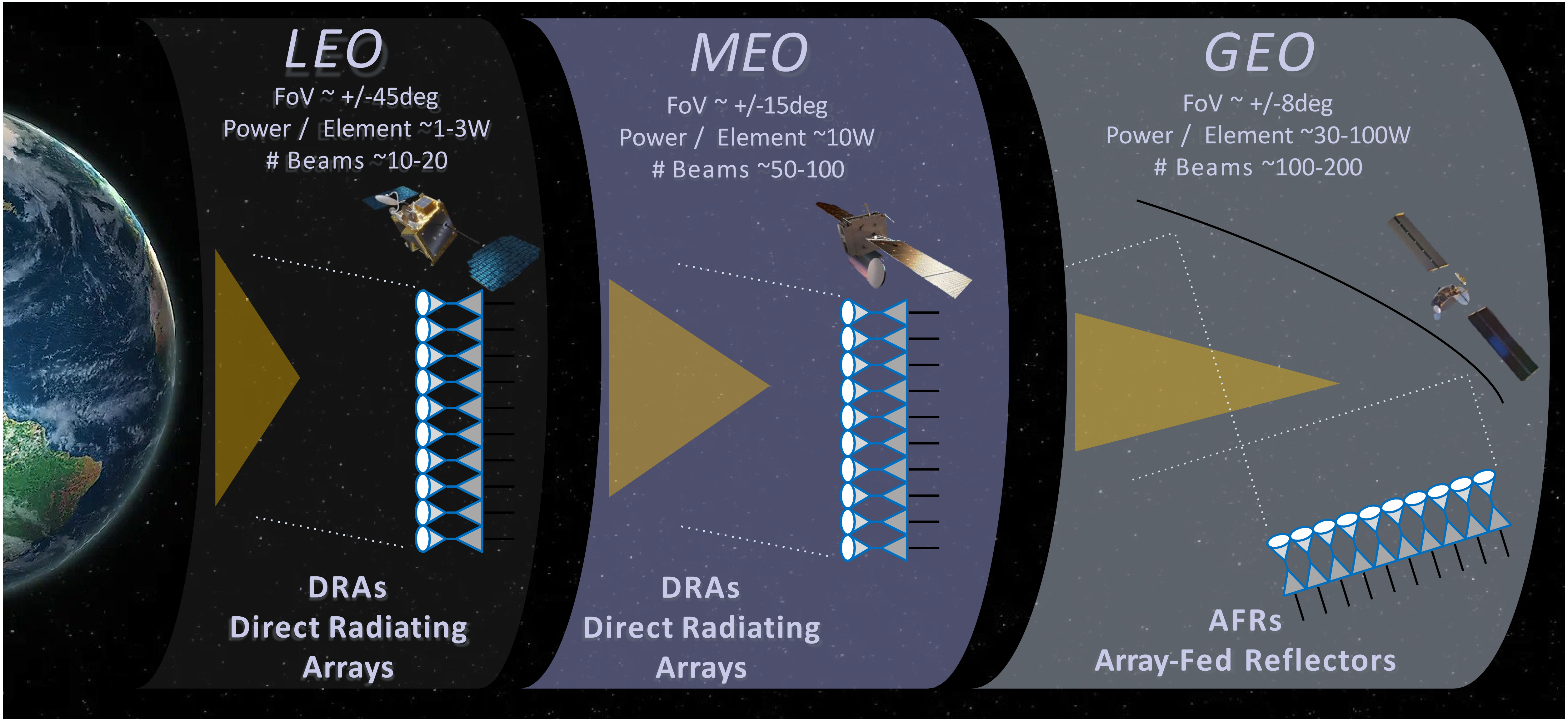
Multibeam Active Array - Principles



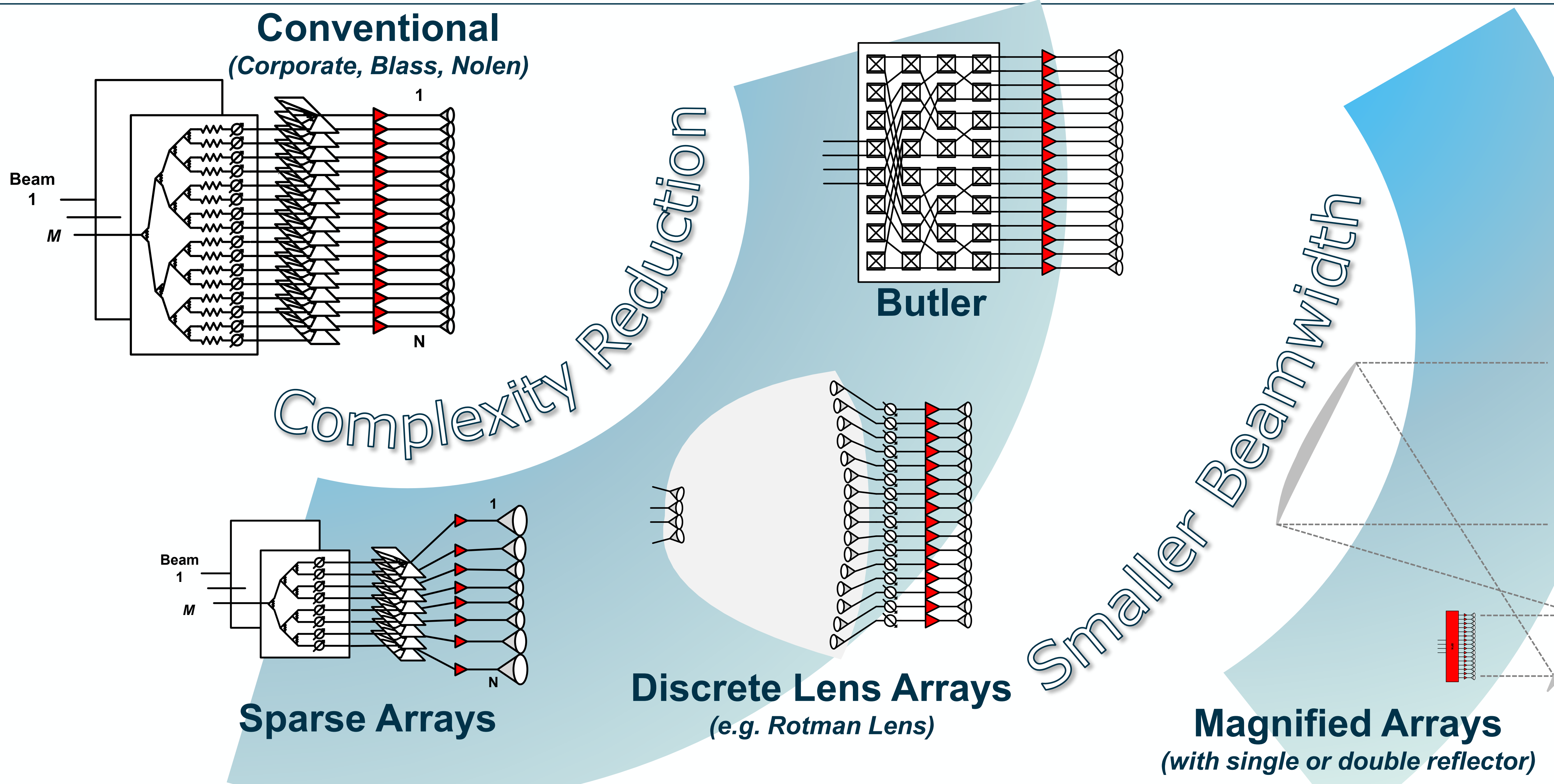
Active Antennas are the natural response to the need of flexibility in terms of:

- *Power Pooling*
- *Coverage Reconfigurability*

Active Antennas in LEO, MEO and GEO



Active Multibeam Antennas / Beamforming



Digital Beamforming - Features

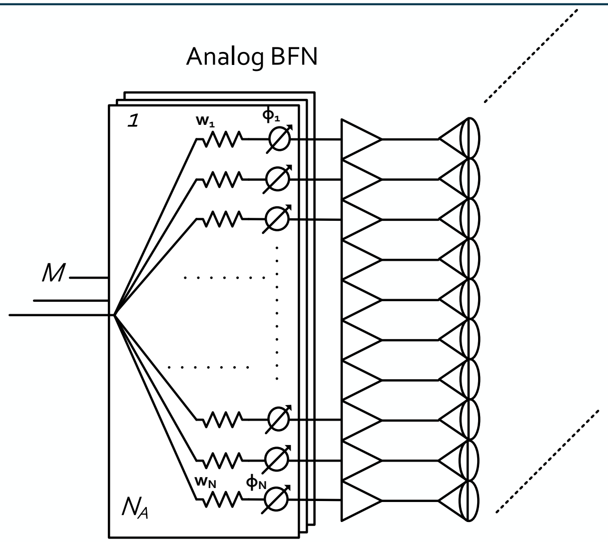
DBF can offer the following non-exhaustive list of the features

- Beams can be individually formed, steered and shaped.
- Beams can be assigned to individual user.
- Beamforming strategy can be software upgraded.
- Interference can be minimised implementing Adaptive Beamforming.
- DSP techniques (filtering, multiplexing, demodulation, signal information extraction, performance optimisation, etc.) can be integrated.

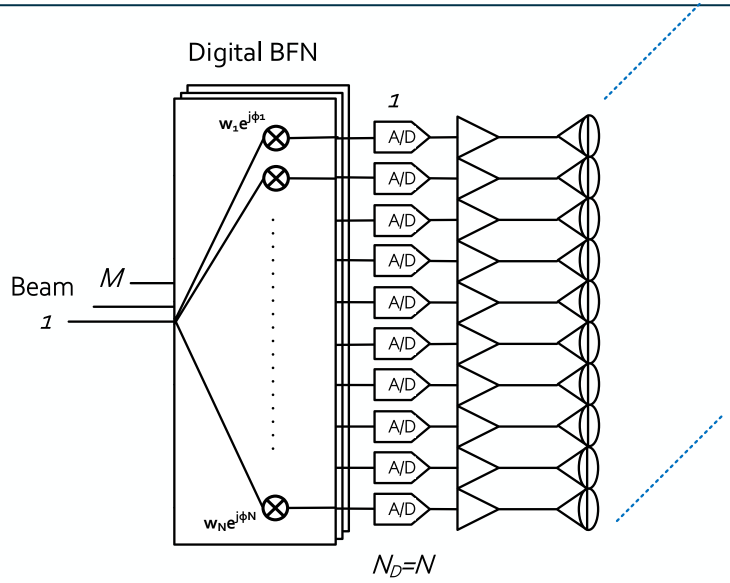
Digital Beamforming Antennas, "the Ultimate Antennas"

A.J. Viterbi

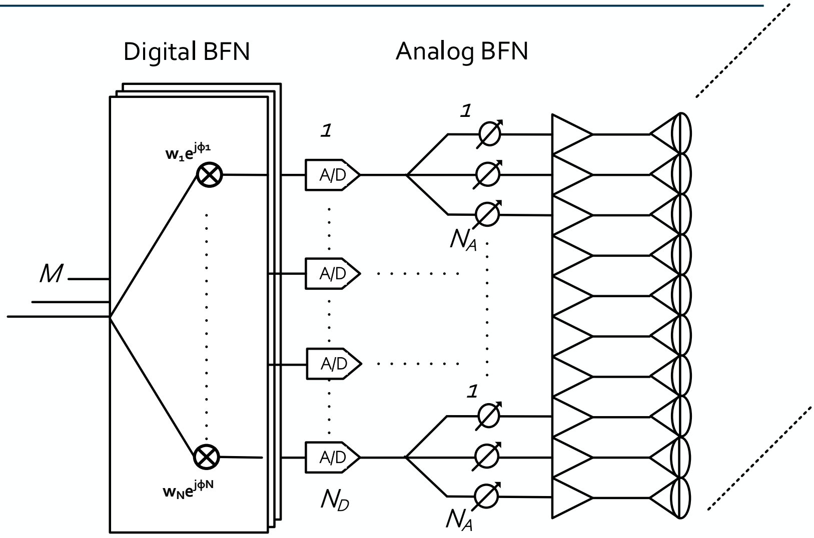
Analog or Digital beamforming? Both!



Analog BFN



Digital BFN



Hybrid BFN

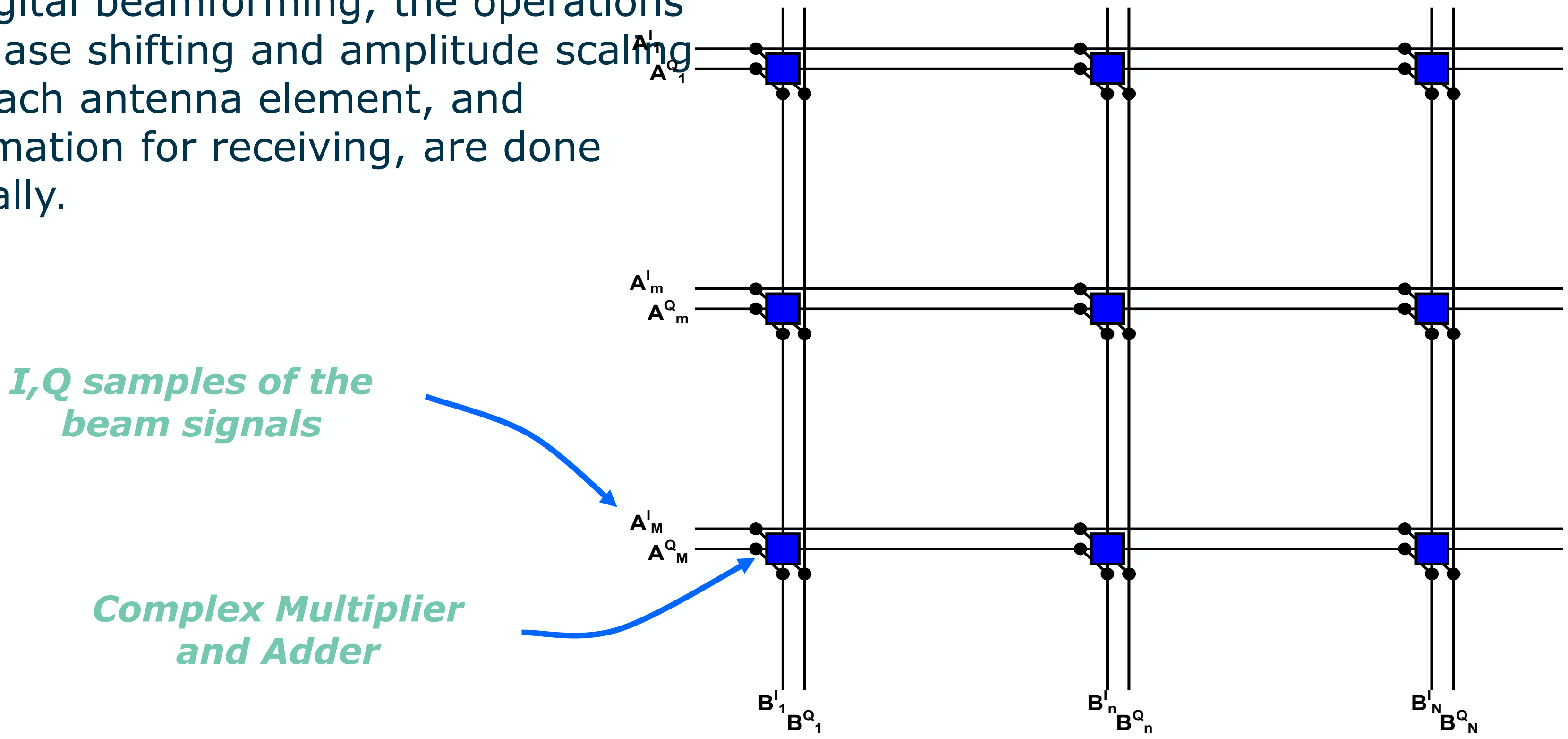
- Cost
- Power consumption
- High number of components for large number of beams
- Mass/Volume
- Precision/Accuracy inferior wrt DBF
- Reduced reconfigurability wrt DBFN

- High flexibility/reconfigurability
- High precision
- High power consumption
- Cost

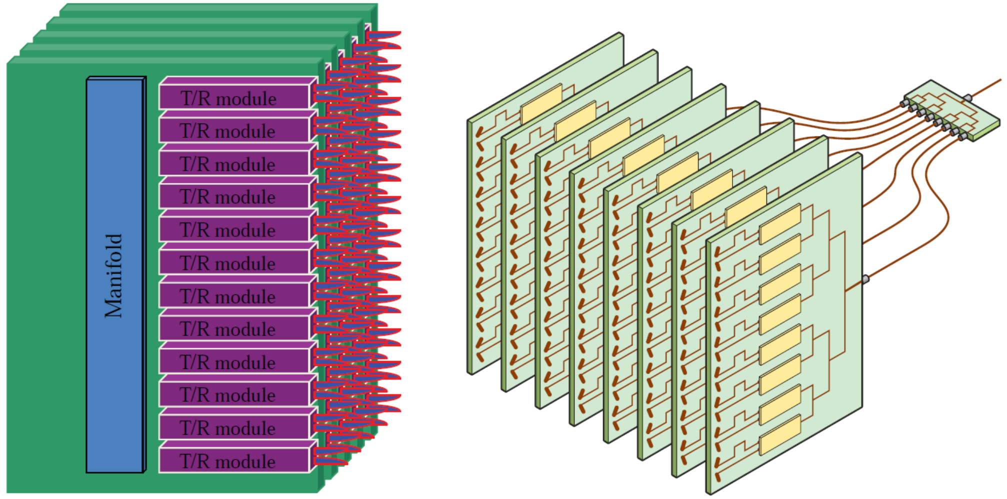
- Good balance between power consumption and flexibility
- Reducing Nr of digital ports (i.e ADCs) with respect to full DBFN
- Complexity/Cost

The other option: Digital Beamforming

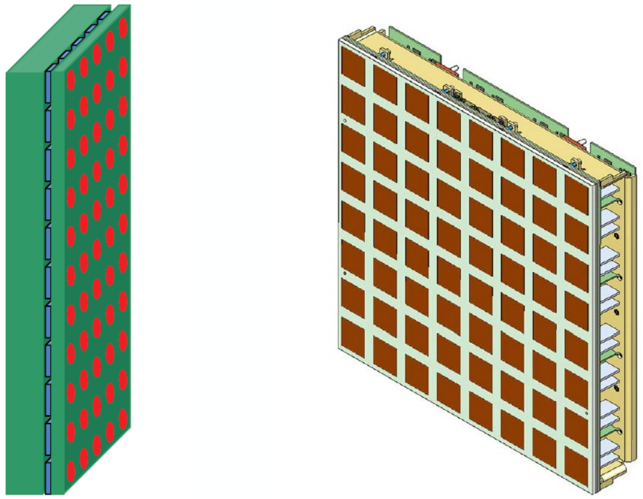
- In digital beamforming, the operations of phase shifting and amplitude scaling for each antenna element, and summation for receiving, are done digitally.



Brick vs Tile Architecture



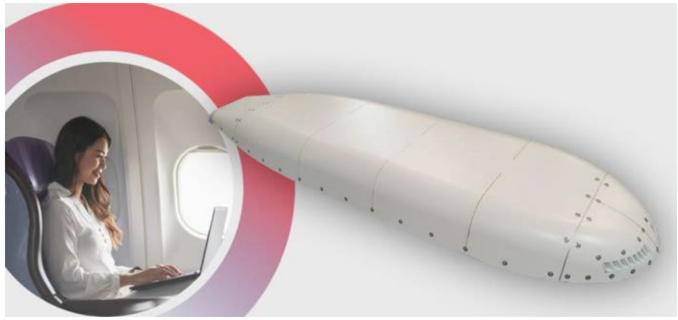
Brick Pictorial Example

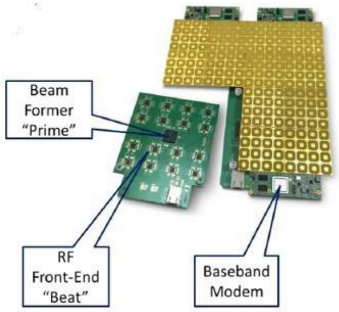


Tile Pictorial example

- Tile Architectures are in principle preferred for size and mass reasons, however practical limitations on technology readiness, power consumption and thermal dissipation lead often to the implementation of Brick Architectures
- Frequency and Tx power per element are also major drivers for the architecture selection
- Typical GEO payloads with active antennas are currently based on the brick architecture, LEO payloads are also moving towards tile architecture

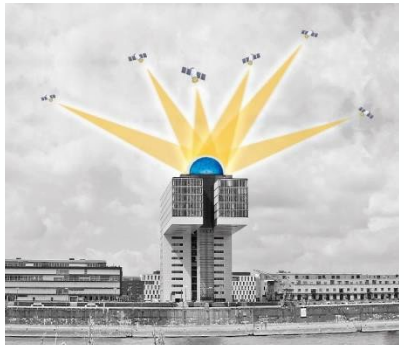
Digital Beamforming (from ground to space and back)





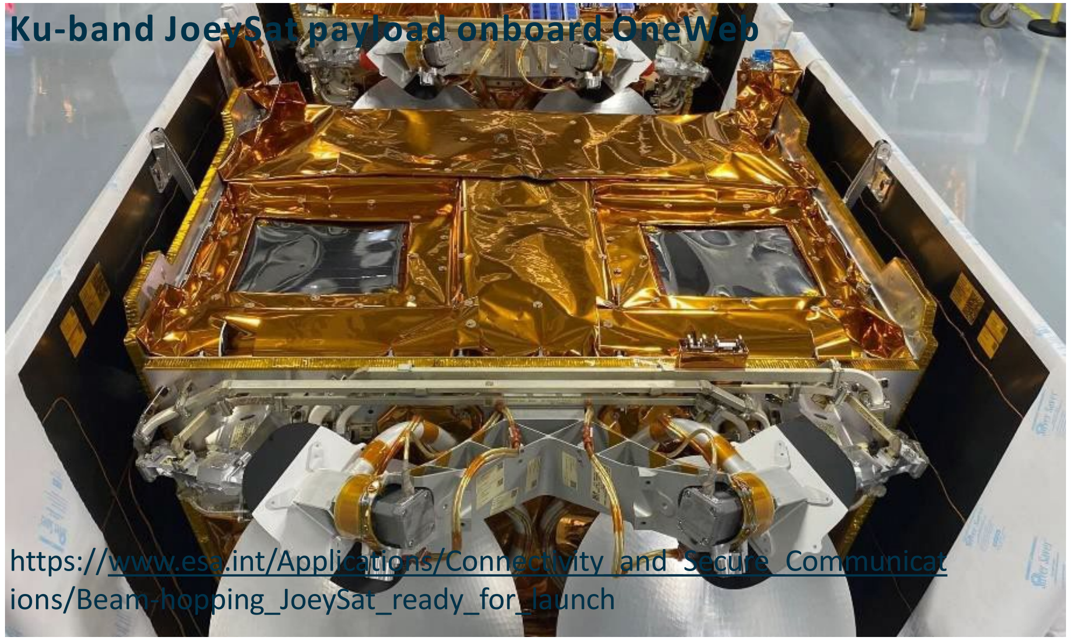
Scalable multi-beam architecture: from eight 1-GHz beams up to 128 60-MHz beams

Game-changer: active antenna gateway demonstrated by Celestia, OneWeb, Satixfy



Beam-hopping DBFN in operation onboard Joeysat since 2023

Ku-band JoeySat payload onboard OneWeb



https://www.esa.int/Applications/Connectivity_and_Secure_Communications/Beam-hopping_JoeySat_ready_for_launch

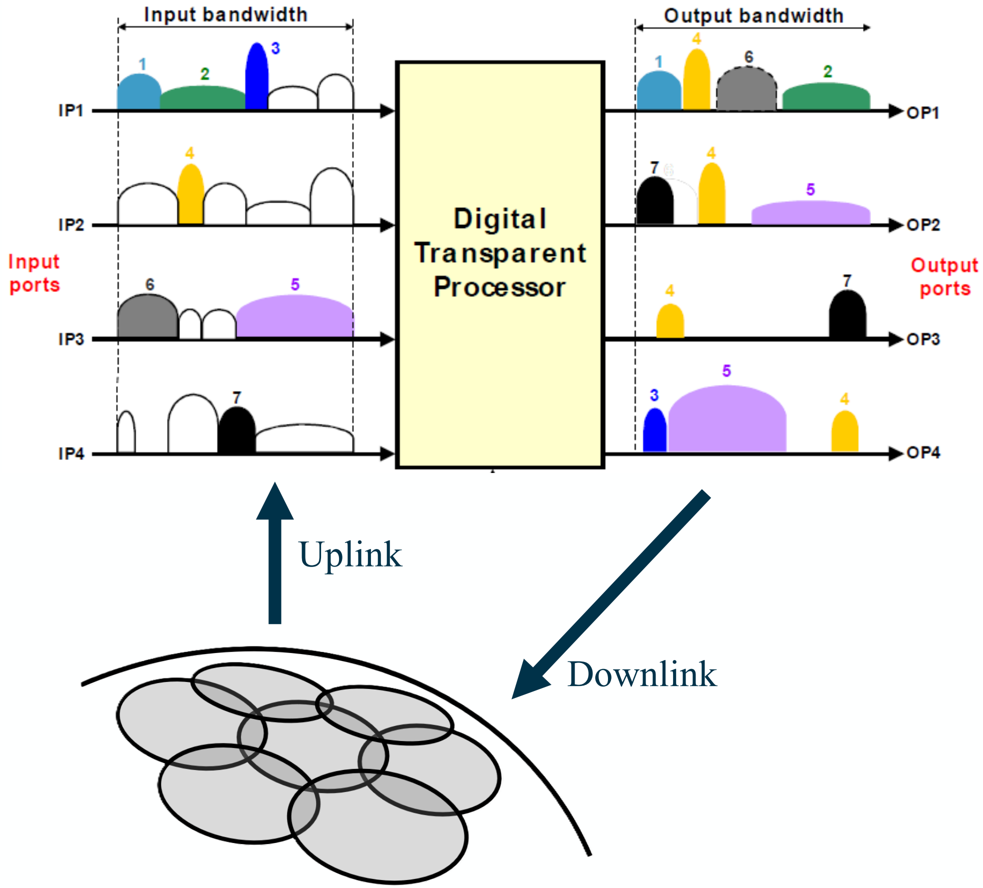
Digital Processors: key enablers for the functionalities of current and next generation payloads

Digital Processors provide critical functions enabling flexibility:

- Communication enabler between GEO, LEO, UAV and terrestrial network systems
- Digital signal/data processing via transparent or regenerative processor: channelisation, routing/switching, digital pre-distortion, digital beamforming, hopping, modem functions
- Active antenna management and beamforming control
- Inter-satellite link enabler via RF or optical links

ESA active support on:

- Technological building blocks (ASICs, FPGAs, ADCs/DACs, HSSLs, packaging)
- Co-design of architectures and algorithms
- Development qualification and in-orbit demonstration



OBP Sizing for HTS

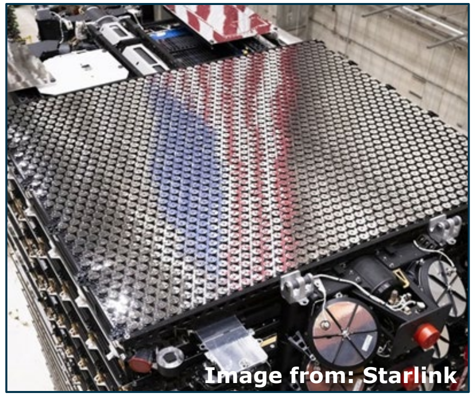
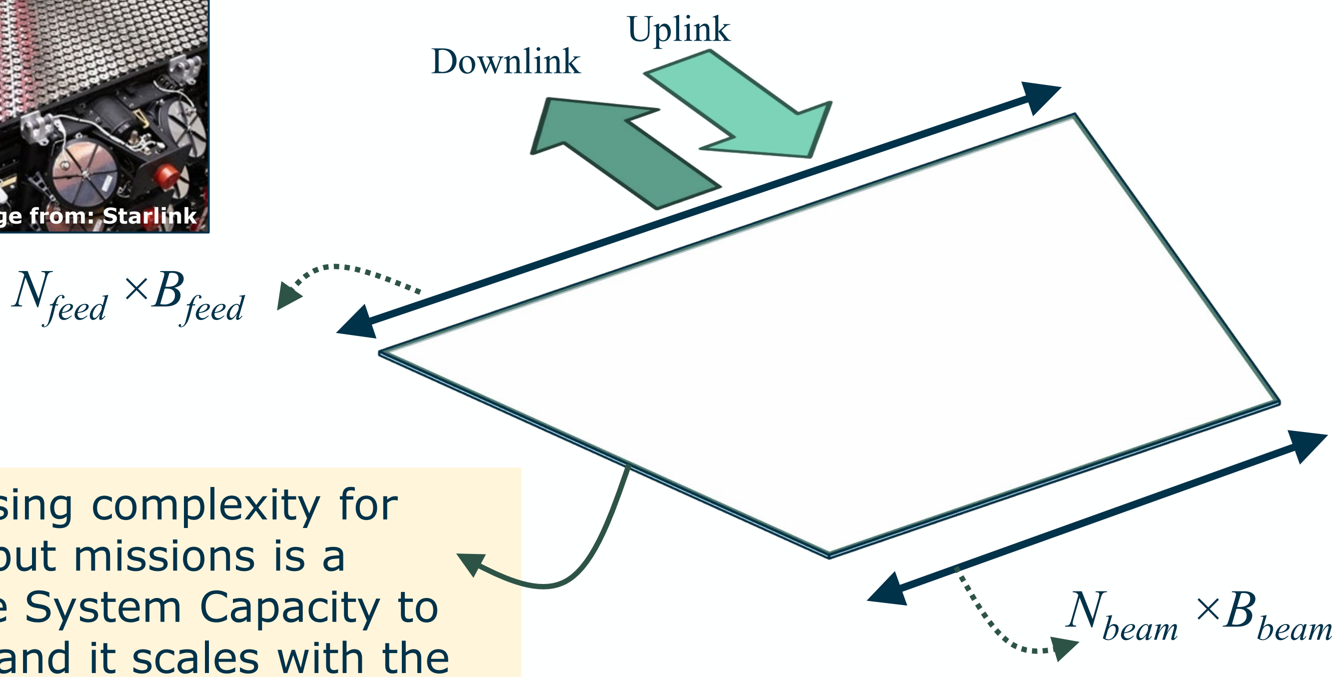


Image from: Starlink



Digital Processing complexity for High Throughput missions is a function of the System Capacity to be processed and it scales with the number of feed ports (N_f) and the beams (N_b) and Bandwidth.

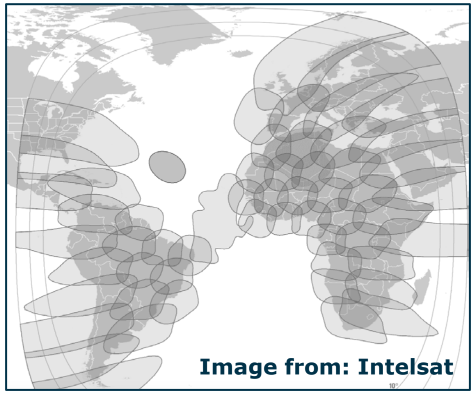
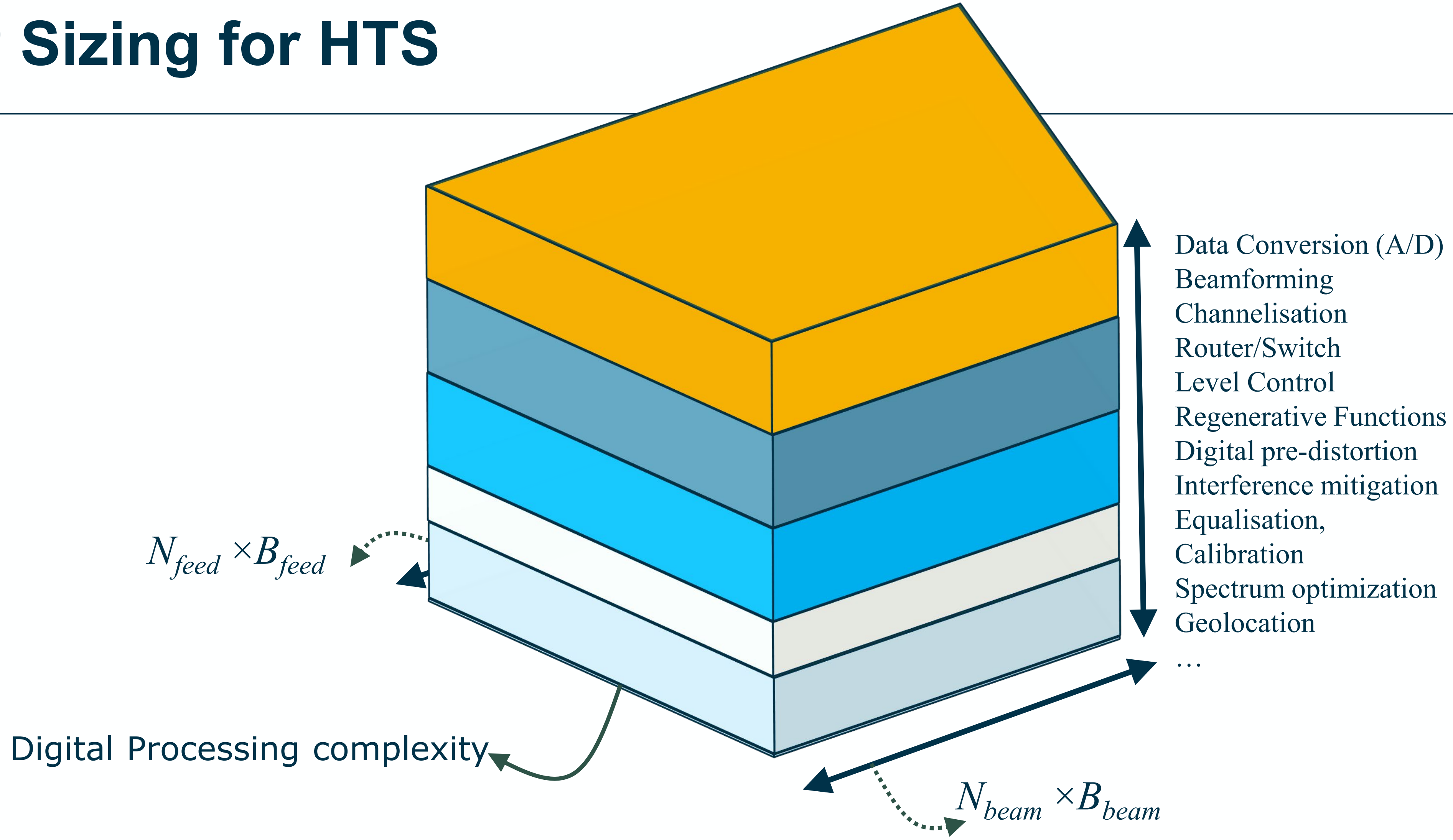
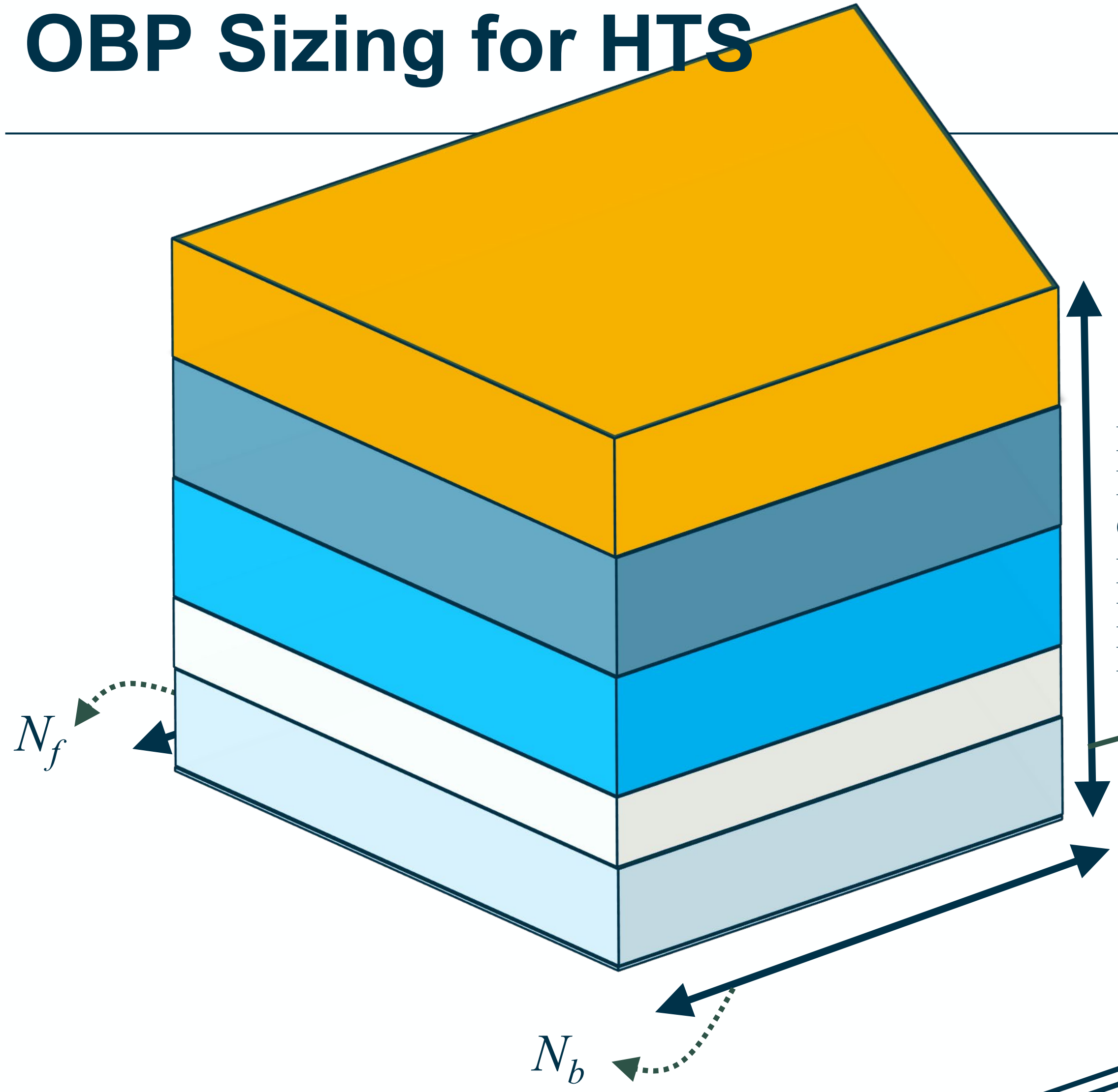


Image from: Intelsat

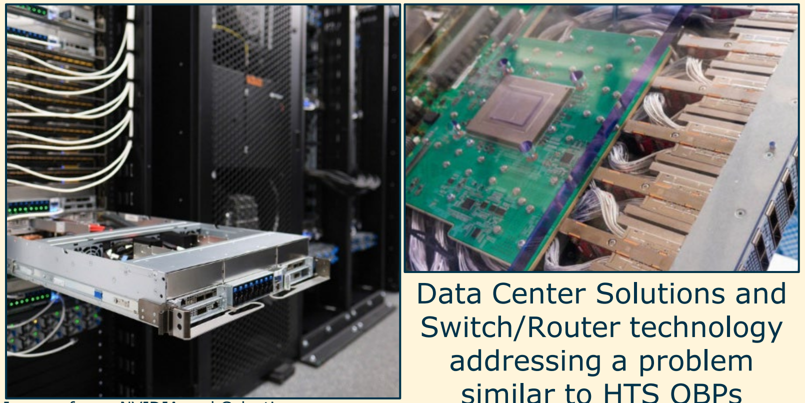
OBP Sizing for HTS



OBP Sizing for HTS

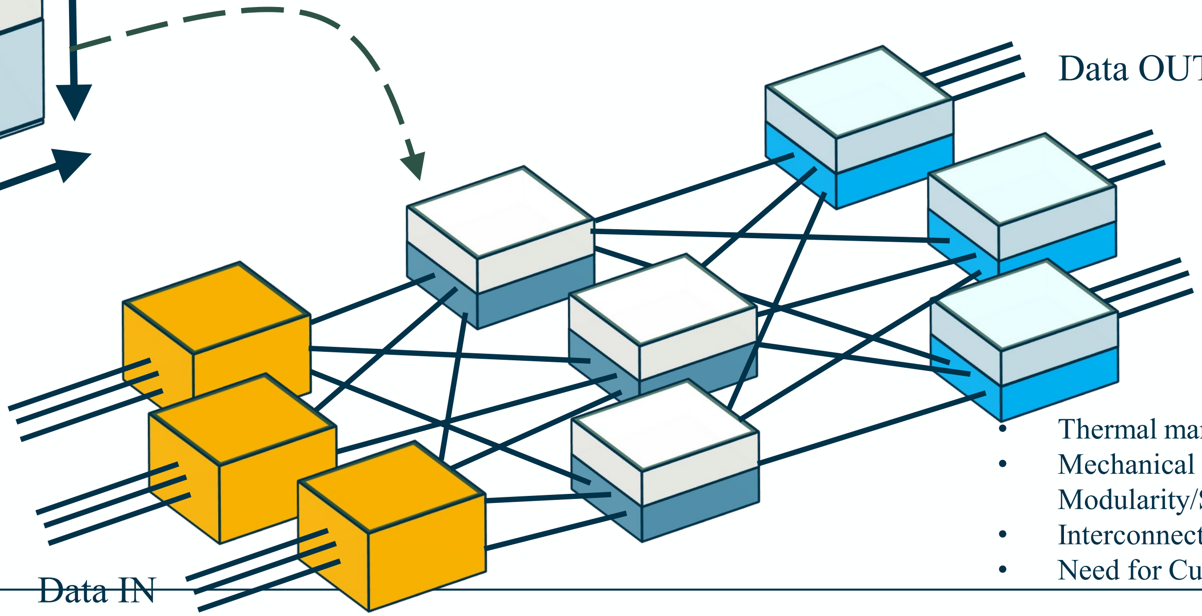


Data Conversion
Beamforming
Channelisation
Routing/Switch
Level Control
Regenerative Functions



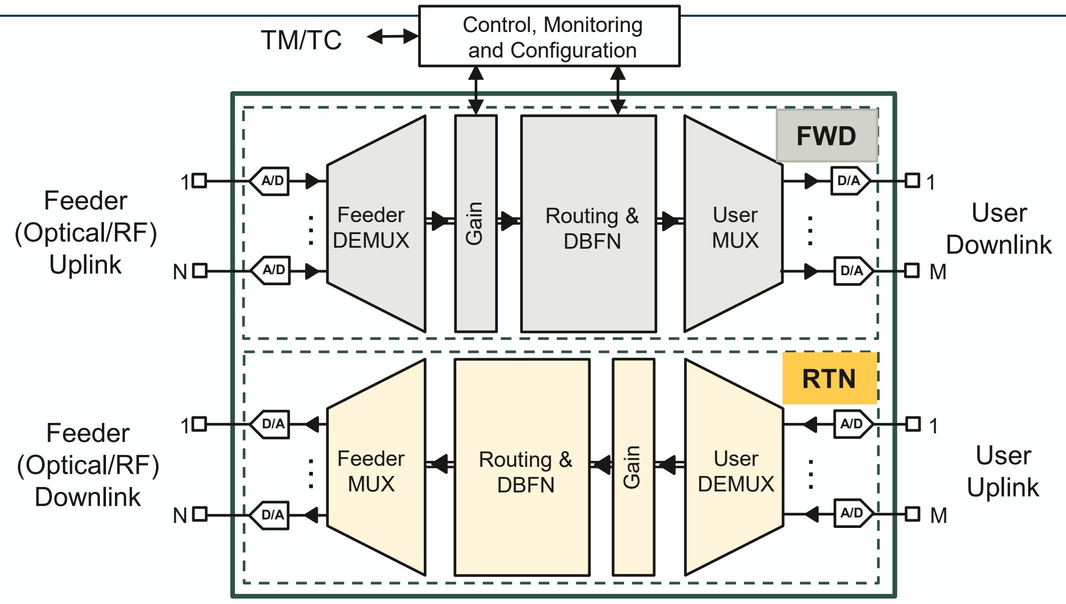
Data Center Solutions and Switch/Router technology addressing a problem similar to HTS OBPs

Images from: NVIDIA and Celestica

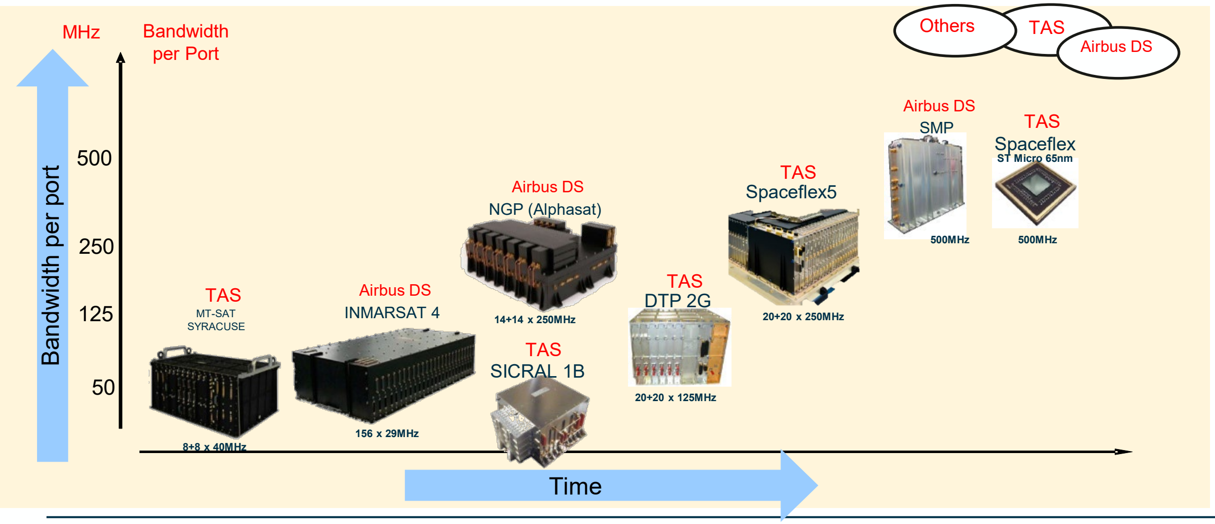


- Thermal management
- Mechanical Constraints and Modularity/Scalability
- Interconnect (HSSL)
- Need for Custom Design

Digital Transparent OBP

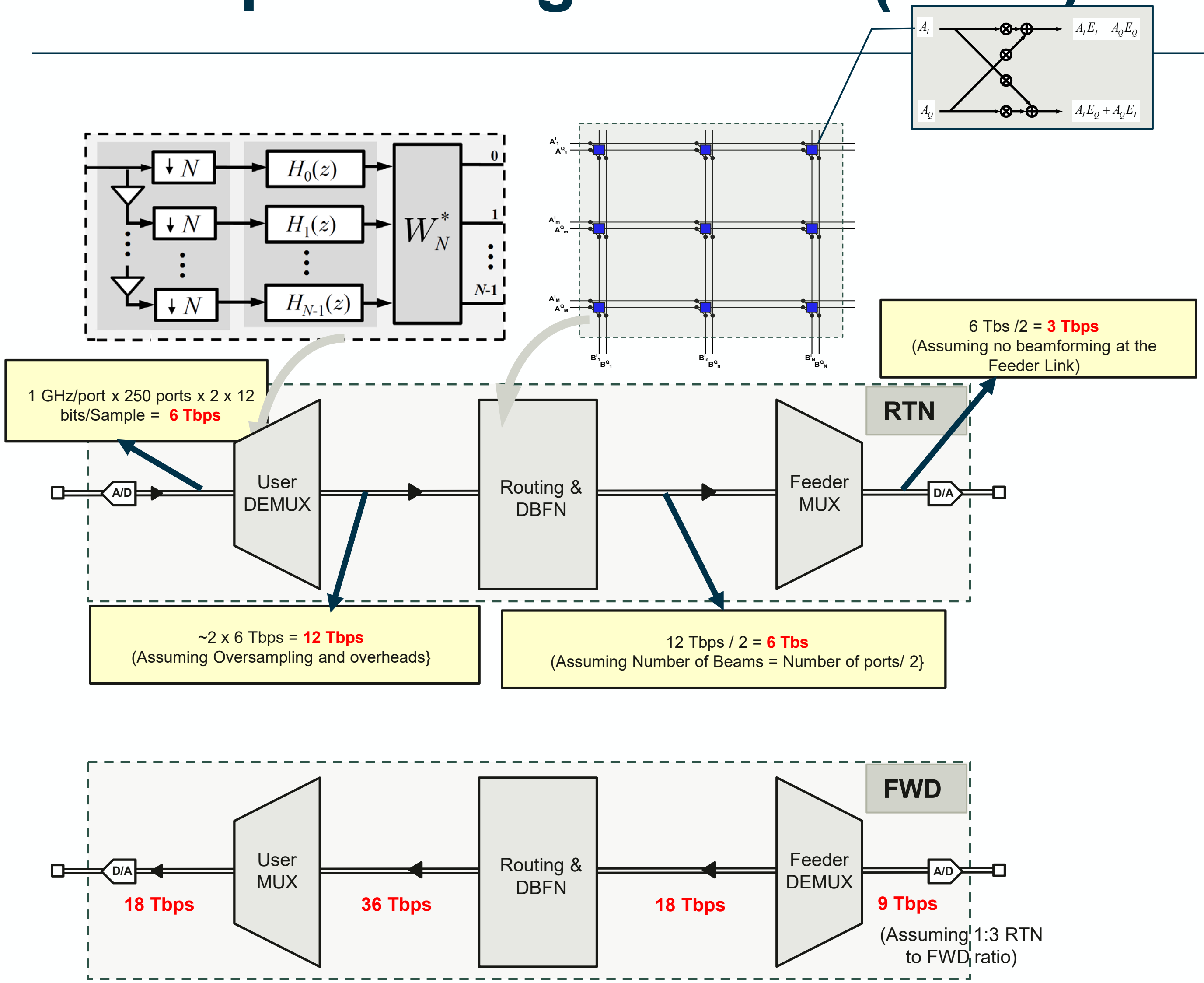


Digital Transparent OBP



- A digital transparent OBP serves as a well-established solution for demultiplexing, routing, and multiplexing signals for reception and transmission for satellites.
- In a high-throughput configuration, the digital processor can also handle a portion or the entirety of the beamforming task.
- Technology developments in High-speed data converters (ADC &DAC), transistor and packaging, interconnect improve the capability and efficiency of these processors.
- Additional processing tasks can be assigned to the OBP to perform; frequency and beam hopping, beamsteering, interference mitigation, level control, dynamic channel switching, equalisation, power control, dynamic resource management, spectrum optimisation and allocation, calibration and linearisation.

Transparent digital OBP (cont.)

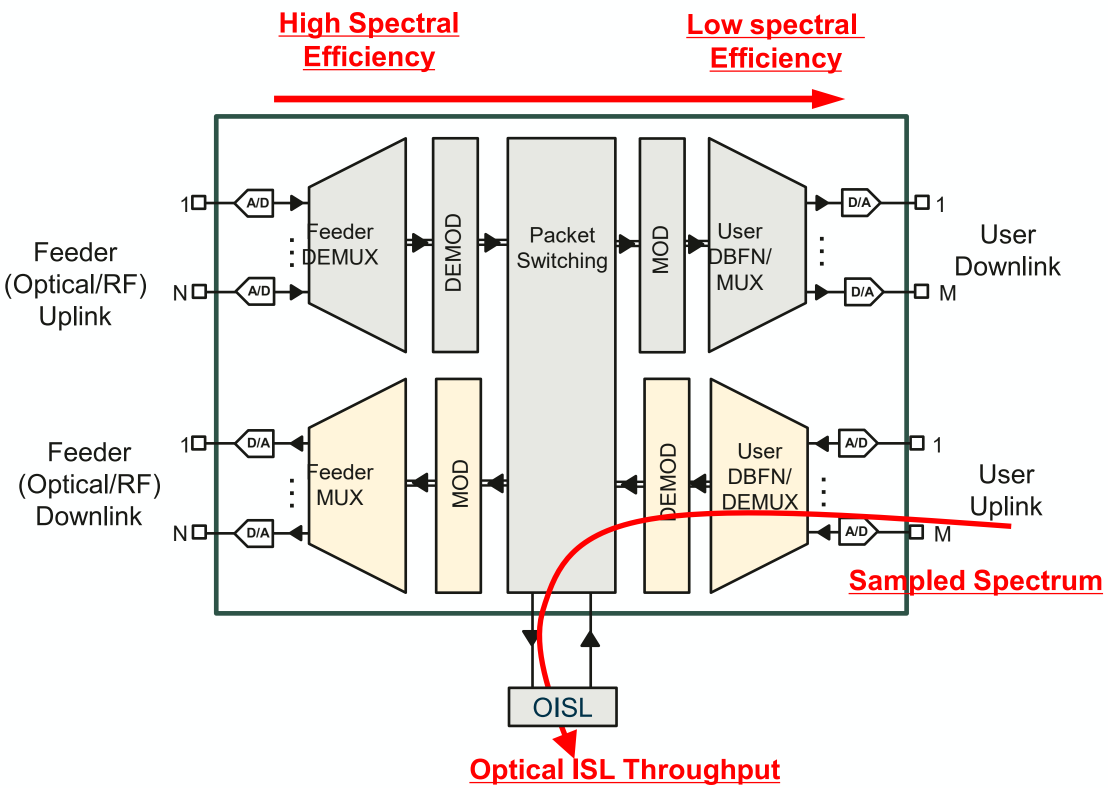


- The design of a transparent OBP becomes more challenging as the volume of data to be processed increases.

  Data Throughput = N_{port} x (2 x BW_{per_port}) x Nb_{per_sample}

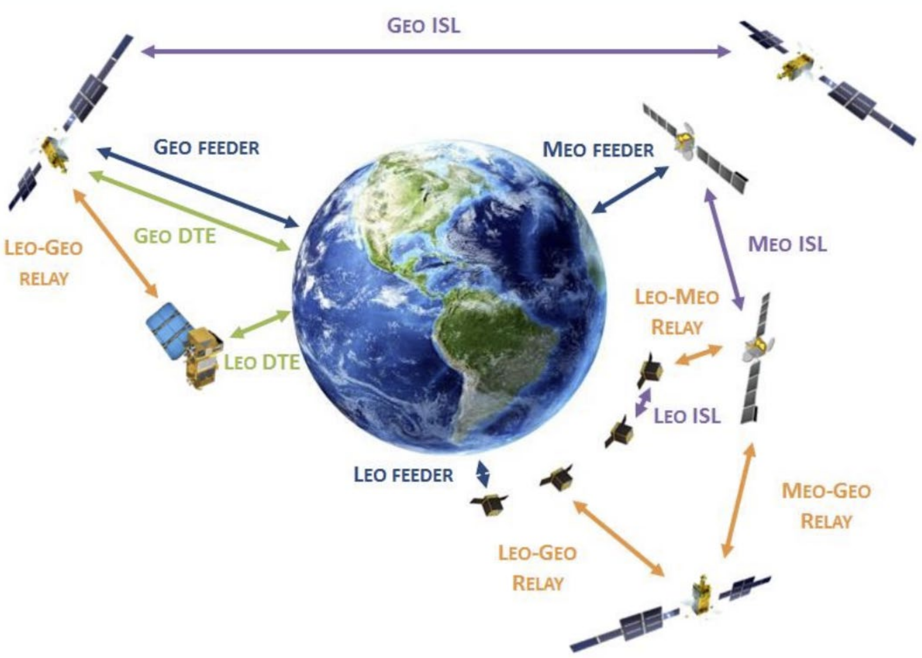
- The utilisation of active antennas and full digital beamforming leads to an expansion in the number of ports on the processor, thereby increasing the data load. In contrary, lower bit resolution would be deemed acceptable when employing large antenna arrays (1000s of antenna elements).
- In digital beamforming, the operations of phase shifting and amplitude scaling for each antenna element, and summation for receiving, are done digitally. The total number of beamforming weights (i.e. multiplications) plays a key role in defining the processing burden.To carry out the complex weighting, four real multiplications and two real additions are be required. Multipliers cost much more than Adders

Regenerative OBP



- Regenerative processing requires additional MODEMs on board for signal encoding and decoding. They can facilitate the transformation of signals between different air interfaces too.
- This approach allows for the separation of the uplink and downlink, but it comes with the trade-off of increased complexity and power consumption in the OBP. Because the spectral efficiency of the feeder and user links differ, it's possible to support the same capacity with reduced bandwidth on the feeder link and on the ISL, thereby reducing the requirement for multiple ISLs and gateways.
- MODEMs also play a crucial role in improving the link performance by providing error correction, enhancing SNR, and optimizing the link budget.
- They could help to establish a 5G/6G connectivity on the telecommunication satellite or to support conventional DVB-S2X, DVB-RCS2 standards or custom waveforms.

Regenerative OBP (cont.)



The concept of having a MODEM onboard aligns well with the integration of the spacecraft in a network of satellites from various orbits and terrestrial networks. This approach allows for the processing of data received from ISL&RF links and facilitates rerouting to the next node in the network, thanks to the regenerative payload.

- Gil Shacham, "On Board Processing Payload"
- Executive Summary Report "Towards the All Optical satellite communications system"

- ASICs are commercially available to deliver MODEM operations. A set of these MODEMS (of ~500 MHz each(*)) would consume a few watts to deliver several Gbps of data. State-of-the-art FPGAs, with a good level of radiation tolerance, can also be an alternative when they are equipped with custom software and firmware as MODEM.
- Transceiver chipsets (with filtering, mixing and data conversion functions) and a digital signal processing unit (the quantity of which depends on the bandwidth to be processed) enables the full reconfigurability of the OBP in-orbit making way to a fully flexible satellite payload.
- The RF Transceivers for SDR have relatively lower bandwidth (200 MHz), whereas wideband (but more power hungry) ADC/DACs (3 GHz bandwidth) can replace them depending on the application. Where needed, these ADC/DACs are good for direct sampling of the RF signal too (up to Ka Band) discarding the need for mixing stages.
- Numerous radiation tolerant alternatives of these digital signal processing platforms are in use in addition to radiation hardened ones.

On-board Regenerative Processors

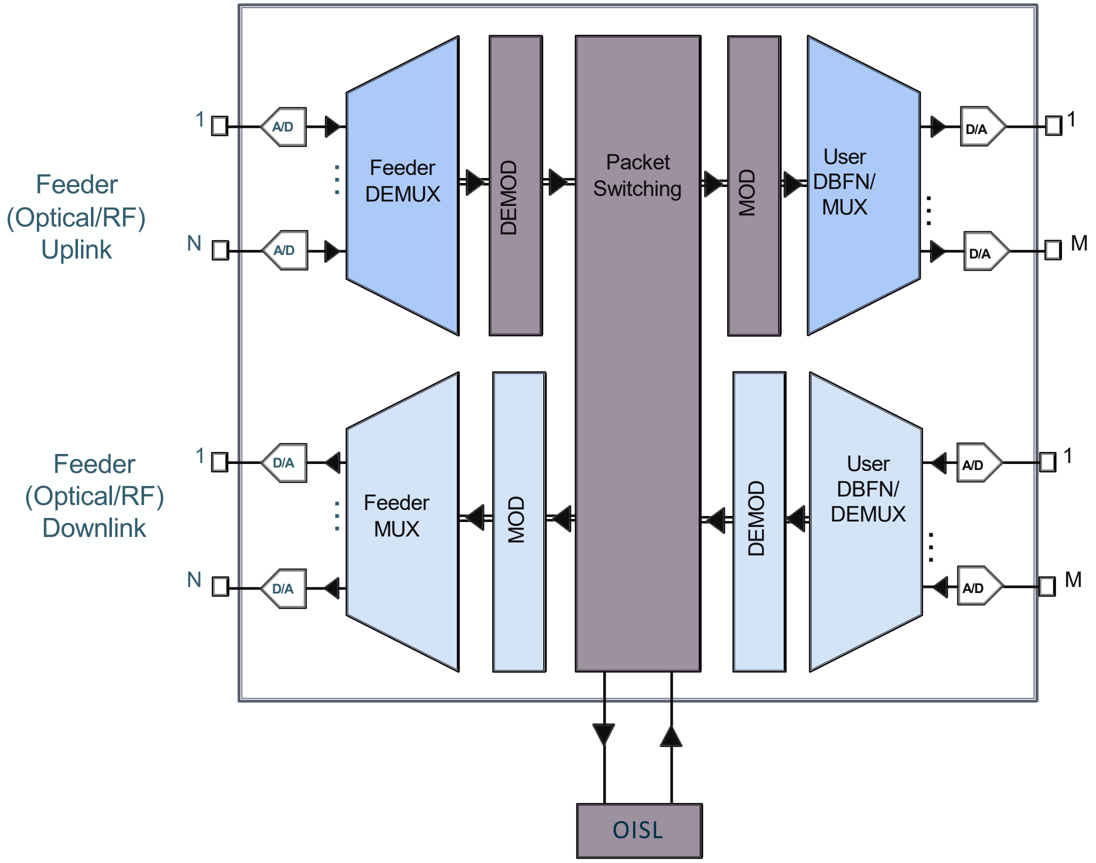
Regenerative Processors are a key element for GEO and LEO future missions, both commercial or for secure communications.

Enabling Technologies:

- UDSM 7nm and beyond
- Digital Photonics High Speed Serial Links up to 112Gbps
- High Integration and Heterogeneous Packaging (SiP, potentially including PIC, chiplet, SoC)

Key potential features and functions:

- Supported throughput (GEO ~ 1THz, LEO ~50GHz)
- Digital Beamforming DBF (GEO~500GHz, LEO~50GHz)
- Large number of ports >500 (Up to 5GHz BW per port)
- Digital IFs at 100Gbps (e.g. for ISL),
- Higher RF interfaces e.g. Q/V-band, W-band
- Dynamic spectrum allocation, Jammer cancellation
- Ethernet Packet Router
- Possible Inclusion of Optical functions TBC (e.g. Optical WDM interfaces, Optical beamforming)
- Compatible with 5G/6G standards



What is coming in the future digital processors?

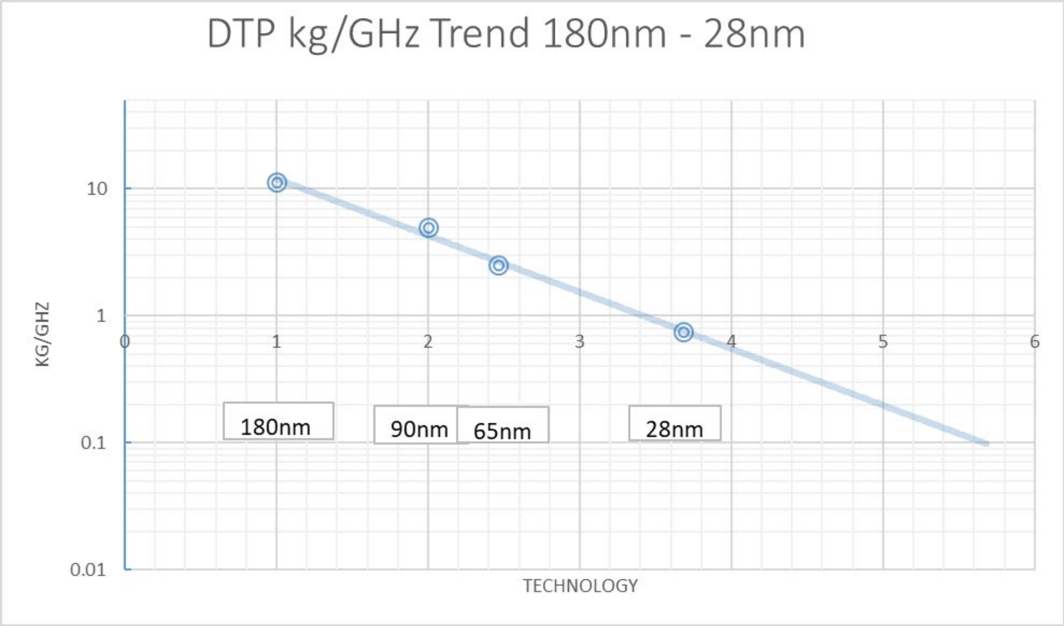
- Regenerative Processors for Next generation Missions
  - Target Missions: VHTS, UHTS, Mega Constellations
  - Key Features: High throughput, flexibility, user density

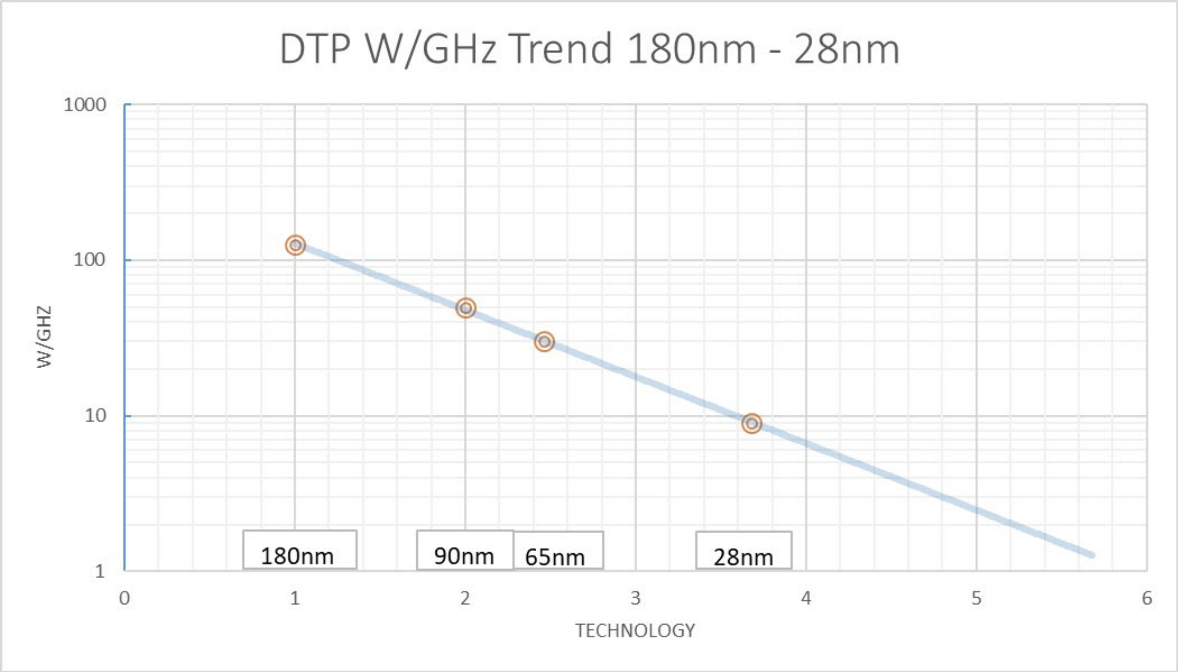
- Generic Reconfigurable Processors (“Full” SDR)
  - Target Missions: Low/Medium size missions (also non-telecom)
  - Key Features: modularity, re-usability for several applications, Applications running on custom firmware/software , Reduced time to market

- Increased use of COTS across the different domains

Historical Evolution – from 180nm to 28nm

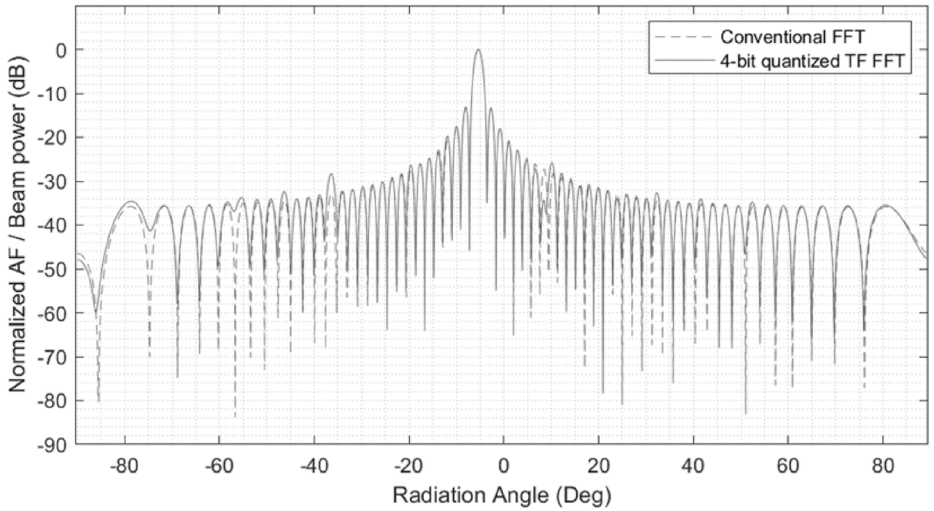
Historical trend of Mass and Power per GHz of processed bandwidth





Efficient Digital Signal Processing

- Numerous algorithmic and architectural enhancements can be implemented in telecommunication processors to improve the efficiency of signal processing.
- Some key areas are:
  - FFT based digttal beamforming
  - Multiplierless designs, utilisation of Reconfigurable Multiplier Blocks
  - Design and use of specialised digital filter, datapath and coefficient quantisation tools
  - Critically Sampled/Reduced over-Sampling Channelisation.
  - Reconfigurable and Tunable Filter banks to enhance flexibility in channel width and centre frequency.
  - Improvements in FFT operations through reconfigurable FFT blocks and coefficient store strategies.
  - Designing additional efficient processing components within ASICs to support multiple missions, air interfaces, and customer requirements
  - Compression of the Interconnect Data.
  - Digital beamformers to support non-uniform antenna arrays and non-uniform beam lattices; true-time-delay beamformers.
  - Exploration of alternative filtering and modulation techniques (Almost Linear Phase IIR filters and DCT/DFT)



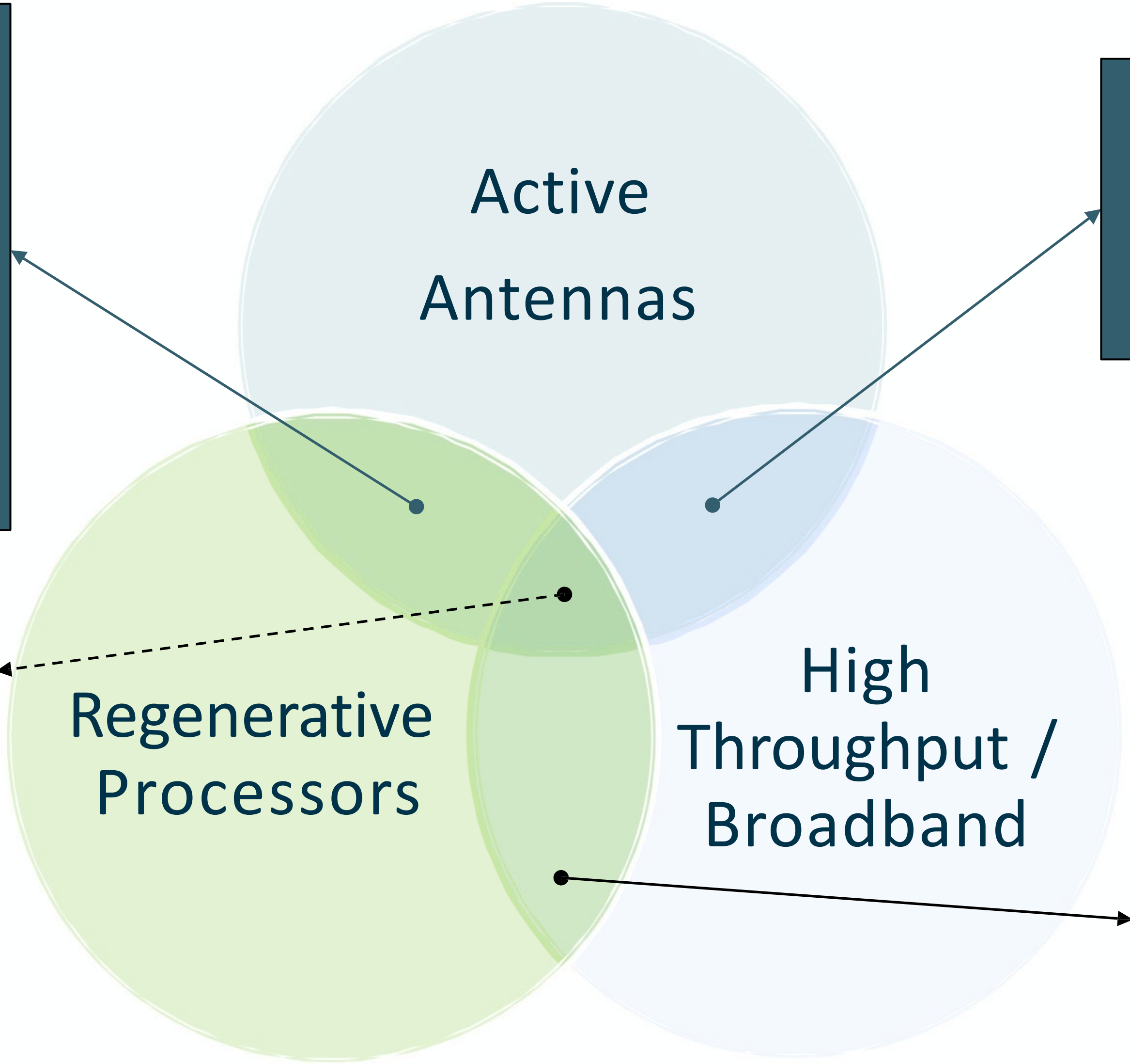
Example of Radiation Pattern Comparison between FFTs implementations

R. Palisetty et. al. “FPGA Implementation of Efficient 2D-FFT Beamforming for On-Board Processing in Satellites”

Satcom Trends: applications and payload mapping

D2D/D2H
- BFN ICs
- Low Channel BW (5-20 MHz) FR1
- Medium aggregated BW
- LEO/VLEO
- Low Cost / COTS
- Hybrid and DBFN
- Regenerative

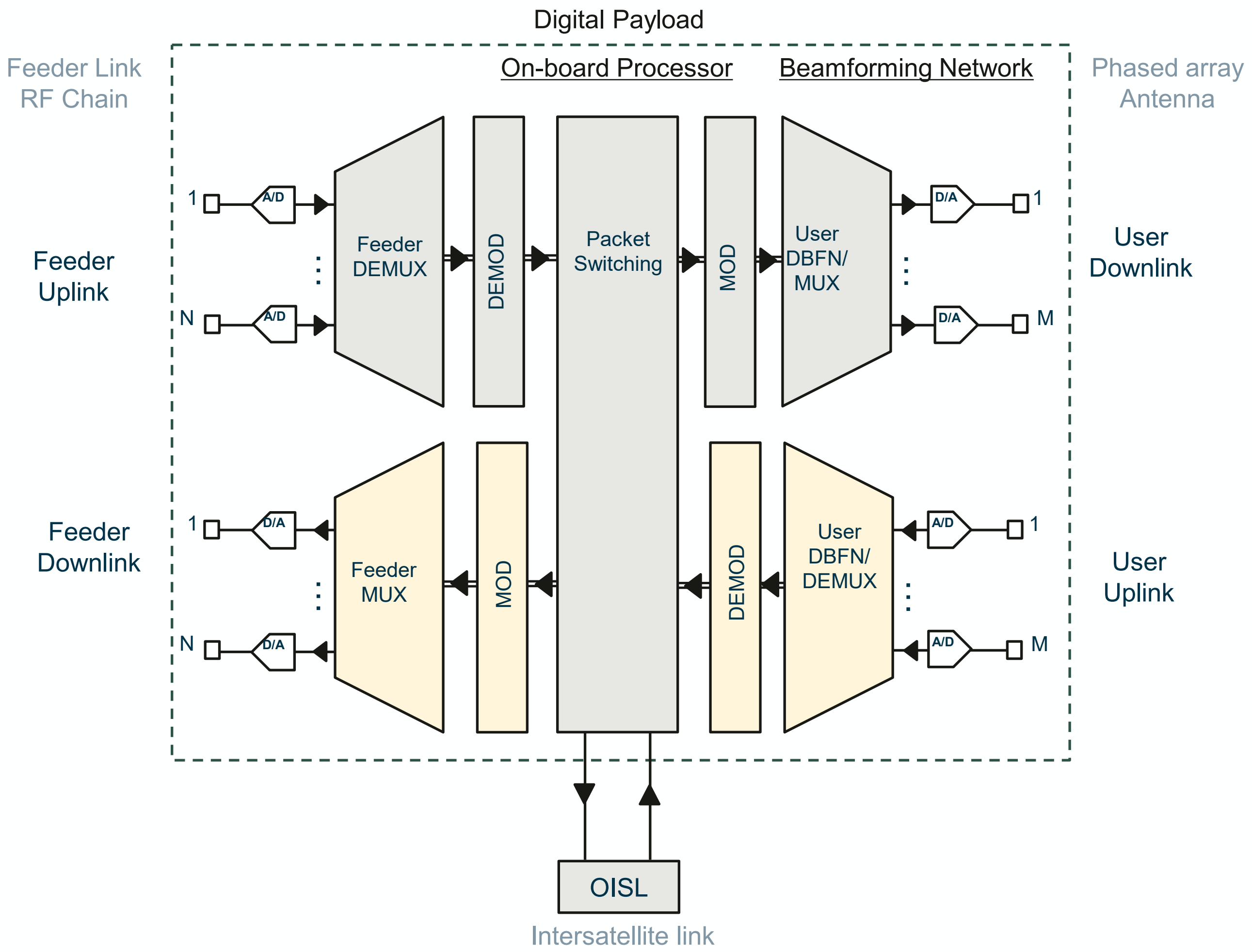
Micro GEO
- Rad Tol
- Low SWaP
- Flexible Channel BW
- Transparent (for now)



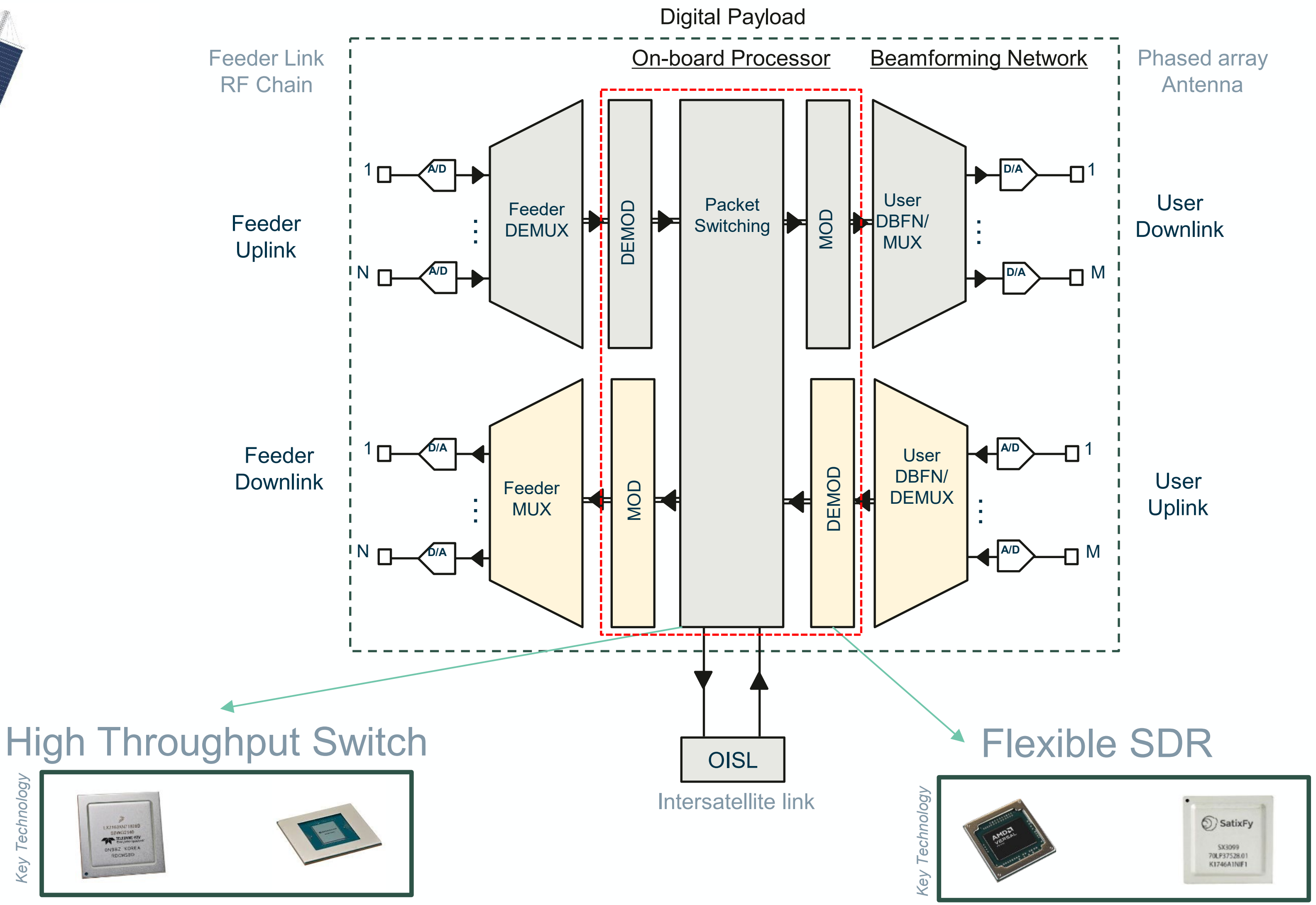
Broadband (GEO/MEO/LEO)
- High Channel BW (~500 MHz)
- High aggregated BW
- Hybrid and DBFN
- Regenerative
- ISL

High frequency Feeder & ISL
- Q/V/W band
- Optical SDR

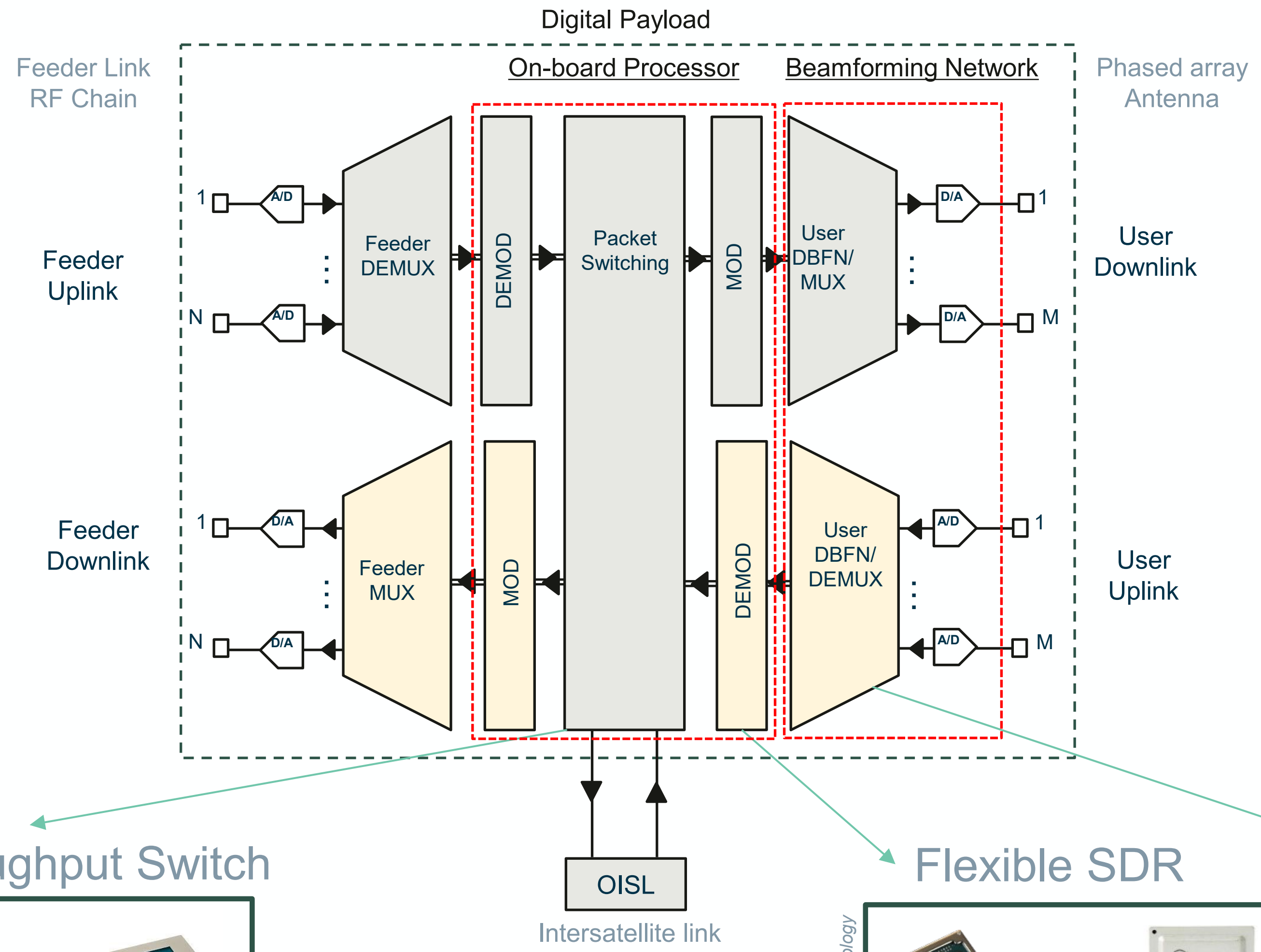
Satcom payloads – Digital Equipment Components



Satcom payloads – Digital Equipment Components

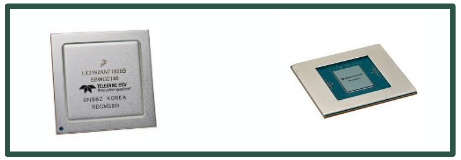


Satcom payloads – Digital Equipment Components



High Throughput Switch

Key Technology



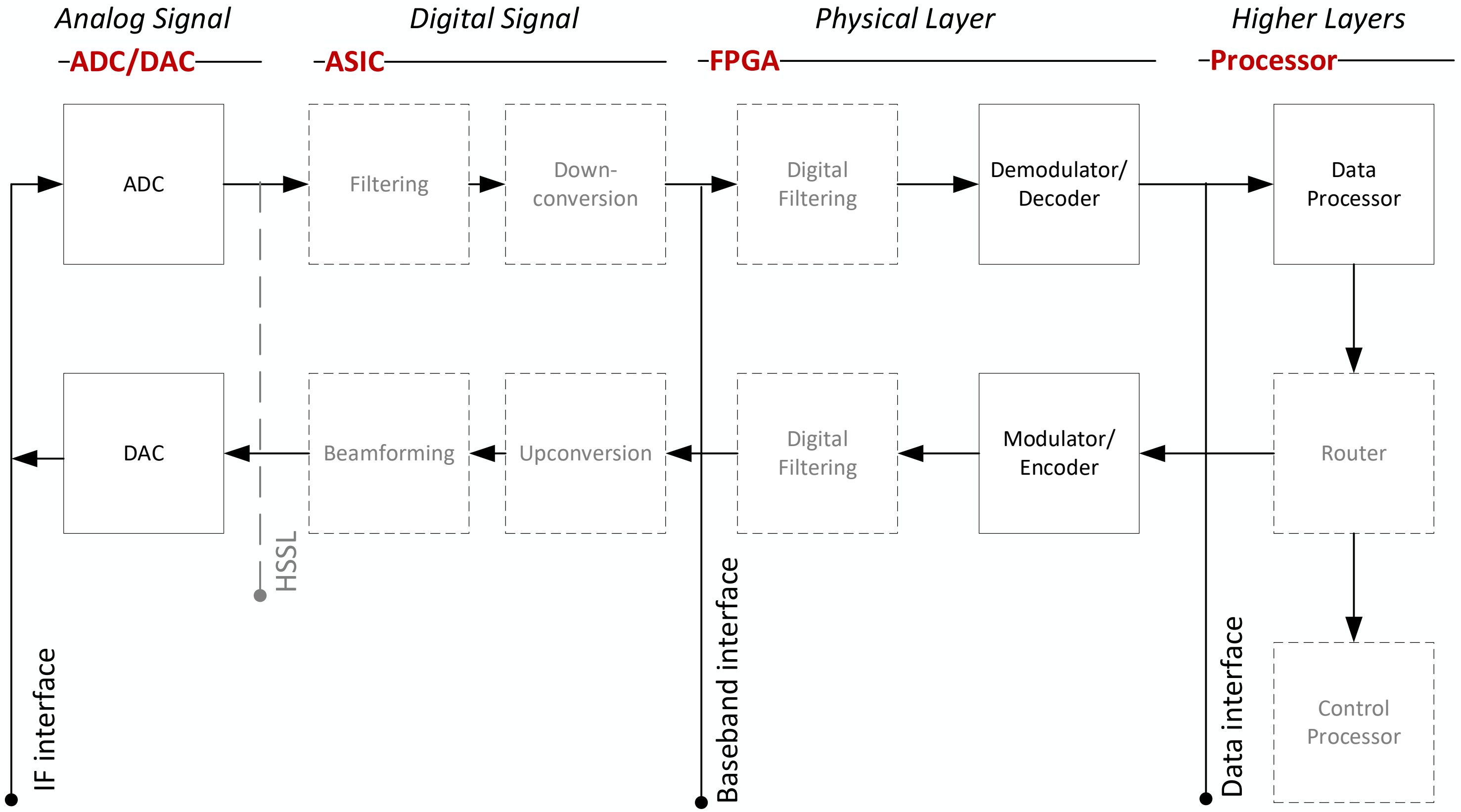
Flexible SDR

Key Technology

Power efficient BFN

Key Technology

SatCom Payload Digital Components



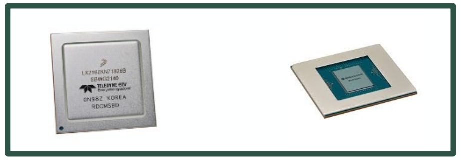
Power efficient BFN

Key Technology

Flexible SDR

High Throughput Switch

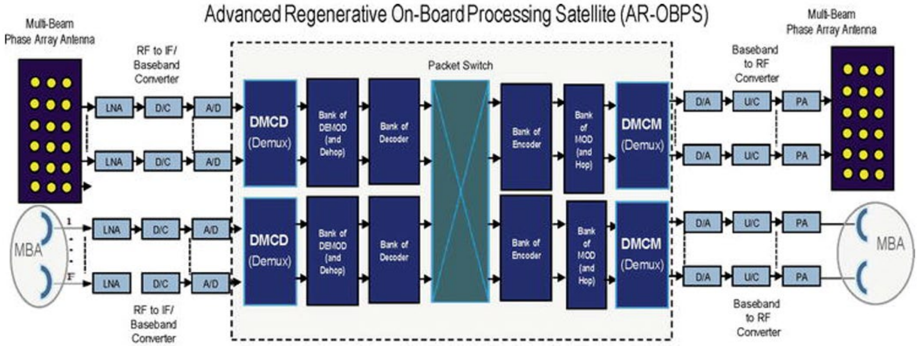
Key Technology



Identification of Needs

On-board Routing and Switching required in Regenerative Processors for

- LEO constellations
- Multi-orbit constellations
- Cloud computing
- 5G/6G NTN



State-of-the-art and future (from Starlink Progress Report 2024)

- V2 (in orbit)
  - 96Gbps aggregated bandwidth per satellite
  - Laser based inter-satellite link
- V3 (in development)
  - 1 Tbps downlink, 160 Gbps uplink
  - 4 Tbps combined RF and optical backhaul capacity
  - Optimised chipsets

BANDWIDTH AND CAPACITY
Each V2 Mini satellite offers a bandwidth of 96 Gbps, quadrupling the 24 Gbps capacity of the previous V1.5 satellites. This substantial increase enables the constellation to handle more customer data, improving overall service quality.

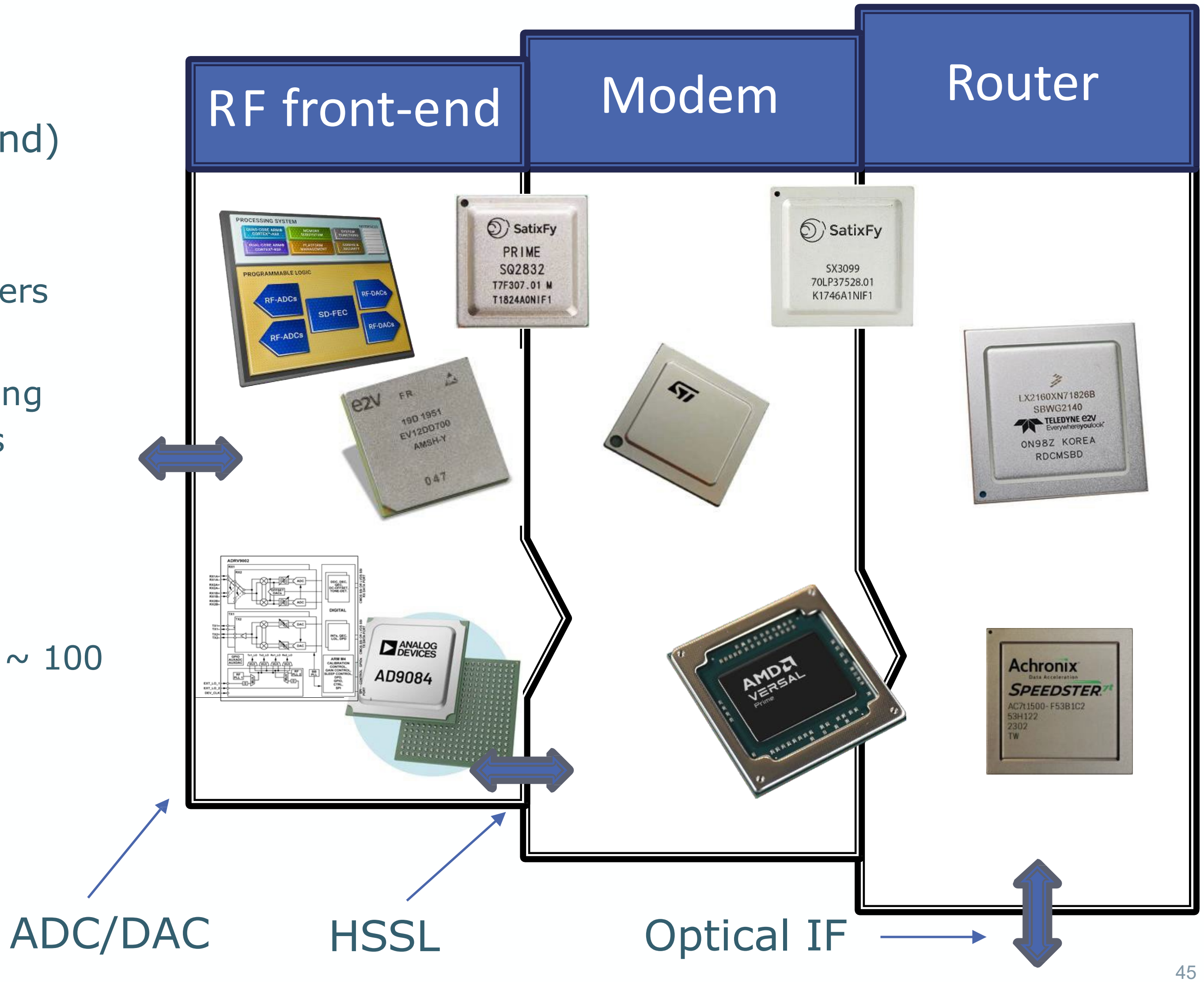
INTER-SATELLITE COMMUNICATION
Starlink V2 Mini satellites are equipped with advanced laser inter-satellite links,

Each V3 Starlink satellite will have 1 Tbps of downlink speeds and 160 Gbps of uplink capacity, which is more than 10x the downlink and 24x the uplink capacity of the V2 Mini Starlink satellites.

The V3 satellite will also have nearly 4 Tbps of combined RF and laser backhaul capacity. Additionally, the V3 Starlink satellites will use SpaceX's next generation computers, modems, beamforming, and switching.

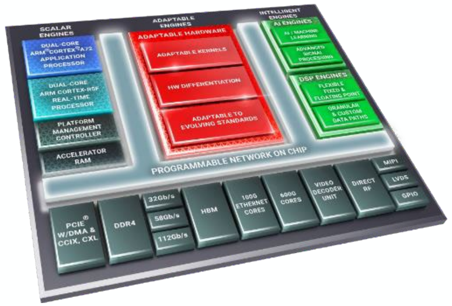
On-Board Processor – Key Components

- **Mixed signal ASIC RF front-end** (> Ka / L-band)
  - Integrated ADC/DAC (FPGA or BFIC),
  - Digital/Hybrid Beamforming
  - Reconfigurable channelization and DDC filters
- **FPGA / SoC / ASIC based Modems** (~ Gbps / chip)
  - Flexible or Reconfigurable Decoding/Encoding
  - DVB-S2/RCS and 3GPP 5G NR protocol IPs
- **SW based packet switching / router** (> 100Gbps)
  - MAC layer handling
  - Feeder link and ISL interface
- **HSSL/SERDES/Ethernet Backend and Frontend** (~ 100 Gbps)
  - High speed digital interconnects
  - Optical Interconnects

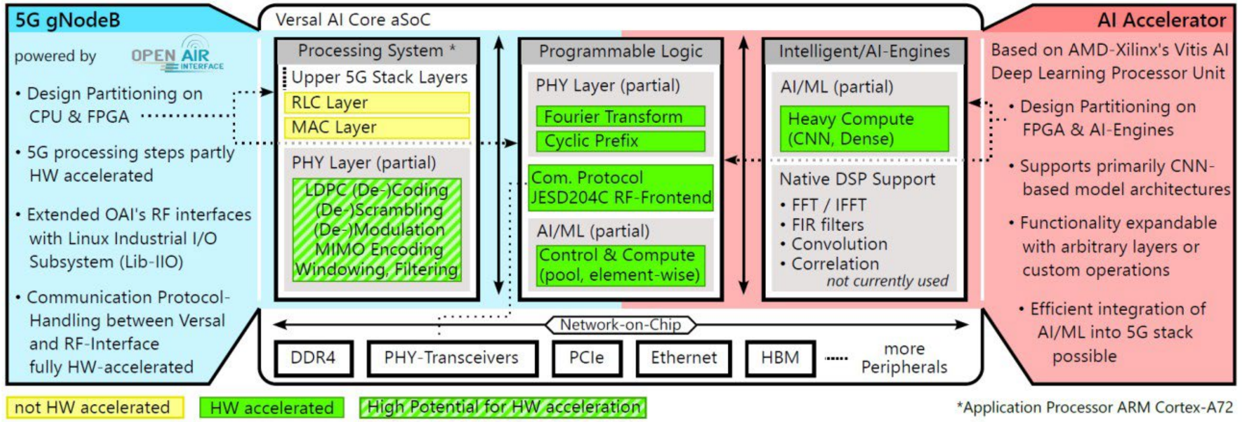


On-Board Processor – Modem / Access module

- Reprogrammable **FPGA** (Field Programmable Gate Array) aiming to increase the processing capabilities and functional density
- Multi-Core **Microprocessor**, e.g. based on open-source RISC-V
- Multiple **RF** Analog to Digital (**ADC**) and Digital to Analog (**DAC**) converter for direct conversion from/ to Ka band and beyond.
- **Accelerators** for Digital Signal Processing (AI, beamforming, …), Encryption (AES), DVB-S2X, ….
- Serializer/ Deserializer (**SerDes**) up to 112 Gbps
- Co-packaged **Optical Transceivers** up to 400 Gbps
- **High Bandwidth Memories,** interface to DDR4/ 5/ GDDR6
- High performance Network-on-Chip (**NoC**)



Xilinx Versal



System Architecture for shared 5G gNodeB and AI/ML applications on an AMD-Xilinx Versal a SoC [*]

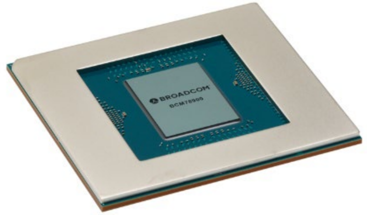
[*] Michael Petry and Raphael Mayr, "AI-enabled 5G base-station with Hardware Acceleration for Non-Terrestrial Networks on a Space-Grade System-on-Chip", 1st SPAICE Conference on AI in and for Space

On-Board Processor – Switch / Router Module

- COTS/ FPGA or dedicated ASIC development needed

  (performance of datacentre switches are far from currently available ASICs)
  - COTS provides highest performance, but radiation testing required
  - Adaptable SoC – flexible, power consumption acceptable
  - Dedicated ASIC – designed for space
  - Number of ports
  - Depends on number of optical terminals/ RF links/ internal connections
- Data rate per port
  - 100G per port state-of-the art
  - 200G/ 400G/ 800G required
  - 224 Gbps SerDes required (e.g. Broadcom Condor TSMC 3nm)
- Interface
  - Optical or electrical PHY
- Protocol
  - Ethernet/ MPLS/ IP state-of-the-art
  - Management plane

Broadcom Tomahawk 5

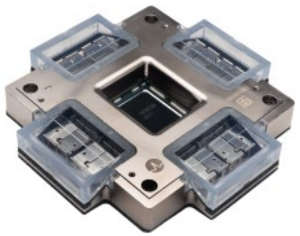


TSMC 5nm
51.5Tbps bandwidth
Peregrine SerDes 112Gb/s PAM4
64 ports x 800GbE
256 ports x 200 GbE

Broadcom Tomahawk 4

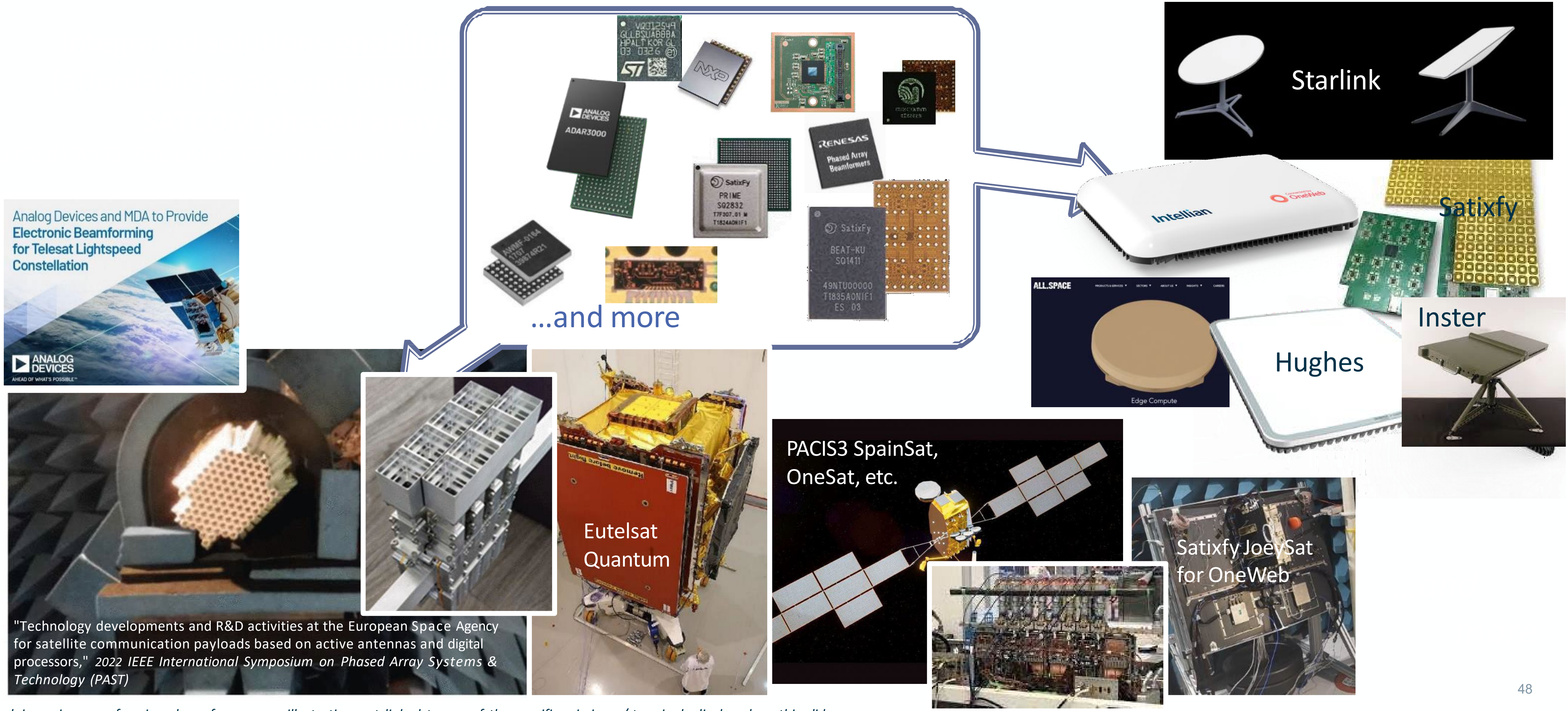
TSMC 7nm
25.6Tbps bandwidth
Osprey SerDes 112Gb/s PAM4
64 ports x 400GbE
256 ports x 100 GbE

Broadcom BCM78909



51.2Tbps bandwidth
Peregrine SerDes 112Gb/s PAM4
64 ports x 800GbE
320 ports x 100GbE
optical engines with CWDM

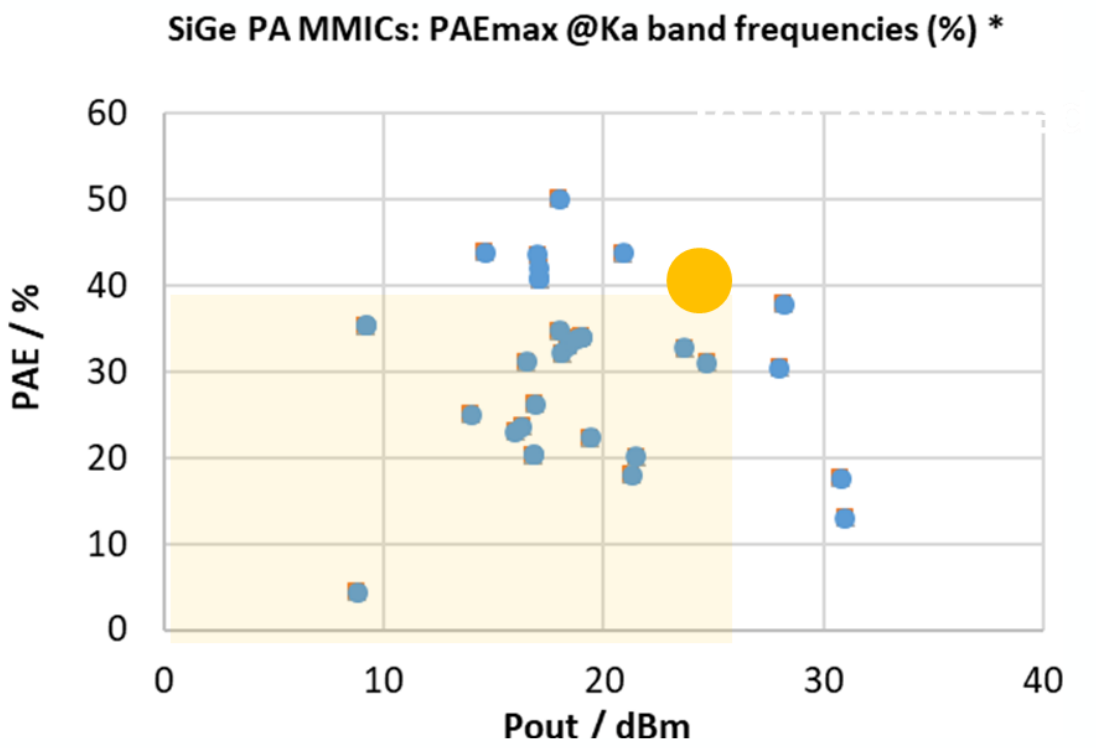
Active Antennas – Towards High Integration



Disclaimer: images of various beamformers are illustrative, not linked to any of the specific missions / terminals displayed on this slide

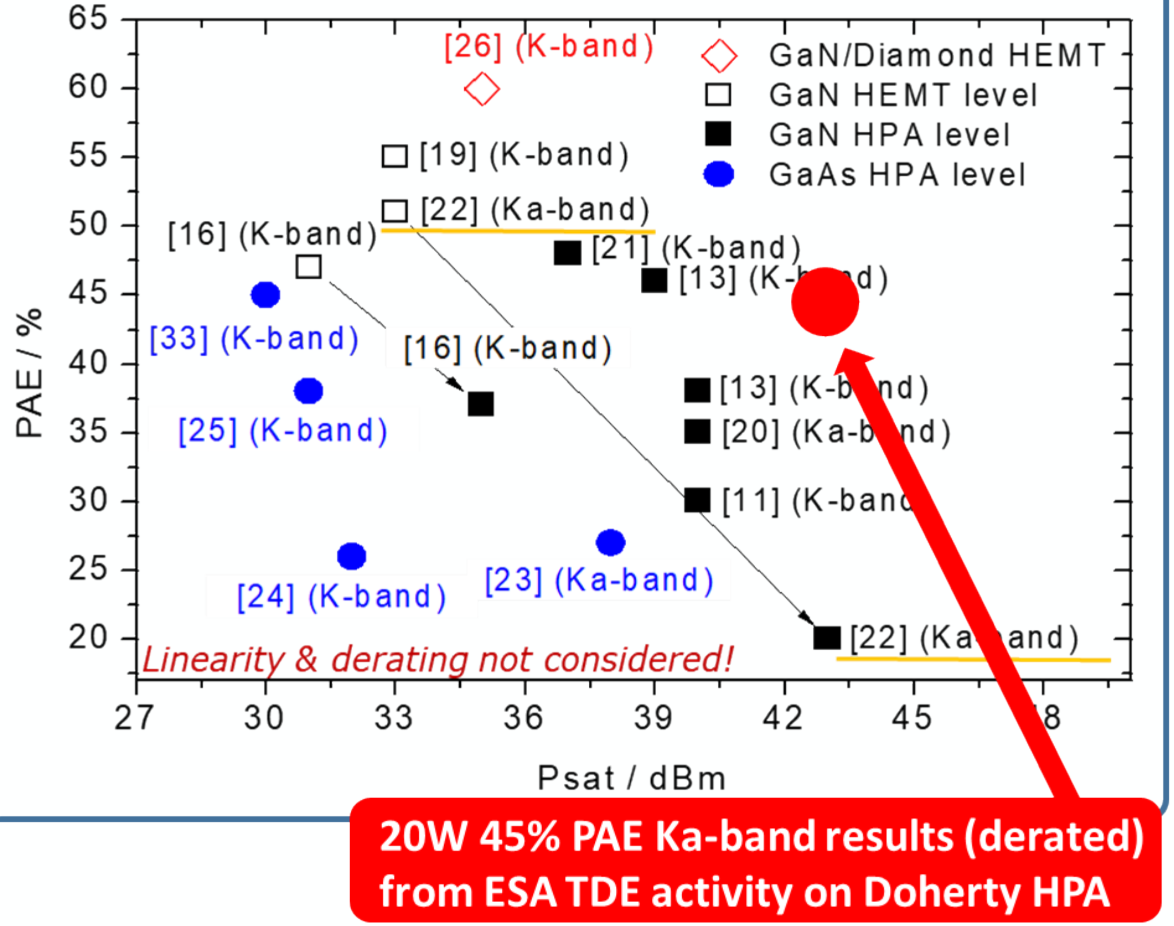
SiGe or GaN ?

SiGe



*note that majority of the reported results are covering the 26-28GHz band, not 17-20 GHz, hence at lower bands the performance is expected to be better

GaAs, GaN

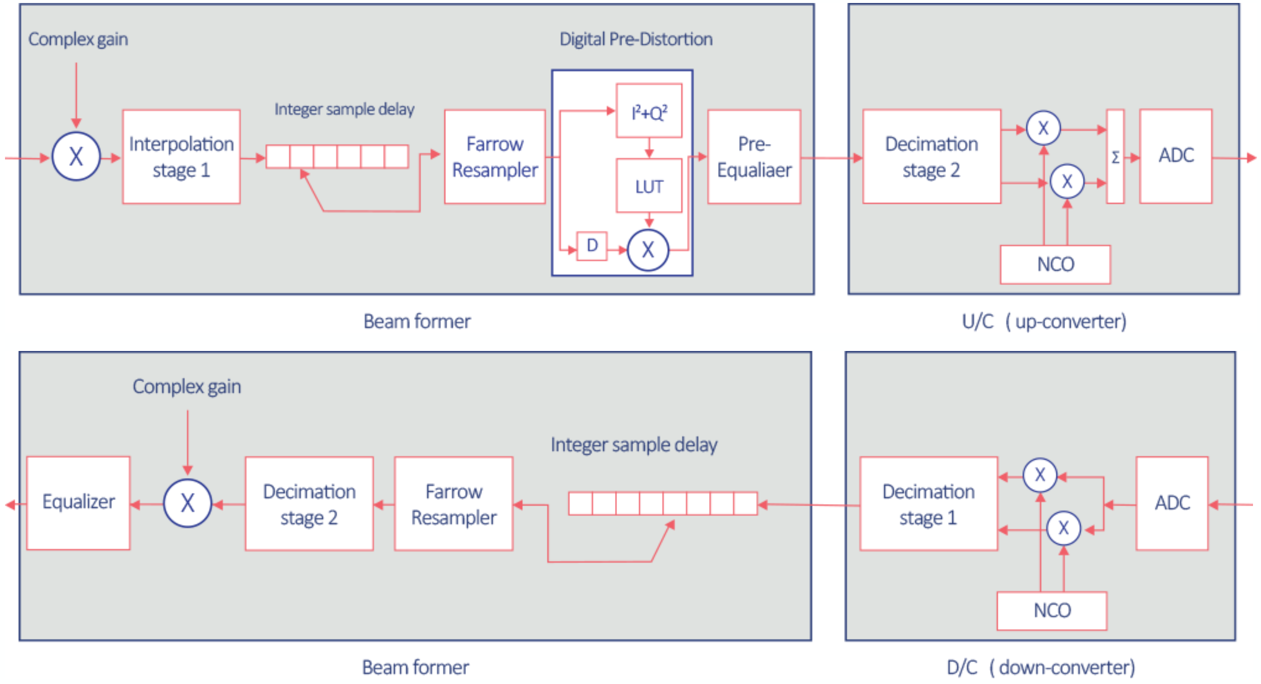


Move towards digital beamforming ICs

Analog Beamforming
•Beam control through **analog phase shifters** and **RF combiners**.
•Limited flexibility; one beam per RF chain.
•Susceptible to hardware drift and component mismatch.
•Difficult to compensate or calibrate after deployment.

Digital Beamforming
•Each antenna element connected to its own **ADC/DAC**.
•Signals processed using **DSP algorithms** for time delay, gain, and phase control.
•Enables **multi-beam** and **adaptive** operation.
•Easily compensates for imperfections and environmental effects.

Digital Beamforming building blocks



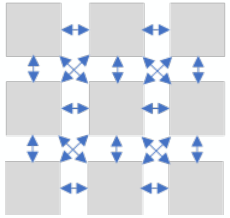
https://www.satixfy.com/prime/

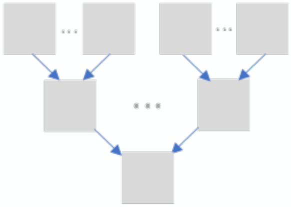
Antenna beam steering is achieved by applying precise time delays to each antenna element, aligning signals for a desired direction.
Each antenna element includes independent digital control for parameters like:
Time delay, Gain, Equalization, Pre-distortion

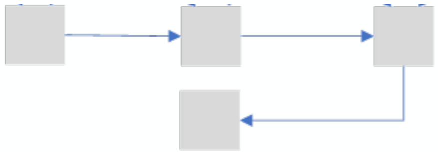
The Beam Former performs all processing in the digital domain using high-speed ADC/DACs for signal sampling and manipulation.

Enables dynamic and adaptive beam shaping to maximize antenna performance and efficiency.

Beamforming Architectures

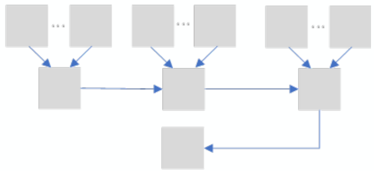






Feature	Mesh / All-to-All	Tree	Daisy-Chain
Beamforming Type	Fully digital	Hybrid (analog + digital)	Analog or digital serial
Architecture	Centralized, dense	Hierarchical	Linear (serial)
Flexibility	Highest	Moderate	Limited
Scalability	Poor (too many links)	Good	Very good
Latency	Low (parallel)	Moderate	Higher (serial)
Power / Mass (Spacecraft)	High	Medium	Low
Typical Use	Fully digital in centralized processor	Hybrid Beamforming payloads with analog BFN subarray and processor	Beamforming integrated chips in user terminals

Combination necessary for large antennas!



Moving towards digital beamforming ASICs

	2022	2024	2027	Future …
Input	Analog	Analog	Analog	Analog
Output	Analog or Dig.	Digital	Digital	Digital
Technology	45nm *	28nm ST *	7nm TSMC *	7/5nm
Beam Steering	PLL	TTD	TTD	FFT or TDD
Beams	32	128	>512-1024*	>3000
Capacity (Routed Bandwidth)	4 GHz	8 GHz	>10 GHz*	>45 GHz
Instantaneous Frequency Span	2 GHz	2.5 GHz	0.5-2.5 GHz*	0.5-2.5 GHz
Scalability (#elements)		32000 in Tree (1024 with 32 devices in daisy chain)		> 1024
Power/Chip	n/a*	n/a*	n/a*	

(assumptions based on public data) *

EEE Space Components

- ESA, EC, DEFIS active in various activities for European EEE relevant for future RF Payloads and Digital Equipment
- ESA GSTP programme: Status of EEE Space Component Sovereignty for Europe (esa.int)
- IP Technology: USDM covers many aspects, HSSL, Analog, DDR, radiation hardening/tolerance

- Components that need to be addressed for RF payloads:
  - BFIC
  - SDR / Modem / FPGA
  - Access / SW Switch / MPSoC
  - Router / Hardware Switch
  - ADC/DAC (Integrated and discrete), RFSoC
  - Others like clock distribution

- Building blocks to be addressed:
  - IP SW/HW missing especially 5G related for this components

- Unit level design to be defined and activities initiated

- Requirements need to be flown down from payload and processor architectures of various use cases

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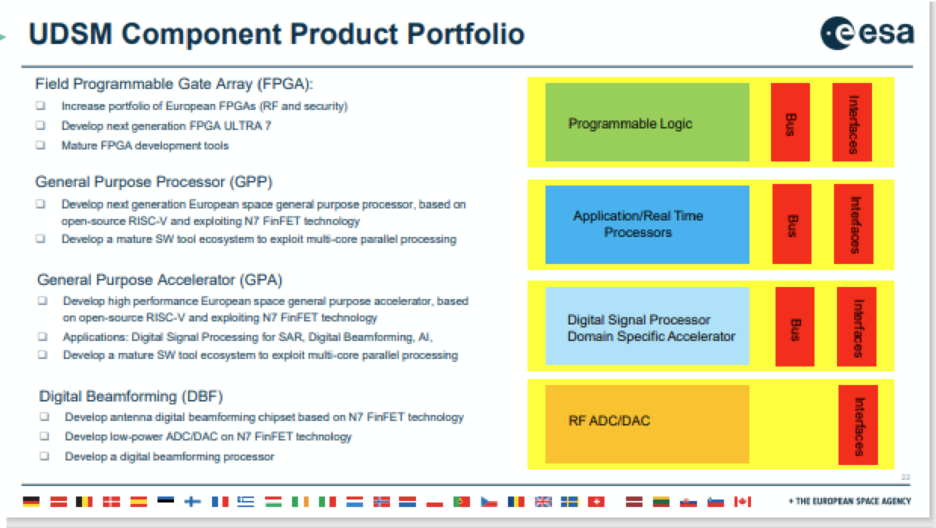
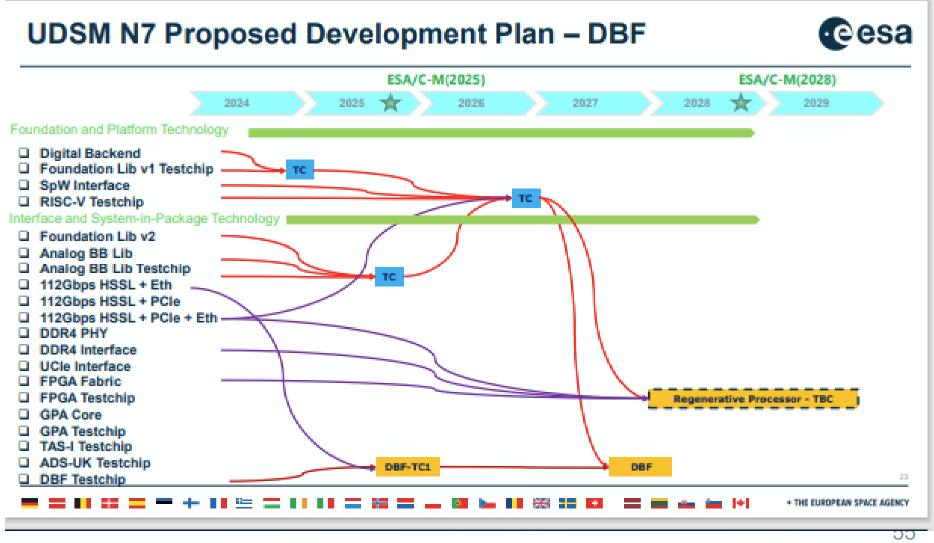


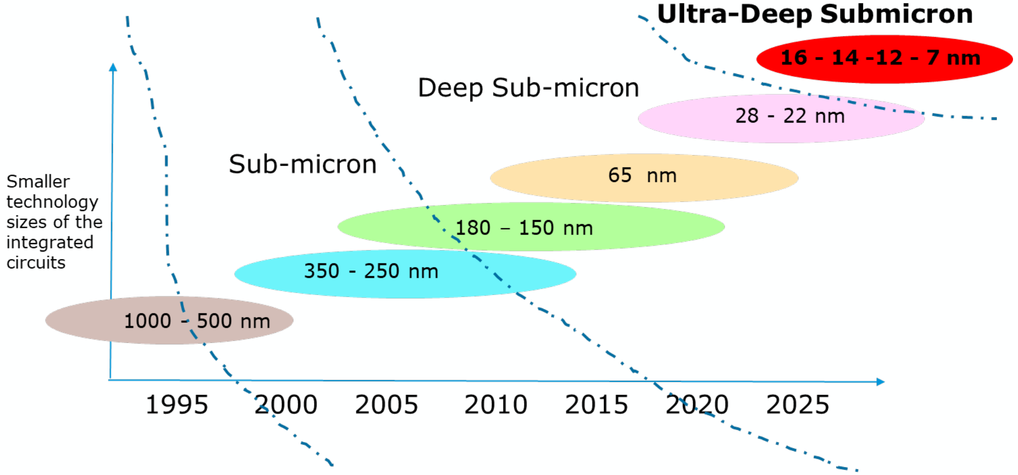


Components - Ultra Deep Submicron technology

- Highly efficient processors needed for on-board processing and beamforming application, which can only be achieved with Ultra Deep Submicron (UDSM) technology
- Commercial-of-the-Shelf (COTS) processors viable in LEO application with significant cost advantage, but require dedicated radiation mitigation and error handling
  - Mostly non-European solutions
  - Not suited for safety and security sensitive application

=> Develop a UDSM Radiation-Hard Application Specific Integrated Circuit (ASIC) mixed-signal standard cell library and IP portfolio based on 7 nm (or beyond) CMOS technology for the design of complex ASIC

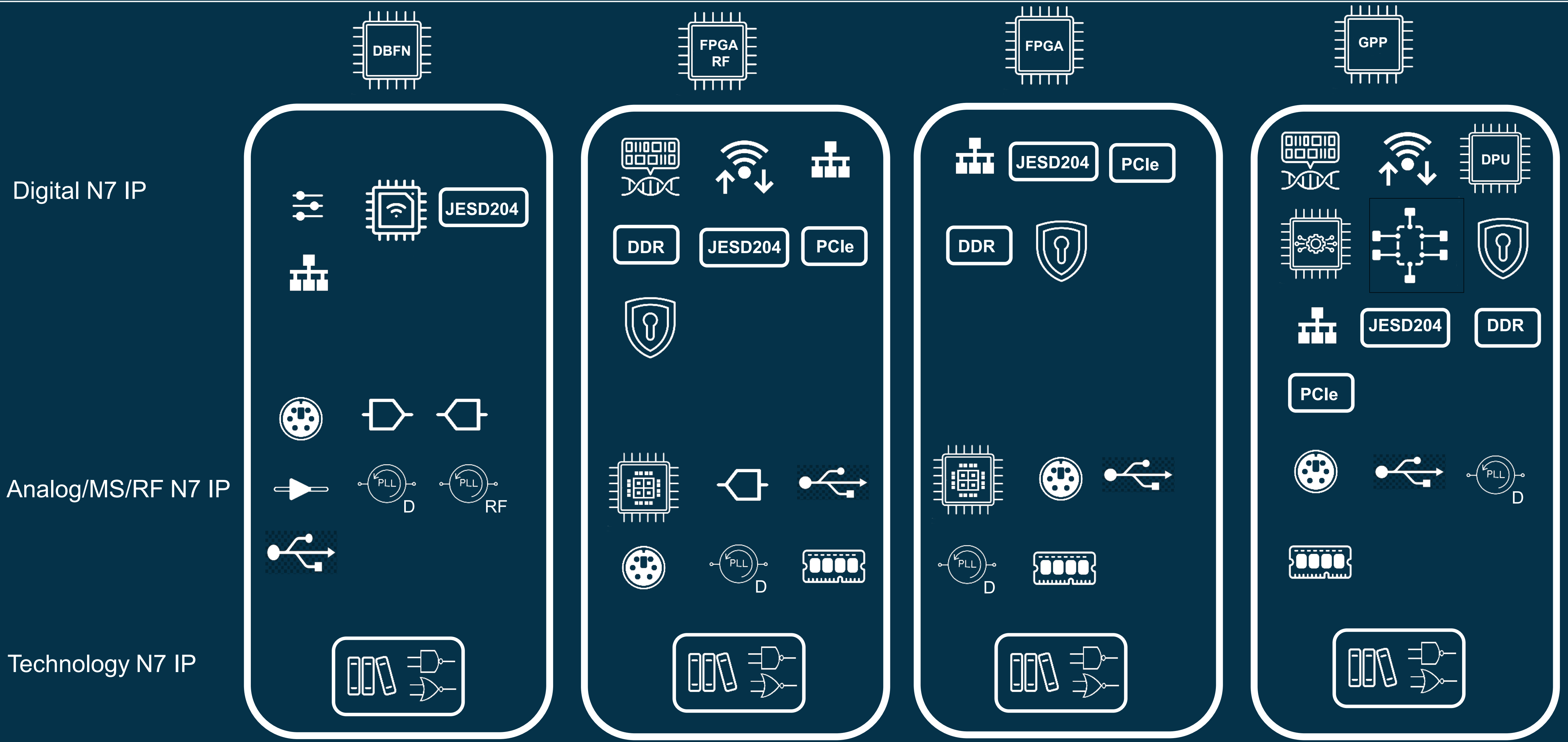
GOAL:
Increase competitiveness for European industry in the telecom sat market, secure/high performance Navigation applications and state of the art Earth Observation payloads to meet future NAV and EO mission challenges.



Satellite Communication Payloads: an overview of past, present and future trends and challenges – Annex on N7 UDSM

Richard Jansen, UDSM Team
TEC-ED, TEC-EF
European Space Agency – ESTEC
12/10/2025

Identified Generic N7 UDSM Components



Identified Generic N7 IP

- RF Front-end
- A/D - Analog to Digital Converter
- D/A – Digital to Analog Converter
- Channeliser - Multiplexor and Demultiplexer
- Beamforming
- Modem
- Codec
- Router core
- Processor core
- Field Programmable Gate Array core
- Tensor Processing core
- Digital Processing Unit (DSP, BBP, …)
- Security

- High Speed Serial Link (PHY)
- JESD204 Controller
- Ethernet Controller
- PCIe Controller
- DDR Memory Interface (PHY)
- DDR Controller
- Phased Locked Loop - Digital
- Phased Locked Loop - RF
- Input/Output ports
- Digital Library

N7 IP and Component Dev. in GTE3-101ED

- **N7 IP Developments**
  - Processor core
  - DDR Memory Interface (PHY)
  - DDR Controller
  - Input/Output ports
  - Modem
  - Codec
  - N7 Digital Library

- **IP not included for Component – GPP and TPU**
  - High Speed Serial Link (PHY)
  - Ethernet Controller
  - JESD204 Controller
  - PCIe Controller
  - Security
  - DPU
  - Router

- **N7 Component Developments**
  - General Purpose Processor
  - Tensor Processing Unit (stand alone or part of GPP)

GPP

TPU DSP

- **N7 IP going to other Components**

FPGA

FPGA RF

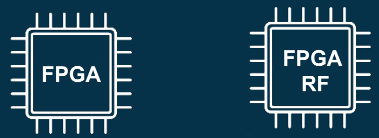
DBFN

N7 IP and Component Dev. in GTE3-102ED

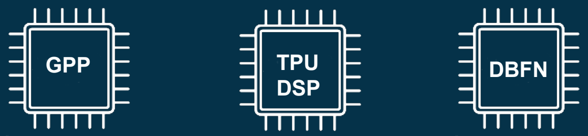
- N7 IP Developments
  - Field Programmable Gate Array core
  - Tensor Processing core
  - High Speed Serial Link (PHY)
  - Ethernet Controller
  - PCIe Controller
  - DDR Memory Interface (PHY)
  - DDR Controller
  - Phased Locked Loop - Digital

- N7 IP not included for Component
  - Input/Output ports
  - N7 Digital Library

- N7 Component Developments
  - FPGA and FPGA-RF



- N7 IP going to Components



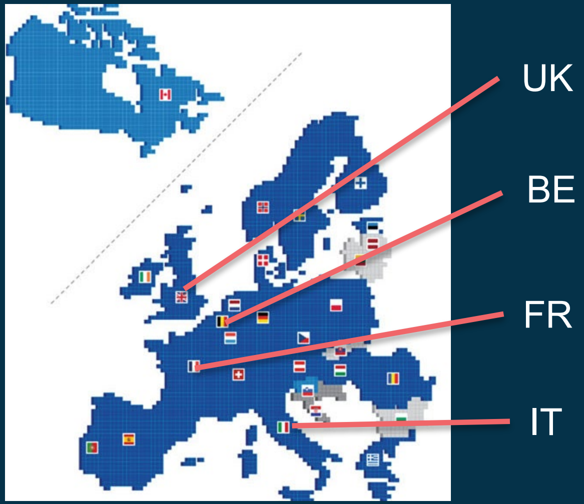
UDSM Technology Development Status

- **Foundation and Platform Technology – GTE3-101ED**
  - Technical Requirements Specification Determined
  - Work package content defined
  - ITT released – Q2 2024
  - Negotiation Successful – Q4 2024
  - Activity KO – Q4 2024
  - Consortium
    - Frontgrade Gaisler (SE)
    - IMEC (BE)
    - IMST (DE)

Signing of Contract – 11/12/2024

GTE3-101ED

- **Interface and System in Package Technology – GTE3-102ED**
  - Delegate support received: BE, FR, IT (expected), UK
  - Technical Requirements Specification Determined
  - Work package content under review (with inclusion of additional UDSM products pre-developments)
  - ITT to be released – Q3 2025



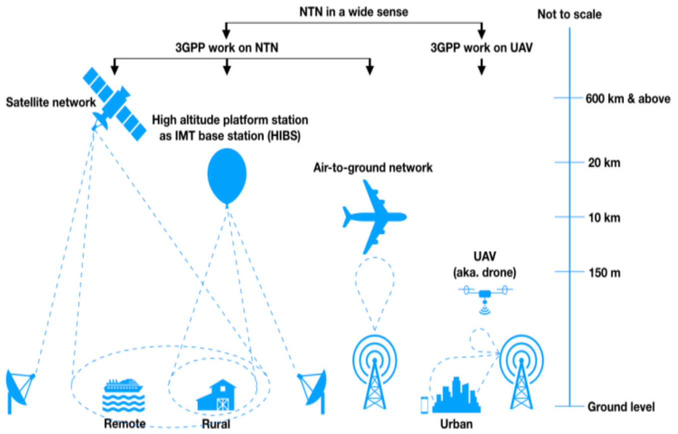
GTE3-102ED

Satellite Communication Payloads: an overview of past, present and future trends and challenges – Annex on 5G/6G

Max Ghiglione, Fabrizio de Paolis, Maria Guta
Connectivity & Secure Communications
ARTES SPL 5G/6G
European Space Agency – ESTEC
02/10/2025

3GPP NTN standardisation activities: 5G, B5G, towards 6G

3D Multilayer Networks



Rel.16 / Rel.17
- 5G NR NTN (3GPP SatCom access)
- **Below 7GHz**
- **Direct to handheld from Satcom**
- NTN-IoT specifications completed

Rel.18
- 5G NR NTN enhancements
- **Above 10GHz**
- **Broadband satellite services**
- Mobility enhancements

Rel.19…
- High power UE
- **Regenerative NTN**
- Coverage enhancements
- Mission critical services

Rel.20…
- **MVSAT**
- **Multi-orbit**
- **Regenerative NTN** Emergency SMS over NAS and/or IMS
- Security
- Coverage enhancements
- Broadcast, RedCap
- Mission critical services

2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030

Rel.17 (5G)

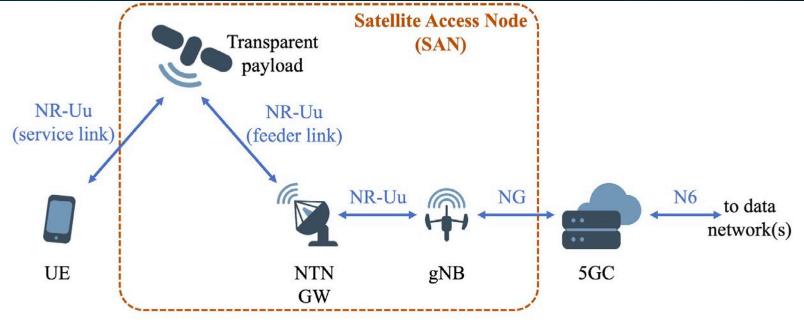
5G-Advanced – B5G (Rel.18/19)

6G & B6G (Rel.20/21/…)

3GPP A GLOBAL INITIATIVE

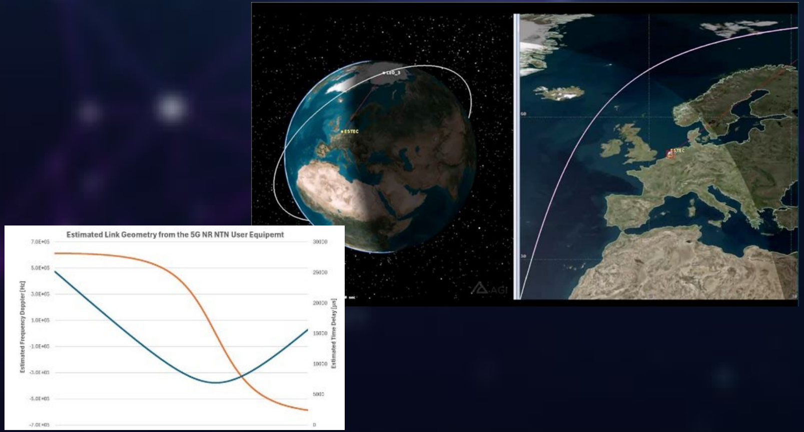
Transparent Payload

- In both Rel-17 and Rel-18, NTN is based on a transparent (bent-pipe) architecture
  - ➢ It limits payload complexity and enables early deployment
  - ➢ Previously deployed transparent payloads can be repurposed for Rel-17/18 NR NTN if it supports the correct RF requirements in the appropriate bands



NTN Transparent Payload [1]

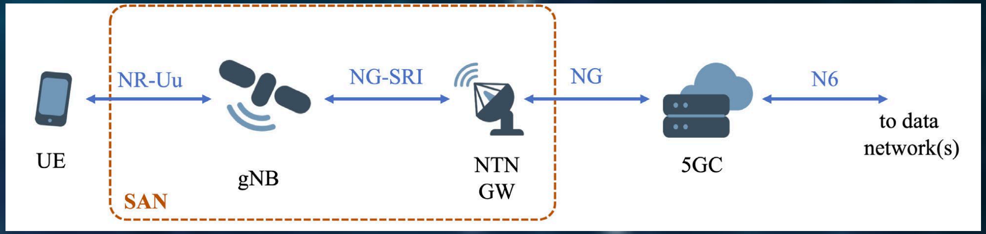
- Example: 5G NTN test at the ESTEC 5G Lab with Telesat LEO3
  - ➢ Amarisoft 3GPP compliant Rel-17 protocol stack
  - ➢ Stable bi-directional link between the gNB and the 5G NR NTN UE
  - ➢ Spectral efficiency of 3 bits/s/Hz (peak) by enabling adaptive modulation and coding from QPSK to 64-QAM.
  - ➢ 32 HARQ processes activated to maximize DL/UL throughput



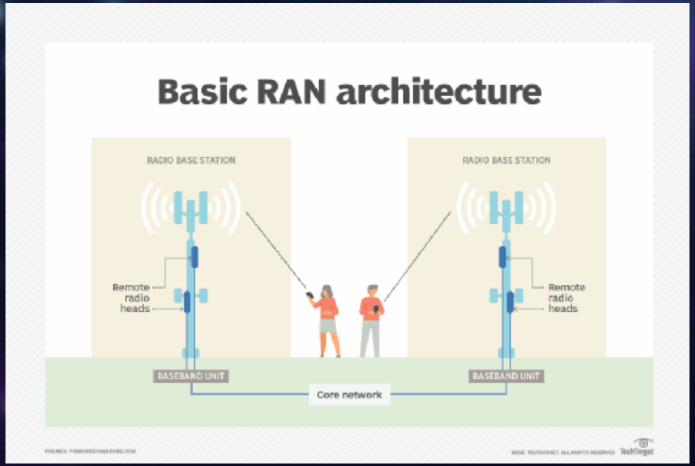
Source: https://connectivity.esa.int/news/esa-telesat-and-amarisoft-achieve-worldfirst-5g-3gpp-nonterrestrial-network-link-over-leo [3]

Full gNB onboard

- Benefits to introduce regenerative payload:
  - reduce delay between UE & gNB (i.e., NR Uu latency reduction)
  - enable more flexible NTN deployment
  - suitable for large LEO networks thanks to the reduction of data rate on the ISL
  - improve service link & feeder link spectrum efficiency
  - increase throughput & capacity
- Rel-19 includes NTN with a regenerative payload, in which a full gNB is placed on the satellite
  - Favorable timing due to 6G studies expected to start in 3GPP in Rel-20 (during 2025), where a CU-DU split might not be justified due to potential future 6G RAN node using a different split architecture



NTN Regenerative Payload without functional split [1]



The radio access network antenna receives information from user equipment and sends it to the core network via the baseband units. Source: https://www.techtarget.com/searchnetworking/definition/radio-access-network-RAN

5G NTN Architecture evolution and impact on Satcom

current status	(wide adoption of 5G)		2026+	
Rel.17	Rel.18	Rel.19	Rel.20	Future 6G
•Transparent •FR1	•Semi-Regen •FR1	•Regenerative •FR2	•Full gNB •Above FR2	•Sensing •Navigation •AI / ML

5G Stack

Payload complexity

Layer-1

- Wide channels (>50 MHz)
- High aggregated bandwidth
- Wideband ADC/DAC

- Very Wide channels (>400 MHz)
- High number of cells

Layer-2

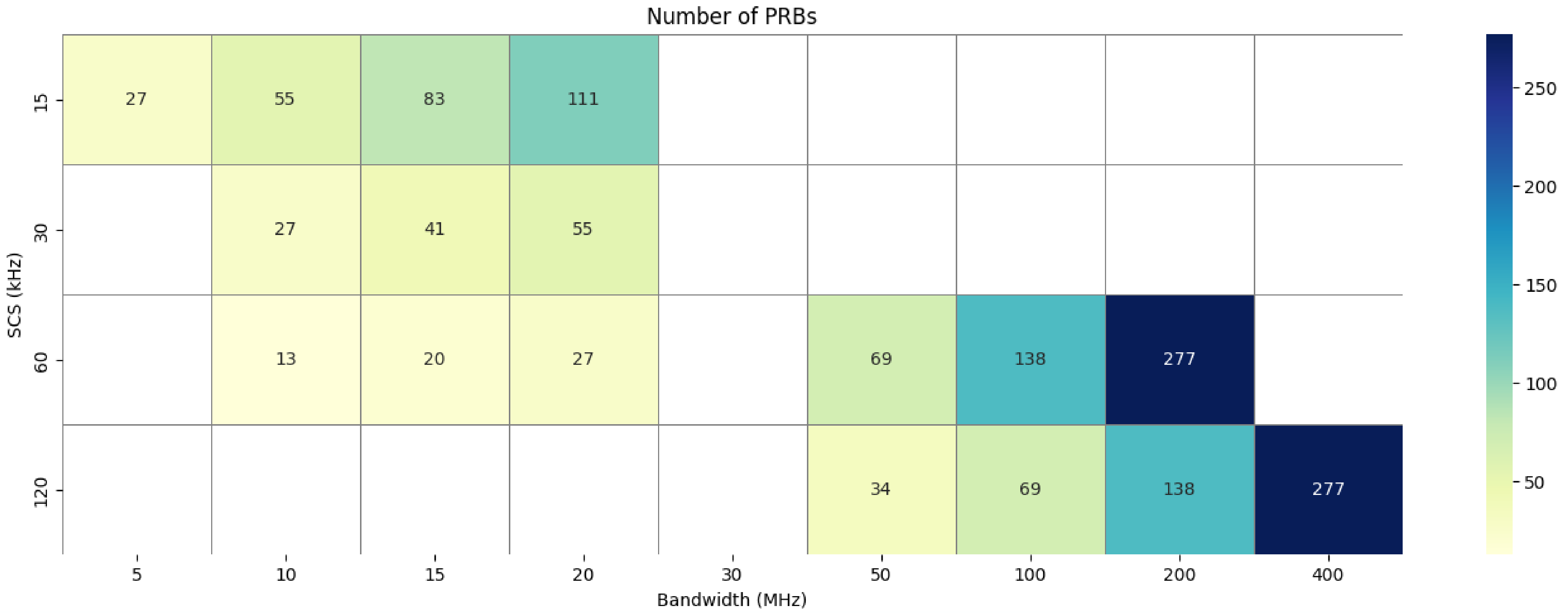
- High number of users/cell
- Software packet processing for DU
- >100Gb Routers

- Full DU on-board
- Security

Layer-3

- CU functions on-board
- Radio Resource Control

5G system capacity and hardware implications

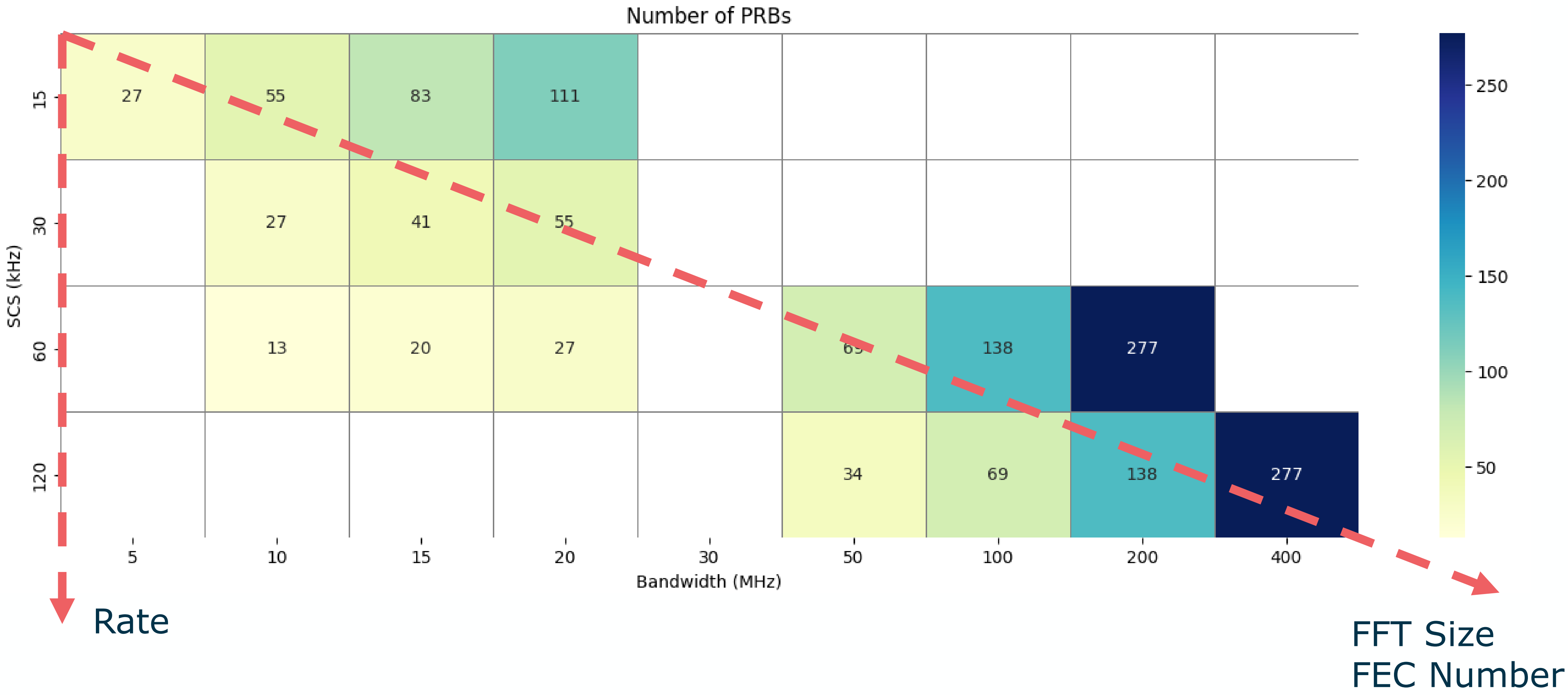


FR1 numerologies (Rel. 17)

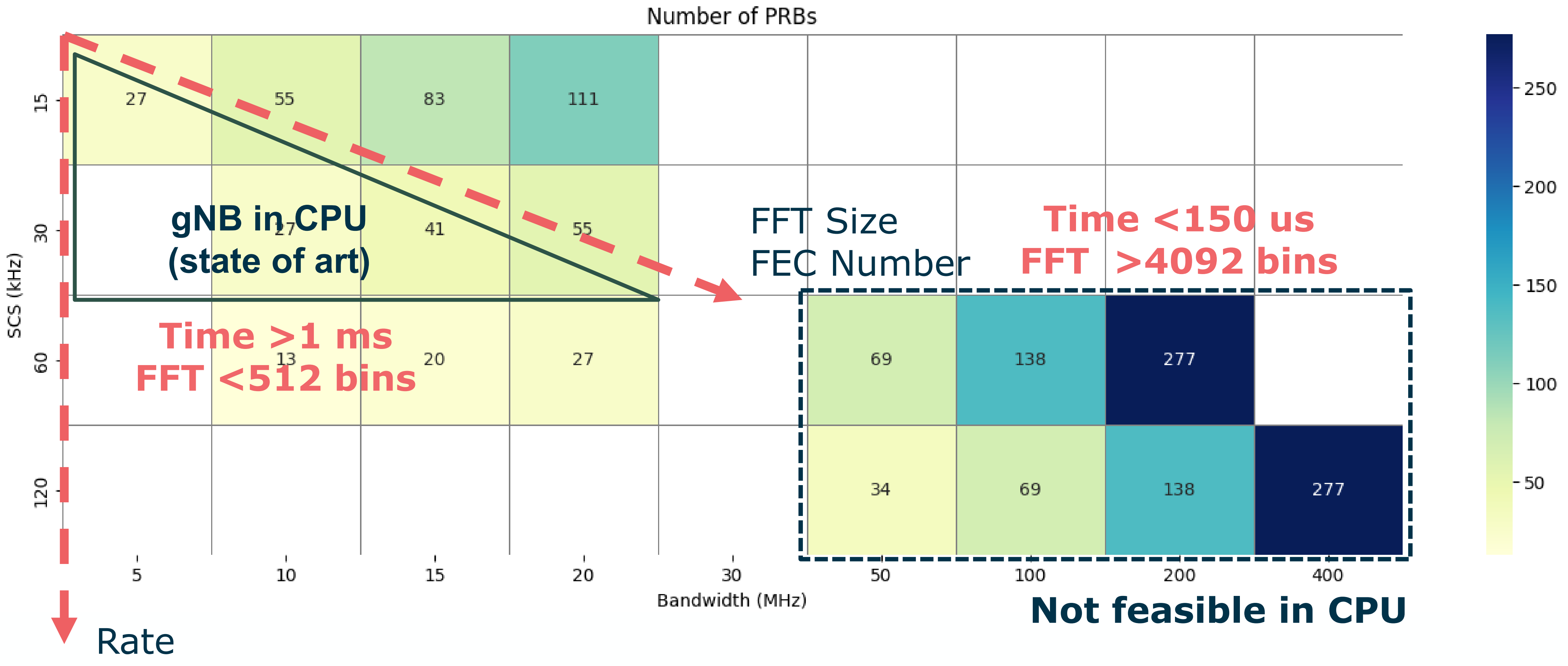
evolution

FR2 numerologies (Rel. 18/19)

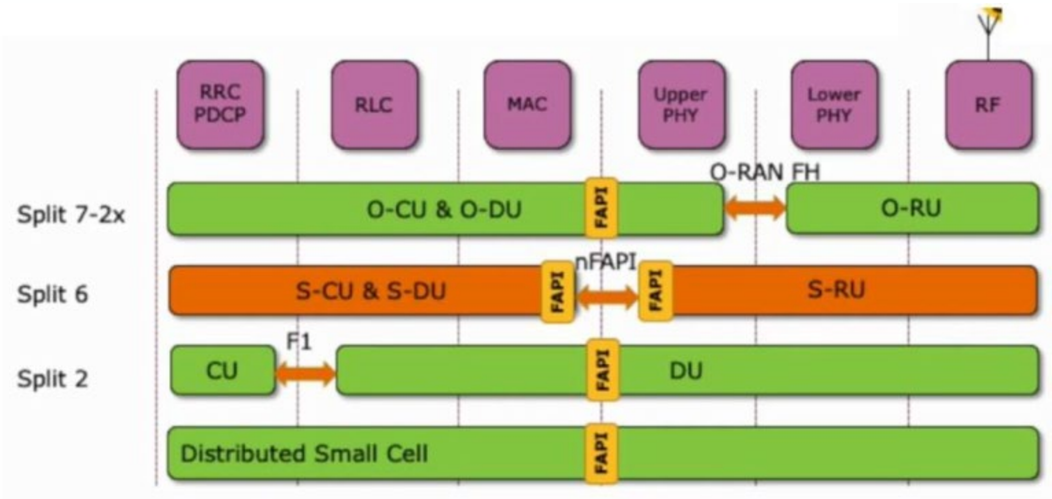
5G system capacity and hardware implications



5G system capacity and hardware implications



5G Non-Terrestrial-Network (NTN) System Splits



5G functional splits and interfaces

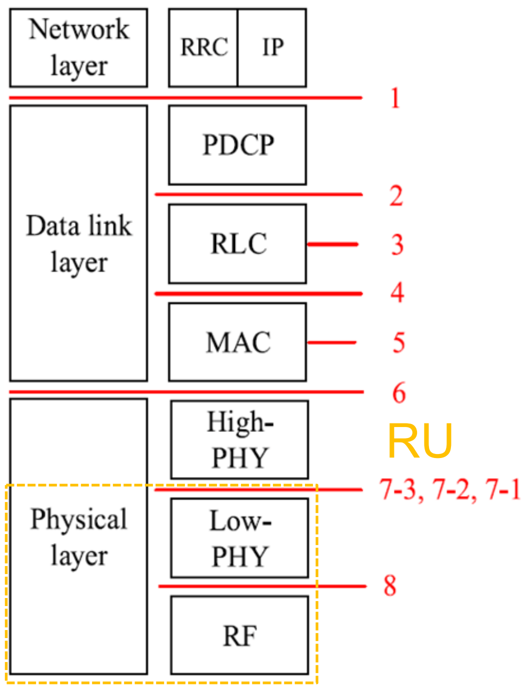
Bandwidth and one-way latency requirements of different functional split options.

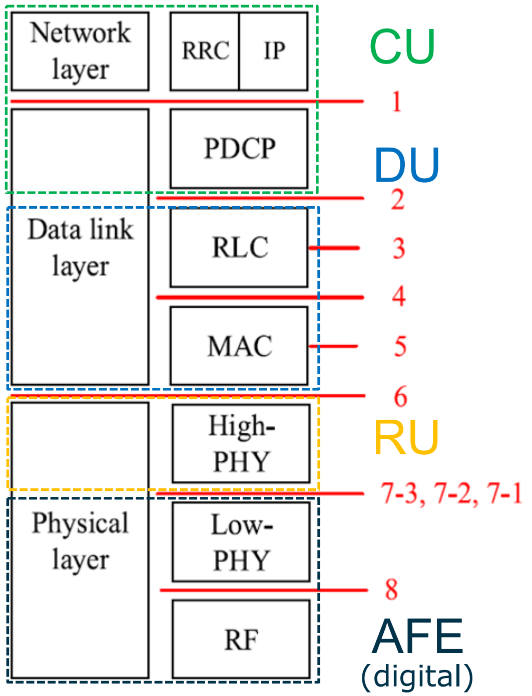
Functional Split	Required Downlink Capacity	Required Uplink Capacity	One-way Latency
Option 2	4016 Mb/s	3024 Mb/s	1–10 ms
Option 7-1	9.2 Gb/s	60.4 Gb/s	250 µs
Option 7-2	9.8 Gb/s	15.2 Gb/s	250 µs
Option 8	157.3 Gb/s	157.3 Gb/s	250 µs

5G functional splits and bandwidths

Payload Complexity

Complexity on ground (State of art)	Complexity on board (Current trend)
• System Split 7-2 • No Payload Split	• System Split full gNB • Payload Split 7-2, 6, 2

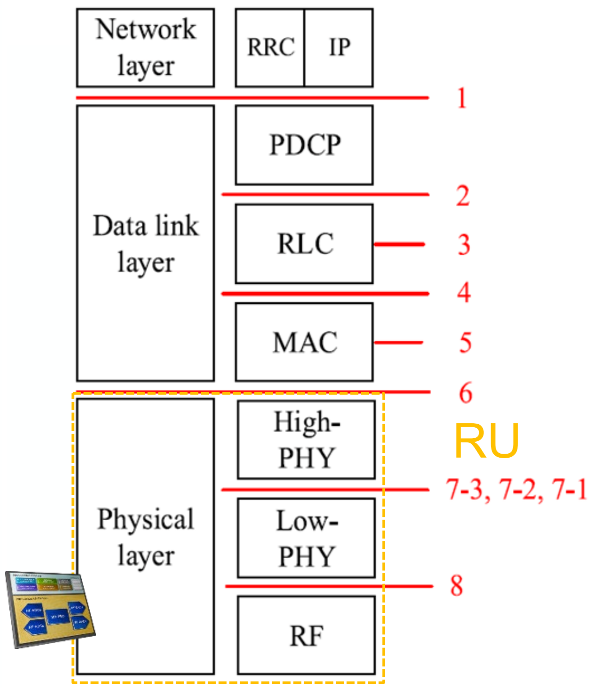


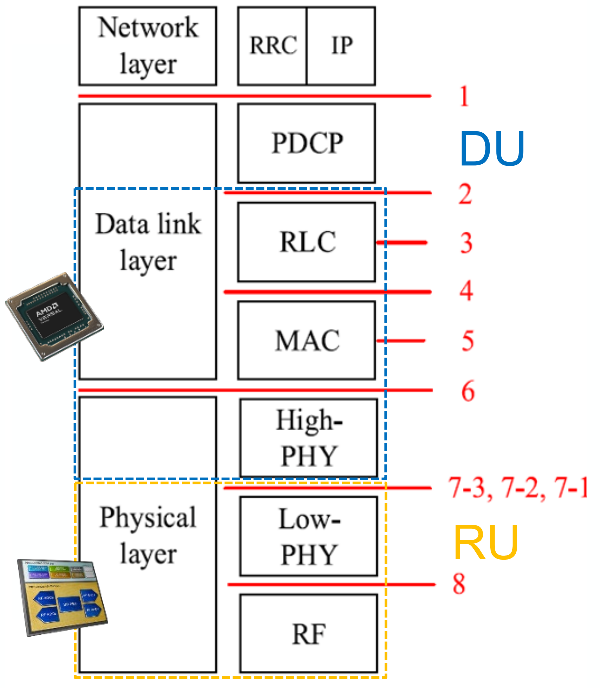


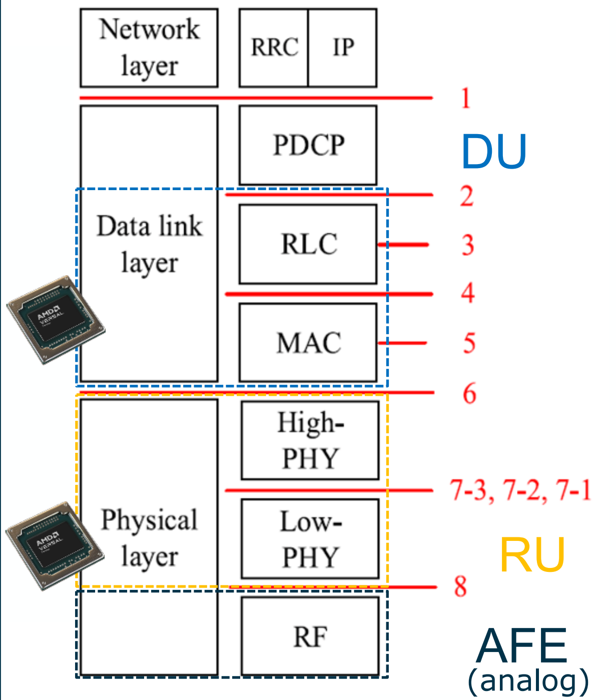
5G Regenerative Payload Split examples

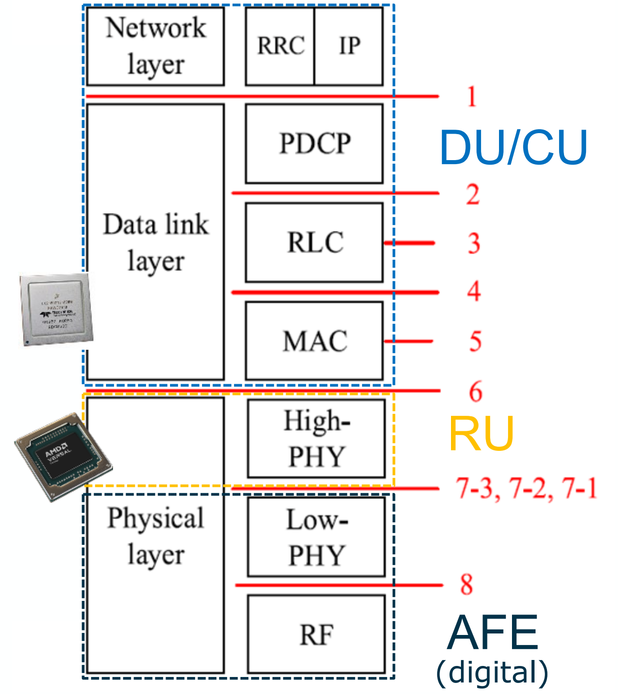
5G system and payload splits distribution of functions on different satellite payloads:

• Low Capacity • Low N. of Beams • Semi-Regen	• Medium Capacity • Low N. of Beams • Fully regenerative	• High Capacity • Medium N. of Beams • Fully regenerative	• Very High Capacity • High N. of Beams • CU functions on DU
• System Split 6 • No payload split	• System Split 2 • Payload Split 7-2	• System Split 2 • Payload Split 6 and 8	• System Split 2, 1 or 0 • Payload split 6 and 7-2x





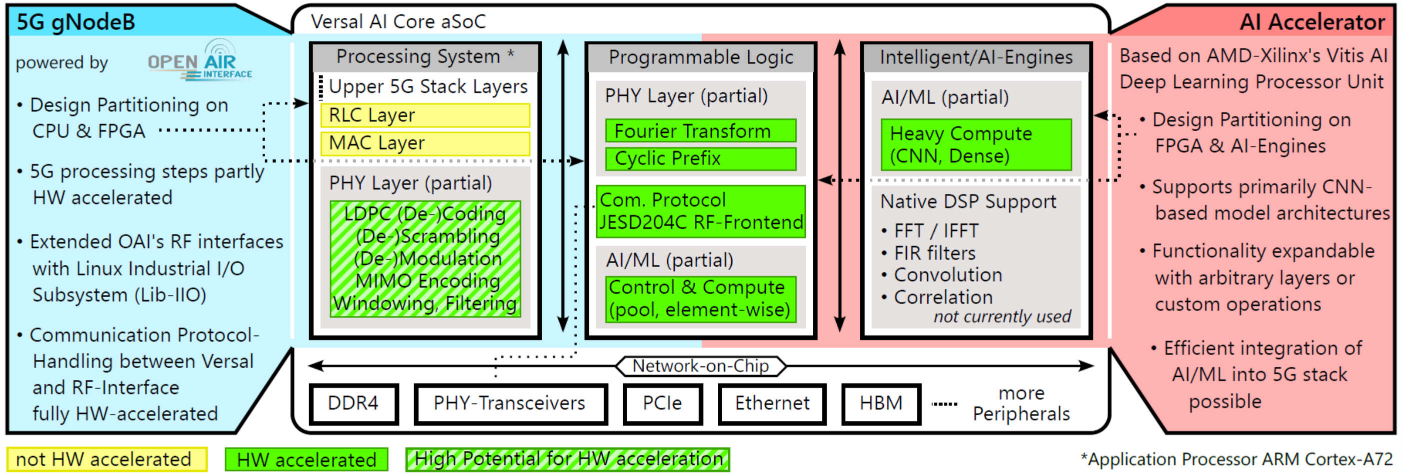




5G Signal and Data processing

Signal - PHY Layer - Porting of SW based gNodeB to embedded processors (e.g. OAI porting) has been carried out:
- Development needed for porting of Rel 19 (higher SCS and BW) - no available open source
- FPGA/DSP acceleration needed for PHY components, such as Coding, Scrambling, Modulation, Filtering
- IP development for wider bandwidths (>50 MHz), especially FR2

Data - MAC and higher layers - First examples of L2-3 processing demonstrated (e.g. to ARM), but not representative capacity:
- Development needed for embedded implementation of L2/3 functions, including interfaces to network
- Porting of x86 code to ARM and RISC-V
- Adaptation of code to NTN to achieve higher number of cells (>1000) and users



System Architecture for shared 5G gNodeB and AI/ML applications on an AMD-Xilinx Versal a SoC [*]

[*] Michael Petry and Raphael Mayr, "AI-enabled 5G base-station with Hardware Acceleration for Non-Terrestrial Networks on a Space-Grade System-on-Chip", 1st SPAICE Conference on AI in and for Space

5G Regenerative Payload – Broadband (now)

AFE RU DU

IF	CPRI			O-RAN		eCPRI		(n)FAPI		
Split	8		7.1	7.2x		7.2	7.3	6	2	1

ADC/DAC	FFT/iFFT	Digital BFN	RE Map	De/Mod	Coding	MAC&RLC	PDCP
ADC/DAC	FPGA	FPGA	CPU	CPU	CPU	CPU	Ground

5G Regenerative Payload – Broadband (next gen)

Broadband AFE RU DU

IF	**CPRI**		**O-RAN**							
Split	**8**	**7.1**	**7.2x**		**7.2**	**7.3**	**6**		**2**	**1**

ADC/DAC	**FFT/iFFT**	**Digital BFN**	**RE Map**	**De/Mod**	**Coding**	**MAC&RLC**	**PDCP**
BFN ASIC	BFN ASIC	BFN ASIC	FPGA	FPGA	FPGA	CPU	Ground

*different specification

5G Regenerative Payload – Broadband

AFE RU DU

IF	CPRI			O-RAN		eCPRI		(n)FAPI		
Split	8		7.1	7.2x		7.2	7.3	6	2	1

ADC/DAC	FFT/iFFT	Digital BFN	RE Map	De/Mod	Coding	MAC&RLC	PDCP
ADC/DAC	FPGA	FPGA	CPU	CPU	CPU	CPU	Ground

Broadband AFE RU DU

IF	CPRI		O-RAN						
Split	8	7.1	7.2x		7.2	7.3	6	2	1

ADC/DAC	FFT/iFFT	Digital BFN	RE Map	De/Mod	Coding	MAC&RLC	PDCP
BFN ASIC	BFN ASIC	BFN ASIC	FPGA	FPGA	FPGA	CPU	Ground

*different specification

5G Regenerative Payload – Direct to Device (now)

AFE

IF	CPRI			O-RAN		eCPRI		(n)FAPI		
Split	8		7.1	7.2x		7.2	7.3	6	2	1

ADC/DAC	FFT/iFFT	Digital BFN	RE Map	De/Mod	Coding	MAC&RLC	PDCP
ADC/DAC	FPGA	FPGA	Ground	Ground	Ground	Ground	Ground

5G Regenerative Payload – Direct to Device (next gen)

Direct to Device AFE

IF	CPRI		O-RAN					
Split	8	7.1	7.2x	7.2	7.3	6	2	1

ADC/DAC	FFT/iFFT	Digital BFN	RE Map	De/Mod	Coding	MAC&RLC	PDCP
BFN ASIC*	BFN ASIC*	BFN ASIC*	Ground	Ground	Ground	Ground	Ground

*different specification than broadband

5G Regenerative Payload– Direct to Device

AFE

IF	CPRI		O-RAN		eCPRI		(n)FAPI		
Split	8	7.1	7.2x		7.2	7.3	6	2	1

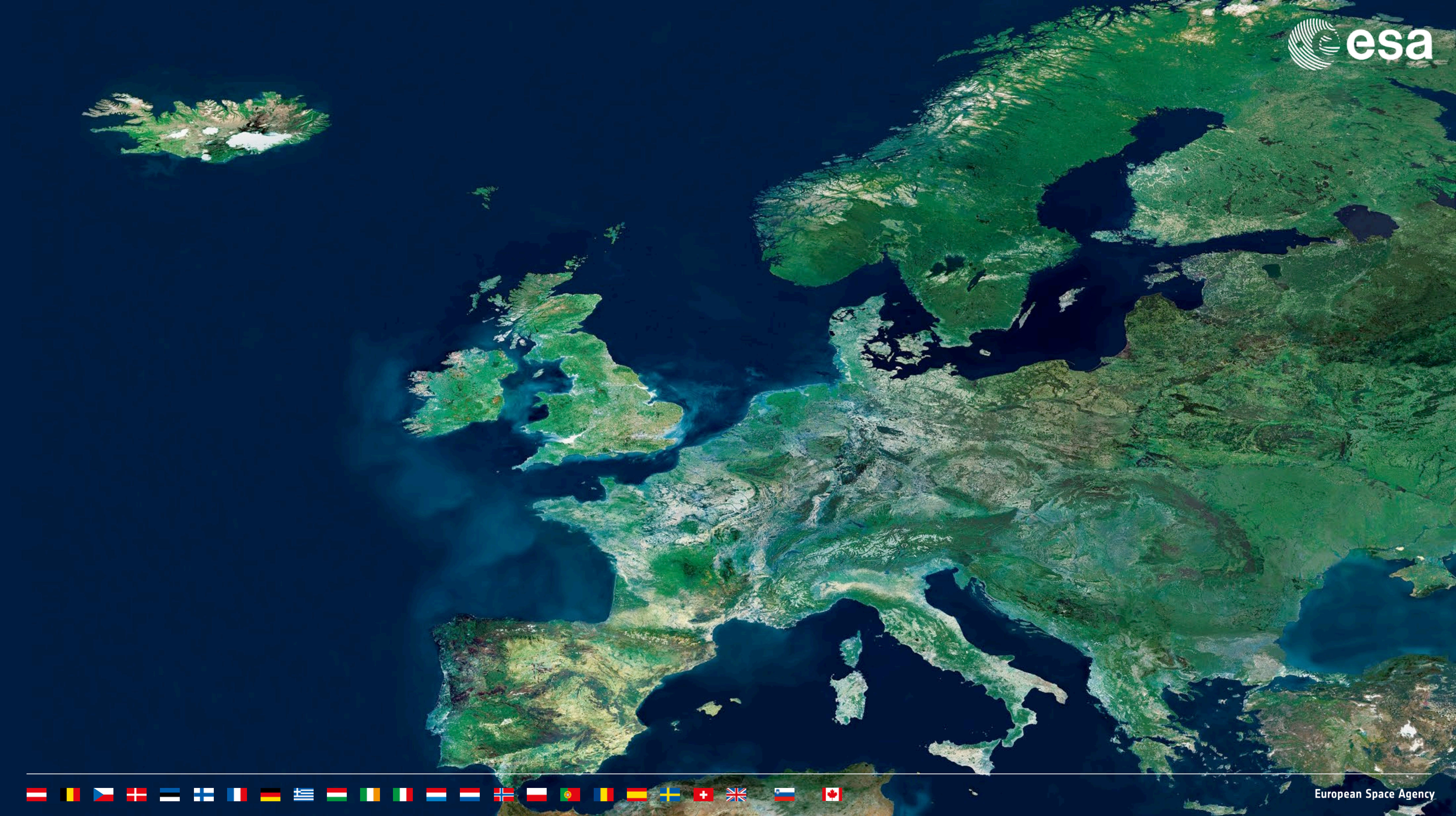
ADC/DAC	FFT/iFFT	Digital BFN	RE Map	De/Mod	Coding	MAC&RLC	PDCP
ADC/DAC	FPGA	FPGA	Ground	Ground	Ground	Ground	Ground

Direct to Device AFE

IF	CPRI		O-RAN					
Split	8	7.1	7.2x	7.2	7.3	6	2	1

ADC/DAC	FFT/iFFT	Digital BFN	RE Map	De/Mod	Coding	MAC&RLC	PDCP
BFN ASIC*	BFN ASIC*	BFN ASIC*	Ground	Ground	Ground	Ground	Ground

*different specification than broadband


European Space Agency