A New CubeSat Design with Reconfigurable Multi-band Radios for Dynamic Spectrum Satellite Communication Networks

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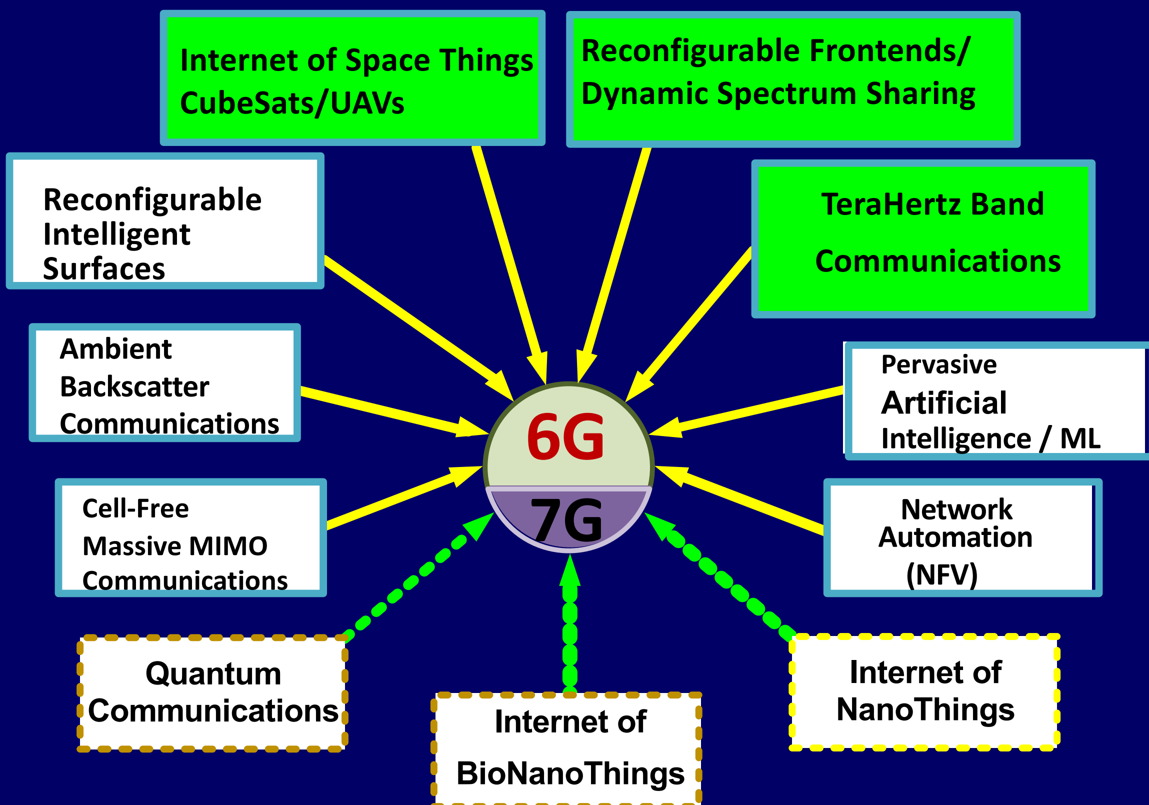
KEY ENABLING TECHNOLOGIES FOR 6G

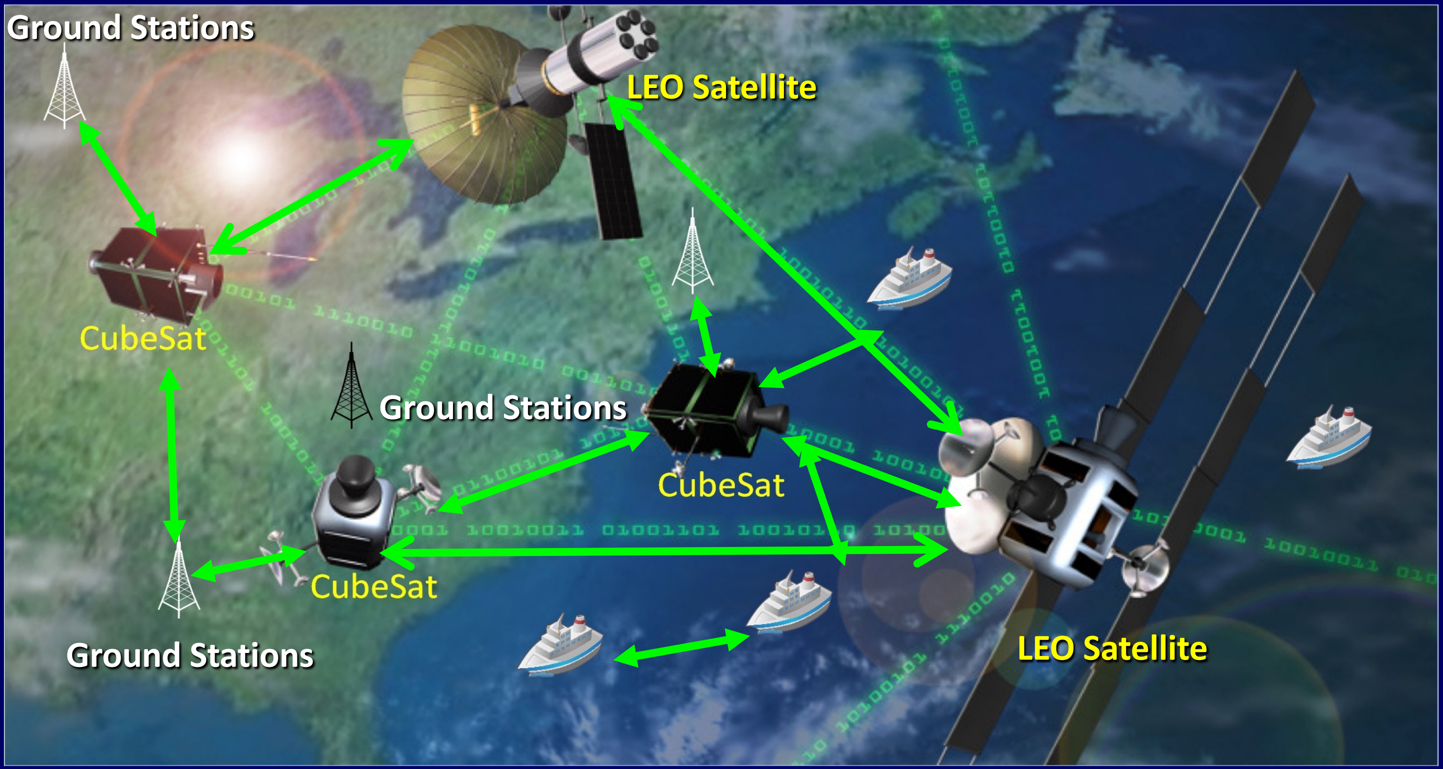
I. F. AKYILDIZ, A. KAK, S. NIE

"6G AND BEYOND: THE FUTURE OF WIRELESS COMMUNICATIONS SYSTEMS",

IEEE ACCESS JOURNAL, VOL. 8, PP. 133995-134030, JULY 2020.



INTERNET OF THINGS IN SPACE/CUBESATS



Internet of Space Things/CubeSats

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I. F. Akyildiz, J. M. Jornet and S. Nie,
“A New CubeSat Design with Reconfigurable Multi-Band Radios for Satellite Communication in Dynamic Spectrum Frequencies”,
Ad Hoc Networks (Elsevier) Journal), vol. 86, pp. 166-178, April 2019.

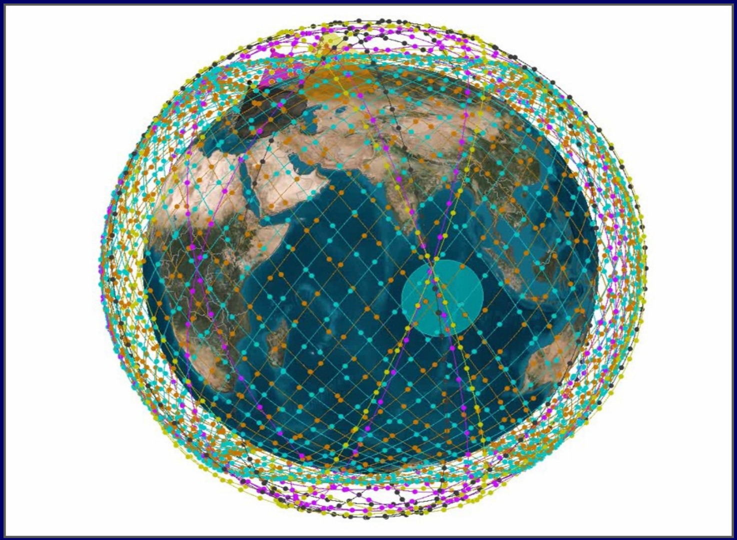
I. F. Akyildiz and A. Kak,
"The Internet of Space Things/CubeSats”,
IEEE Network, vol. 33, no. 5, pp. 212-218, Sept.-Oct. 2019

I. F. Akyildiz, A. Kak, and S. Nie,
“Network Employing Cube Satellites,”
US Patent: WO 2020/124076 A1, Fall 2020.
Publication Date: Dec. 14, 2018.

What Are Small Satellites?

- Why small satellite communications?
  - Conventional satellites have higher costs and longer development cycles
  - Great potential for mass-productions

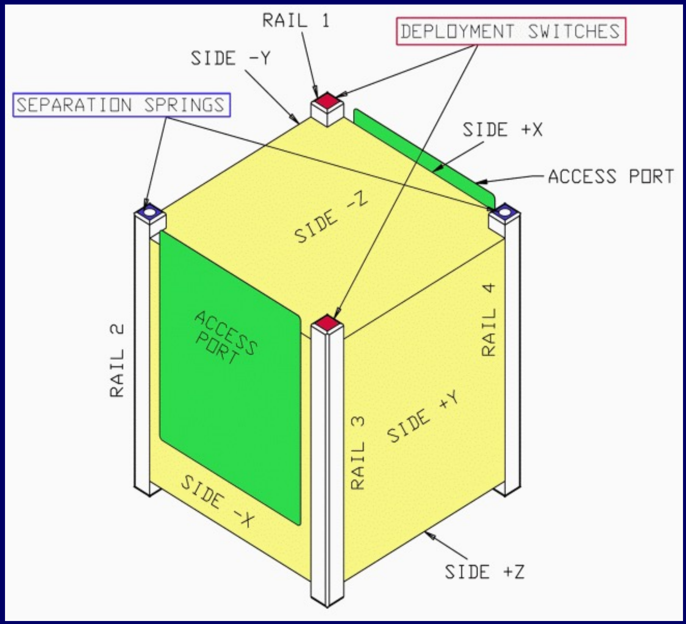
Class of Small Satellites	Mass [kg]
Minisatellites	100–180
Microsatellites	10–100
Nanosatellites (CubeSats)	1–10
Picosatellites	0.1–1
Femtosatellites	< 0.1



SpaceX's Starlink constellation with 4,425 satellites

WHAT IS A CUBESAT?

- Small satellites originally used at CalPoly in 1999
- Also referred as “nano/micro satellites”
- 1U = 10 cm × 10 cm × 10 cm → mug size
- Can be airborne launched

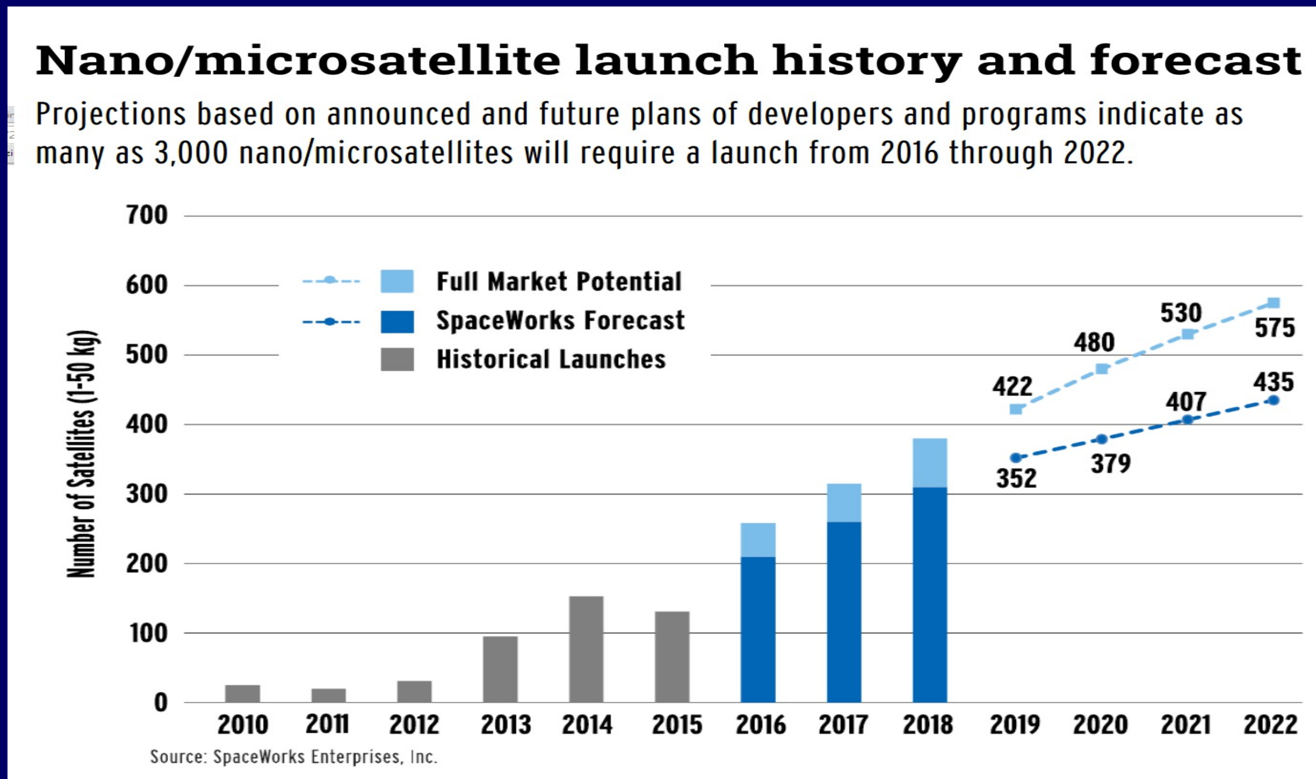


Original CubeSat Specification

ADVANTAGES OF CUBESATS

- Scalable
- Flexible
  - Cooperation with Drones, UAVs
- Built with commercial off-the-shelf components
- Short "development to deployment" period

CUBESAT LAUNCHES PER YEAR 2010~2022



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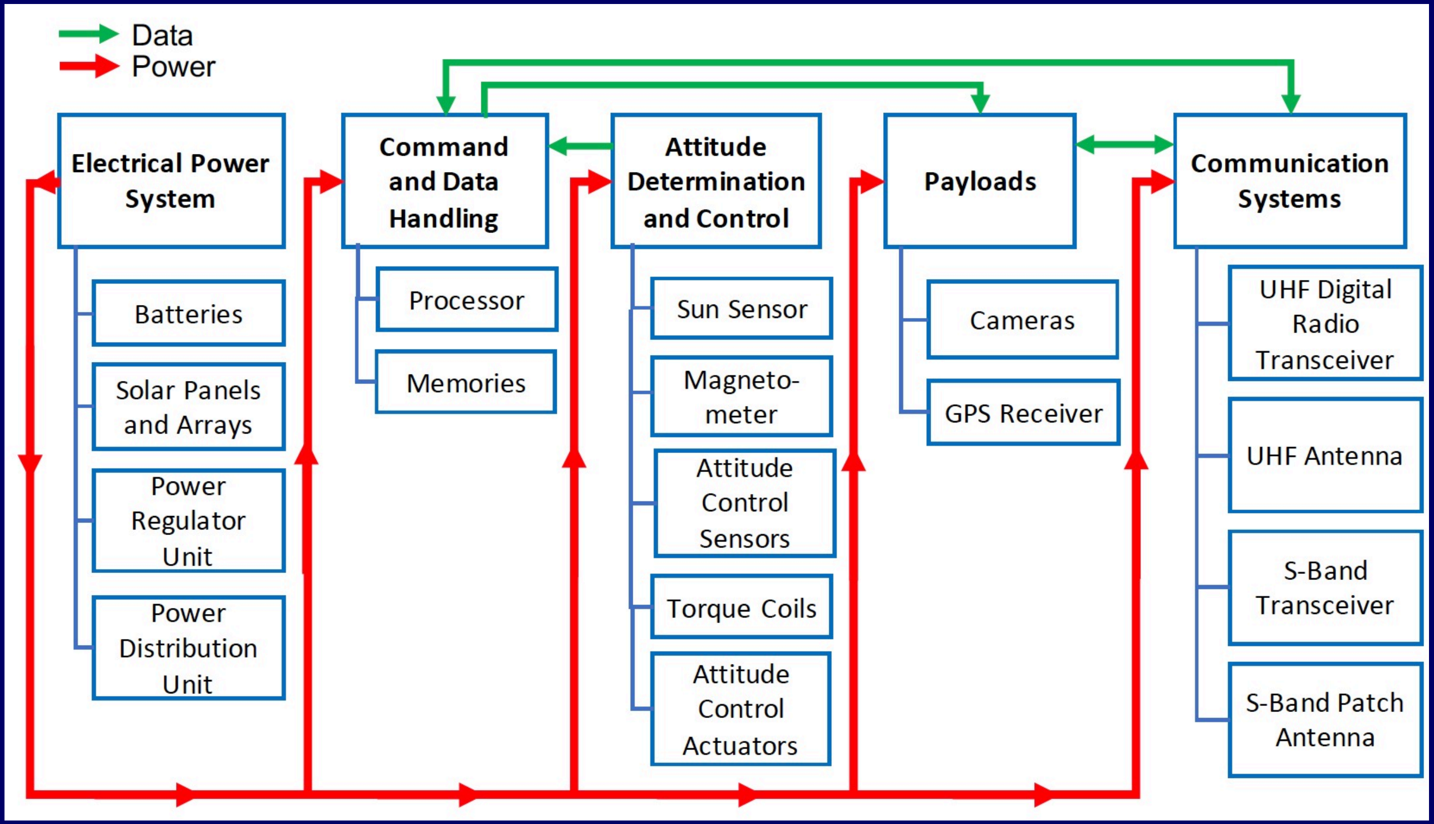
FUNCTIONAL COMPONENTS IN CUBESATS



EXISTING SATELLITE-BASED IoT AND BROADBAND NETWORKS

Name of Satellite	Iridium NEXT SensorPOD	Tintin	Astrocast	Fleet	KIPP	Aistech
Company	Iridium Comm., USA	SpaceX, USA	ELSE, Switzerland	Fleet, Australia	Kepler, Canada	Aistech, Spain
Purpose	Sensing & communications	Broadband network	IoT & M2M	IoT	Satellite backhaul	IoT, M2M & asset tracking
ISL Capability	Only to host satellite	Yes	Yes	N/A	Yes	N/A
Deployment Year	2015	2015 (Trials)	2018	2018	2018	2018
Orbital Altitude	780 km	340, and 1200 km	450–600 km	580 km	500–650 km	N/A
No. of Satellites	66	7518 and 4425	64	100	140	100
Form Factor	4.5U	Not a CubeSat	3U	1.5U, 3U, and 12U	3U	6U
Weight	4-5 kg	100-500 kg	4 kg	N/A	5 kg	N/A
Frequency Band	L and Ka	V, K_a, K_u	L	N/A	K_a and K_u	N/A
Self-sustained	No (Host dependent)	Yes	Yes	Yes	Yes	Yes

Note: "N/A" means the parameter is not available in published sources.

LIMITATION OF EXISTING CUBESAT SOLUTIONS

- Lack of continuous global coverage
  - Limited number of satellites (Iridium NEXT SensorPod– 66, Astrocast – 64, Fleet - 100) → Continuous coverage not possible

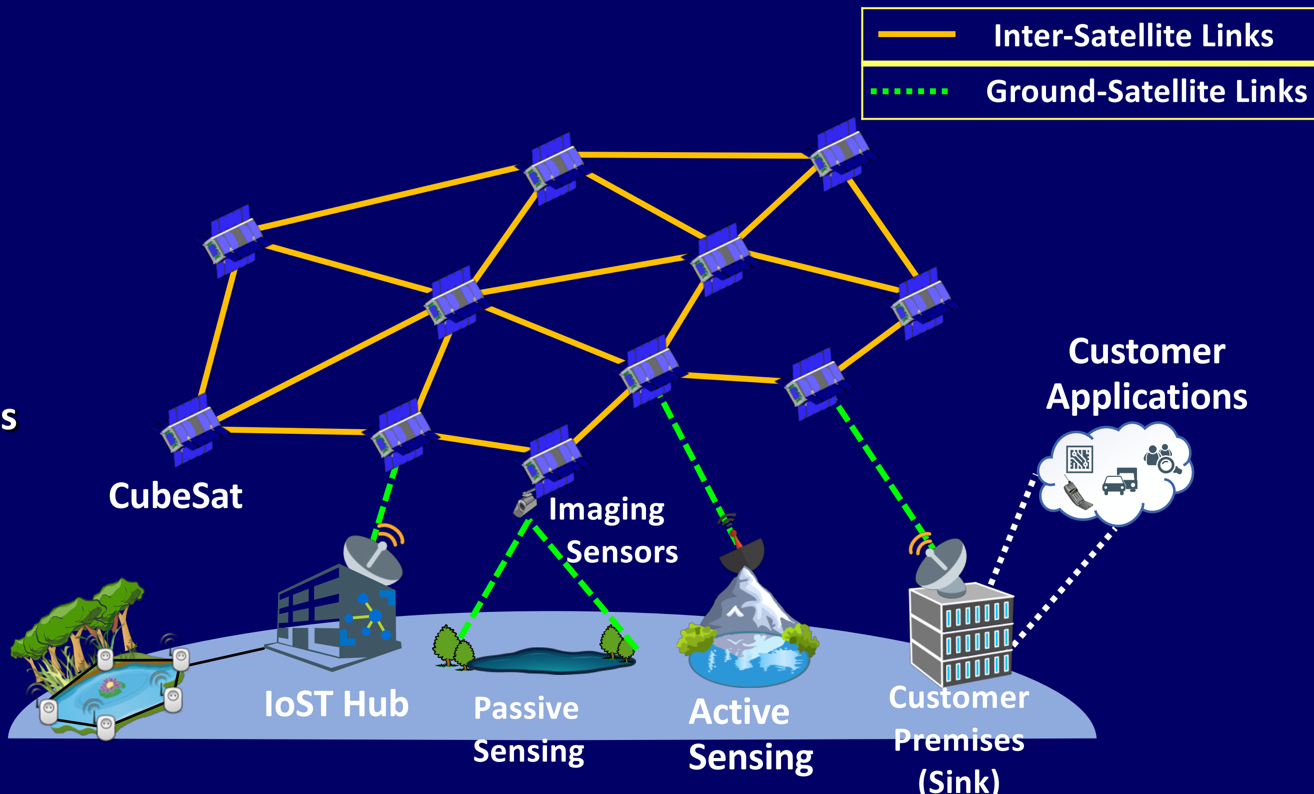
- Low data rates
  - Iridium NEXT SensorPod: up to 1 Mbps
  - AstroCast: kbps range
  - Keppler: 1-40 Mbps

- mmWave and THz bands are underexplored for active communication in space

- Use conventional satellite communication frequencies → Already very congested with limited bandwidth
  - Iridium NEXT SensorPod: L- and K_a-band
  - AstroCast: L-band
  - Keppler: K_u-band
  - Hiber: S-band

INTERNET OF SPACE THINGS – ARCHITECTURE

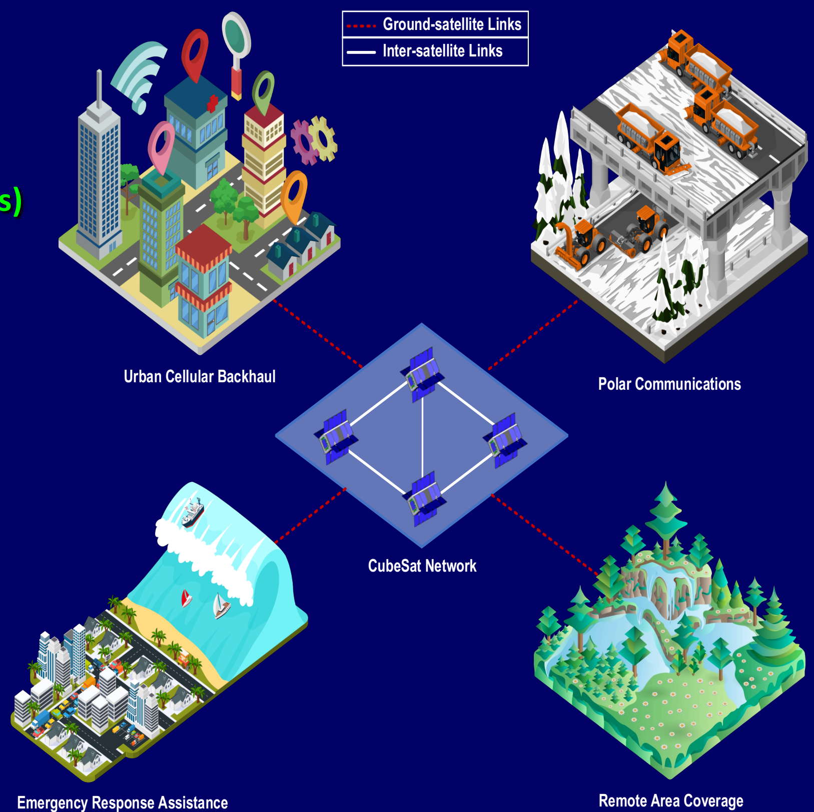
- Primary components
  - IoST hubs
  - On-Earth, and near-Earth sensing devices
  - CubeSat Network



USE CASES OF IoST

Backhaul in the Sky

- Remote areas connectivity (e.g., North and South Poles)
- Pervasive tracking
- Emergency infrastructure after natural disasters (Earthquakes, tsunamis, or tornados)
- Network Security Concern in Terrestrial Networks
- Traffic Offloading from Congested Terrestrial Networks



Eyes in the Sky

- Terrain Monitoring
- Disaster Prevention and Monitoring

Our Design: UbiCube

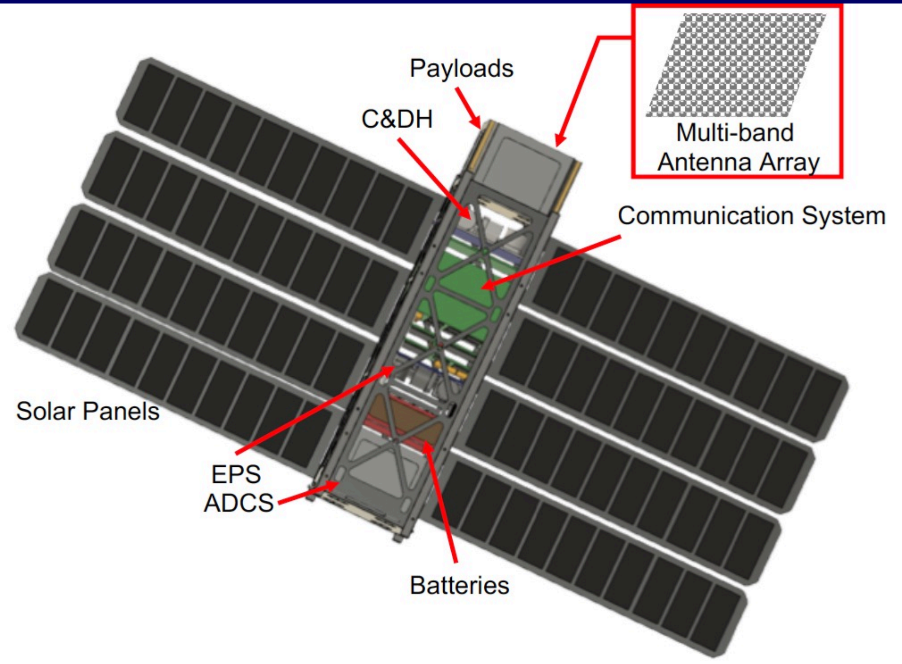
I.F. Akyildiz, et. al.

"A New CubeSat Design with Reconfigurable Multi-Band Radios for Satellite Communication in Dynamic Spectrum Frequencies,"

Ad Hoc Networks (Elsevier) Journal, vol. 86, pp. 166-178, April 2019.

Patent Applied in Dec. 2018.

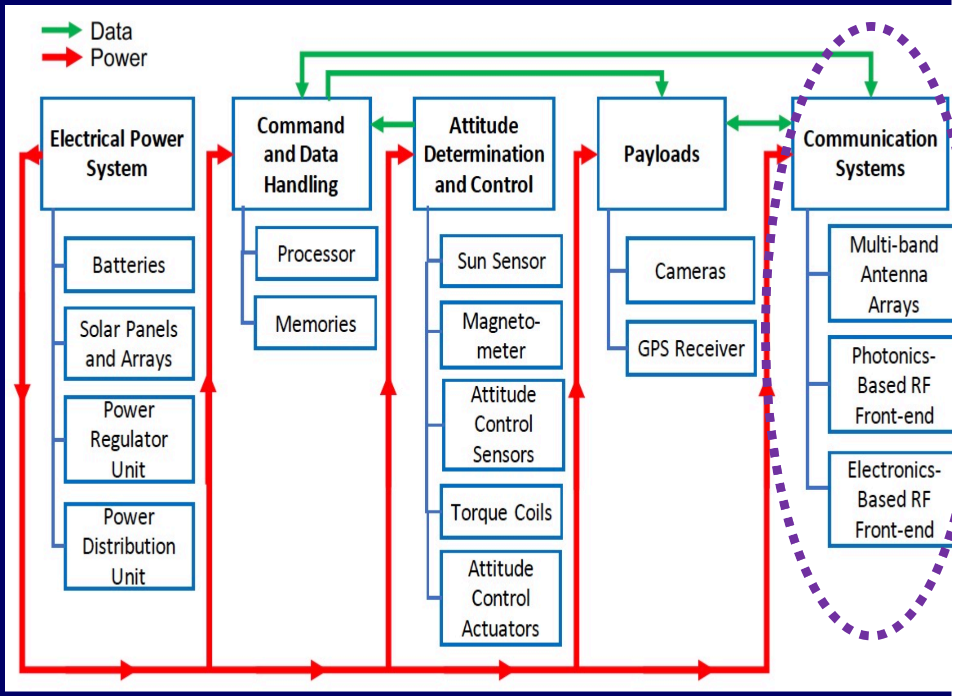
- Dimension: 3U (10 cm × 10 cm × 34 cm)
- Weight: 5 kg max.
- No propulsion system
- Solar panels expand 45 minutes at deployed to target orbits
  - 8 independent solar panels flexible to change orientations for max. area of sun exposure



NOVELTIES IN OUR DESIGN

– **Multi-frequency Front-End Design**

- L-band (1–2 GHz)
- S-band (2–4 GHz)
- C-band (4–8 GHz)
- X-band (8–12 GHz)
- K_u-band (12–18 GHz)
- K_a-band (26.5–40 GHz)
- Mm-wave (30 – 300 GHz)
- THz frequency band (0.3 – 1 THz)



– **Multi-frequency Antenna Design**
– **Flexible PHY and Link Layer Design**
– **Ultra Massive MIMO & Distributed MIMO**
– **Dynamic Resource Allocation Algorithms**

MULTI-FREQUENCY COMMUNICATION IN IoST

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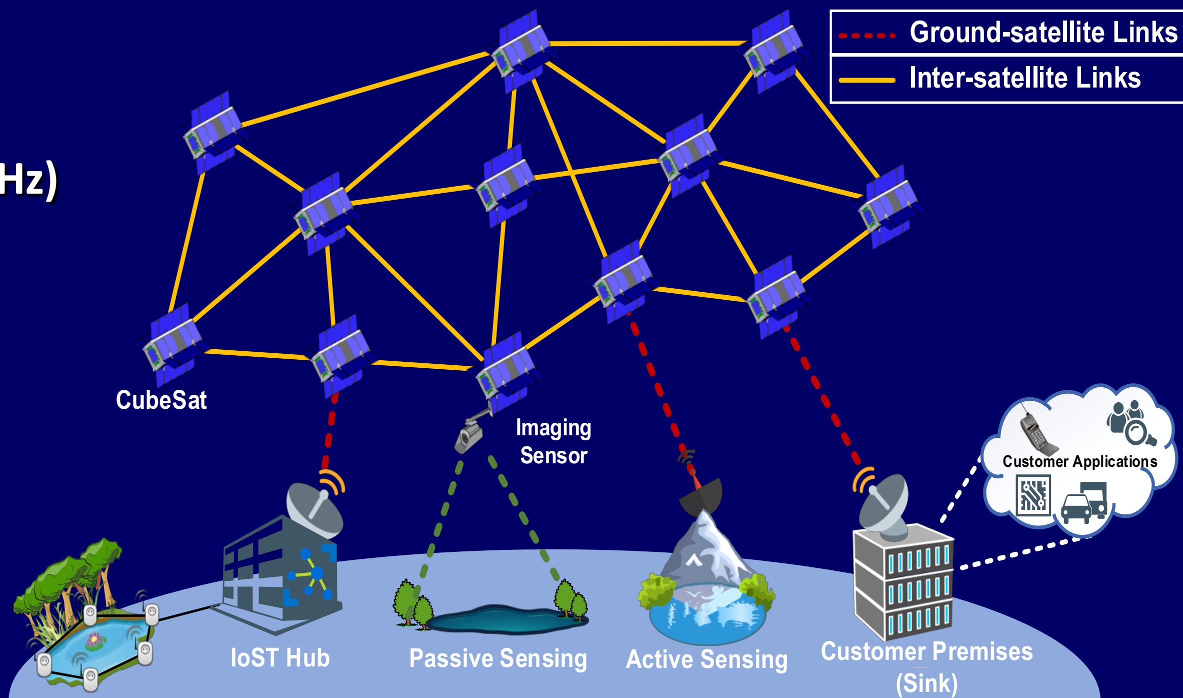
Inter-Satellite Links

- Mm-wave (30 – 300 GHz)
- THz frequency band (0.3 – 1 THz)

Ground-Satellite Links

- L-band (1–2 GHz)
- S-band (2–4 GHz)
- C-band (4–8 GHz)
- X-band (8–12 GHz)
- K_u-band (12–18 GHz)
- K_a-band (26.5–40 GHz)
- Mm-wave (30 – 300 GHz)
- THz frequency band (0.3 – 1 THz)



MULTI-FREQUENCY (1 GHz - 1 THz) FRONT-ENDS

- A solution to design, implement, and optimally operate frequency-agile, ultra-broadband reconfigurable system communicate over the spectrums ranging from 1GHz – 1THz

- Ultimate Goals: MAXIMIZE
  - Spectrum Utilization
  - Data Rates
  - Network User Capacity (including in Space and on Earth)

WHY mm-WAVES and THz Bands in ISLs?

- Molecular absorptions by oxygen for mm-waves and water vapors at THz-band → heavy attenuation
- Do not exist in the Space → Very low concentration of absorbing molecules above the atmosphere
- Very high data rates are possible
- Small wavelengths at mm-wave and THz , the size of antenna arrays can be significantly reduced.
- More antenna elements (massive and ultra-massive MIMO) are possible.

DESIGN IDEAS FOR RECONFIGURABLE MULTIFREQUENCY TRANSCEIVER

- Three metrics weigh in the design to generate signals at various frequency bands for space communication

    i) Dimension Constraints,

    ii) Power Source and Energy Consumption,

    iii) Achievable Performance.

- **Hardware Design:**
    - Multi-Stream Electronic Frequency Up-conversion Chains

MULTI-STREAM ELECTRONIC FREQUENCY UP-CONVERSION CHAINS

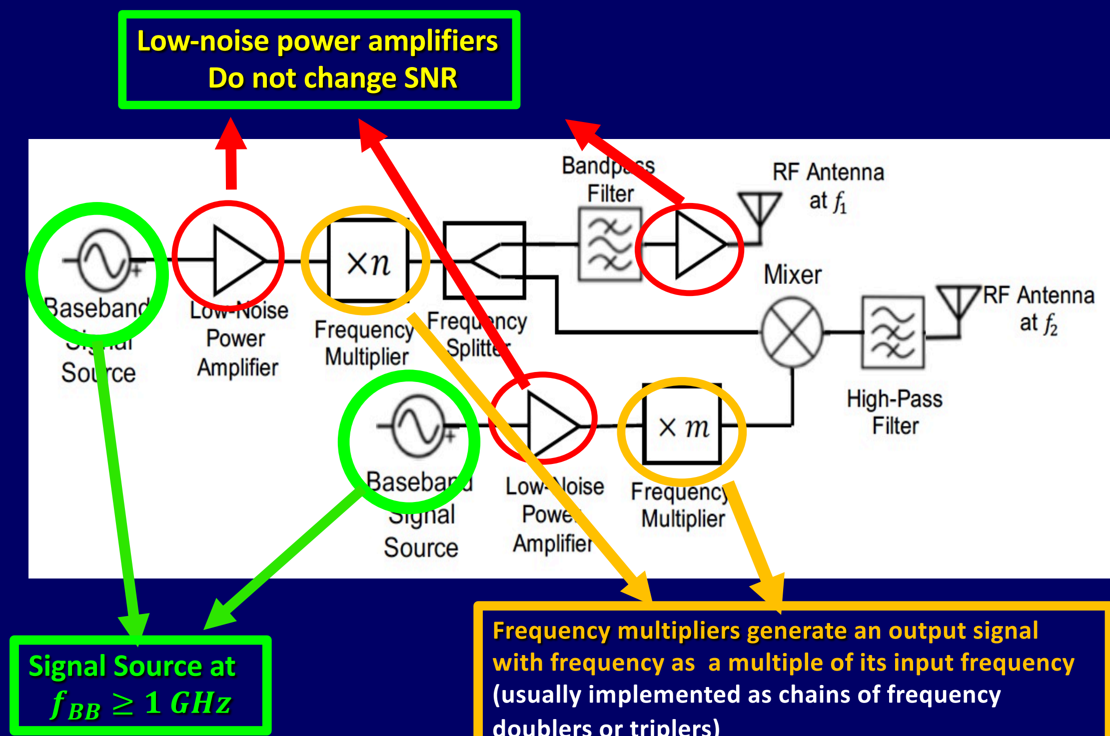
- Signals at different frequencies are generated by a chain of freq multiplication and up-conversion

General Idea

Use frequency splitters to divide the input signal into 2 identical output signals after frequency multipliers to extract intermediate frequencies for outputs.

Signal at f_1 is considered as the intermediate output when producing signals at a higher f_2.

Similar structures can be cascaded to provide more output streams.



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MULTI-FREQUENCY ANTENNA SYSTEMS

- Physically reconfigurable antennas for various resonant frequencies
  - Nano-/micro-electromechanical (NEMS/MEMS)
  - Origami structures

  Problems: Delay associated to the control of the NEMS/MEMS systems, specially when targeting very high data-rates, as well as the size and integration complexity of NEMS for the THz-band antennas.

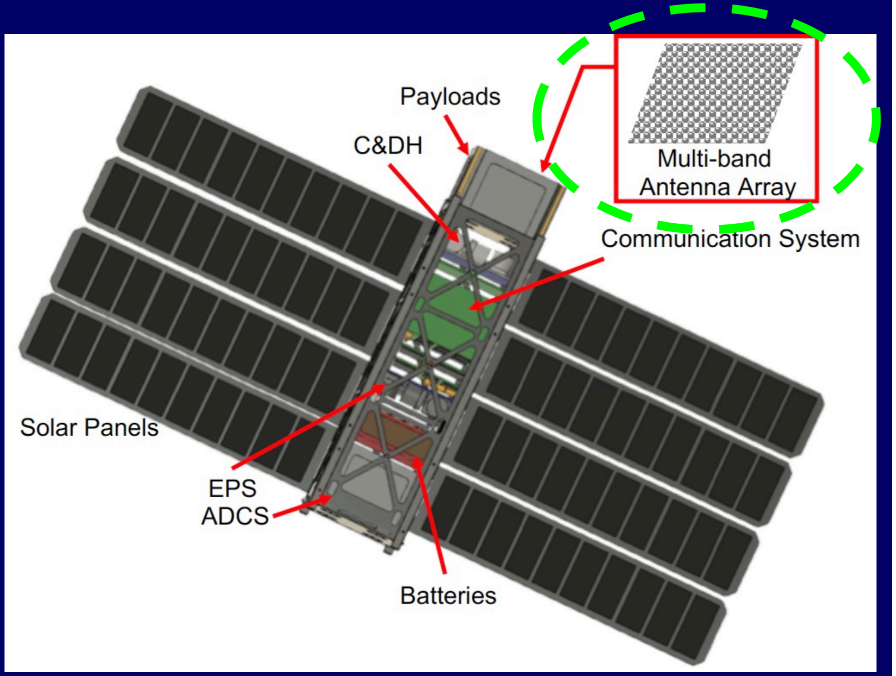
- Software-defined or electronically tunable nano-antennas
  - Graphene-based plasmonic nano-antenna arrays

- Electronically controlled tunable phase reflectarray antennas
  - Dynamically adjust radiation patterns
  - Simpler and cheaper in mass production → suitable for CubeSat deployment

UbiCube Multi-band Antenna Arrays

- Multi-band antenna array can operate in frequencies
  - C-band (3.4–6.4 GHz)
  - X-band (8–9 GHz)
  - Ku-band (12–18 GHz)
  - Ka-band (23–27 GHz)
  - Mm-wave (30 – 300 GHz)
  - THz frequency band (0.3 – 1 THz)

Conventional Satellite Comm. Freq.



MULTI-BAND RECONFIGURABLE ANTENNA ARRAY

- **Plasmonic Reflectarray Antennas on CubeSats**
  - Efficiently radiate at target resonant frequencies
  - Much smaller than the corresponding wavelength → $\lambda/20$ for graphene
  - Multi-band communications with suppressed mutual coupling effect
- **Able to control signal propagation**
  - Wave steering
  - Polarization tuning
- **Directivity of reflectarray antennas**

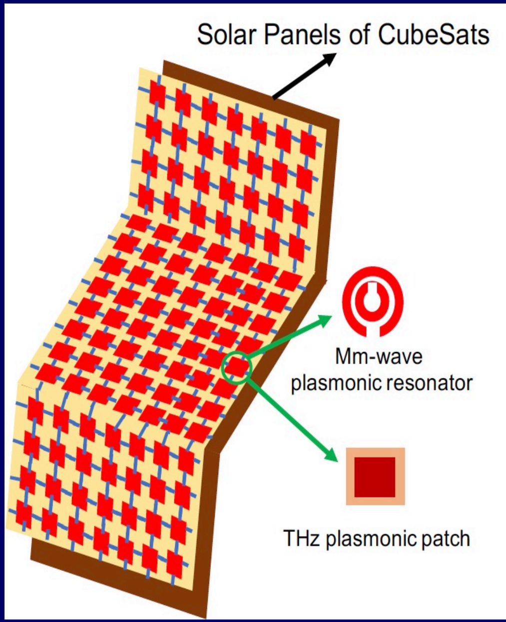


Illustration of plasmonic antenna array on CubeSats

ULTRA-MASSIVE MIMO

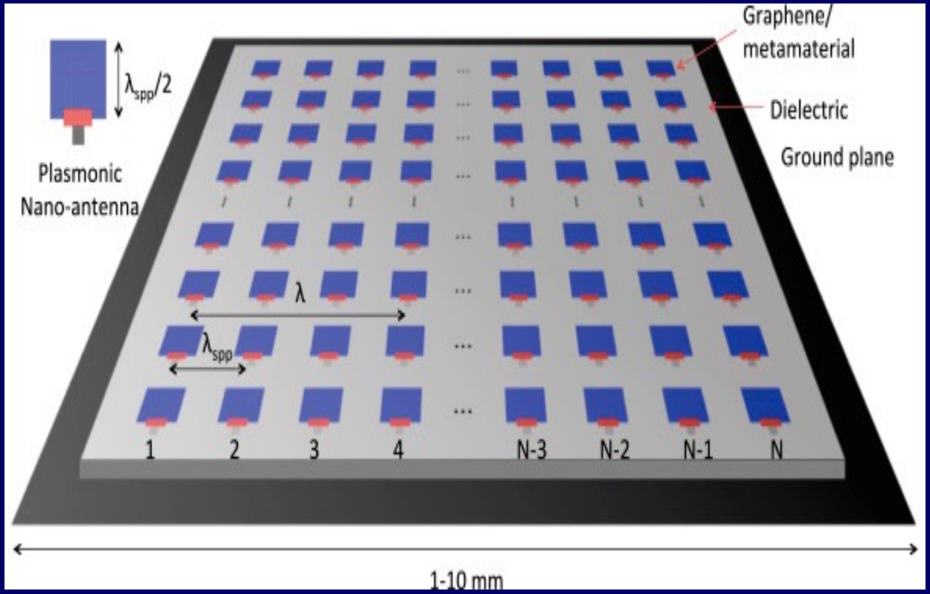
I. F. Akyildiz and J. M. Jornet

"Realizing Ultra-Massive MIMO Communication in the (0.06–10) TeraHertz Band"

Nano Communication Networks, (Elsevier) Journal, Vol. 8, pp. 46-54, March 2016;

U.S. Patent 15/211,503 awarded on Sept. 7, 2017.

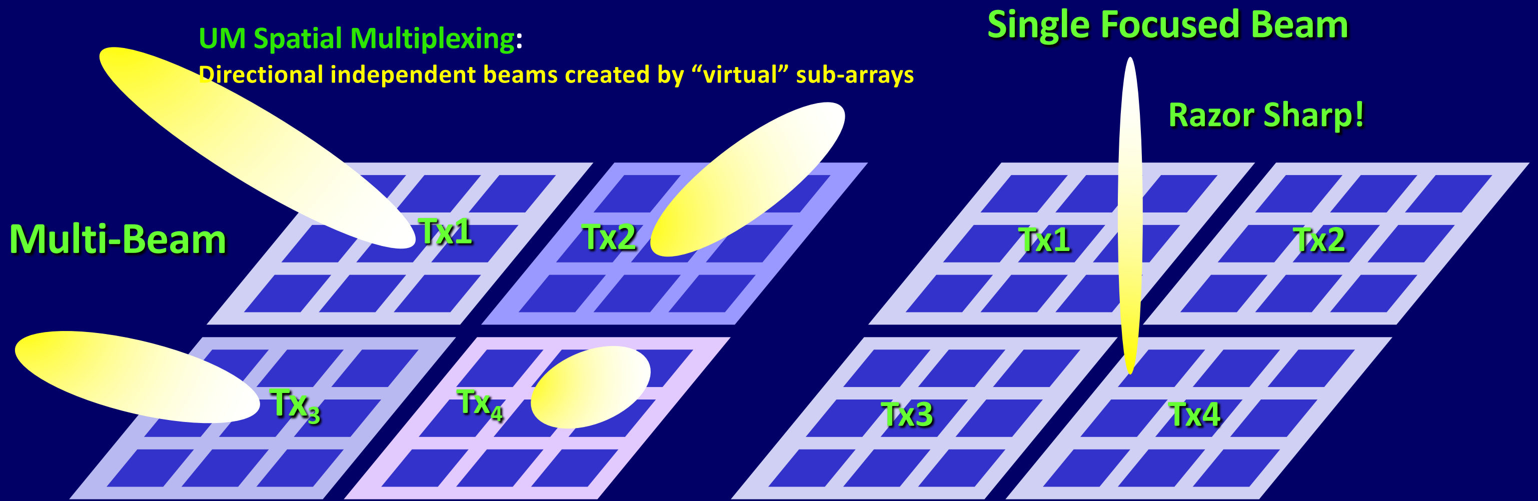
Planar Array with 32x32 antenna elements in total of 1024 elements



DYNAMIC ULTRA MASSIVE MIMO FOR INTELLIGENT BEAMFORMING

S. NIE AND I. F. AKYILDIZ,
"BEAMFORMING IN INTELLIGENT ENVIRONMENTS BASED ON UM MIMO PLATFORMS IN MM WAVE & THZ BANDS,"
IEEE ICASSP, BARCELONA, SPAIN, PP. 8683-8687, 2020

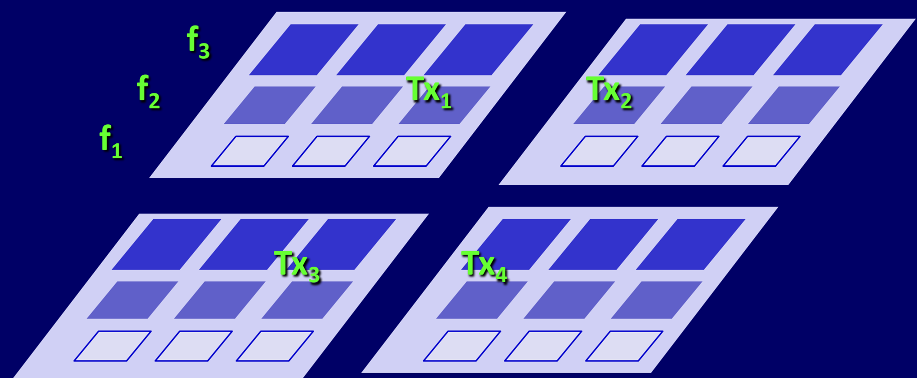
- By properly feeding antenna elements, antenna array can be dynamically switched among different modes
- Increased throughput and multi-user capacity
- Maximum communication range
- Also apply ML algorithms for intelligent beamforming



MULTI-BAND ULTRA MASSIVE MIMO

S. NIE AND I. F. AKYILDIZ,
"BEAMFORMING IN INTELLIGENT ENVIRONMENTS BASED ON UM MIMO PLATFORMS IN MM WAVE & THZ BANDS,"
IEEE ICASSP, BARCELONA, SPAIN, PP. 8683-8687, 2020

Allows simultaneous transmission over multiple transmission windows by electronically tuning the response of fixed-length plasmonic antennas

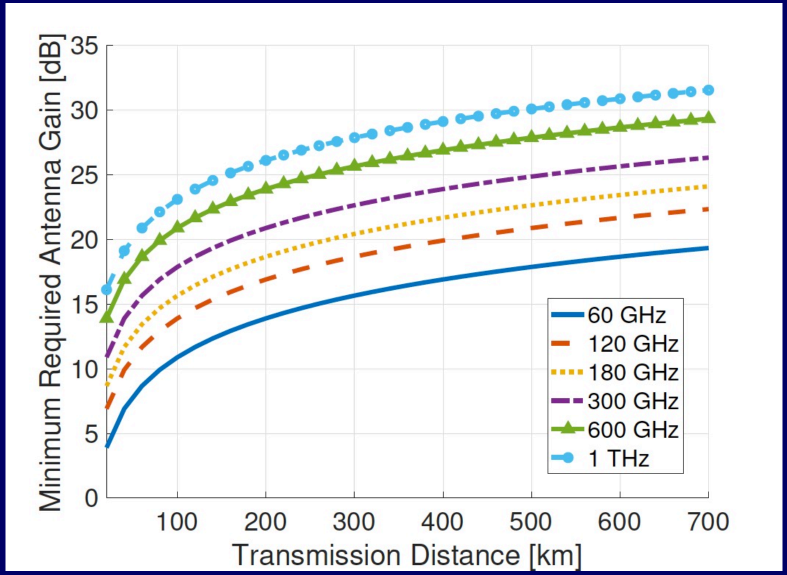


LINK BUDGET ANALYSIS – ISL

Altitude Options of CubeSats:
500, 700, and 900 km in the exosphere

Parameter	Value
Transmitted Power	10 W
min. Bandwidth	10 MHz
Temperature	1500 Kelvin (to capture the temp variability)
Transmission Distance	10 km min. 700 km max.

Thermal Noise Power: $P_n = k\,T\,B$
k – Boltzmann constant
T – Ambient temperature
B – Bandwidth



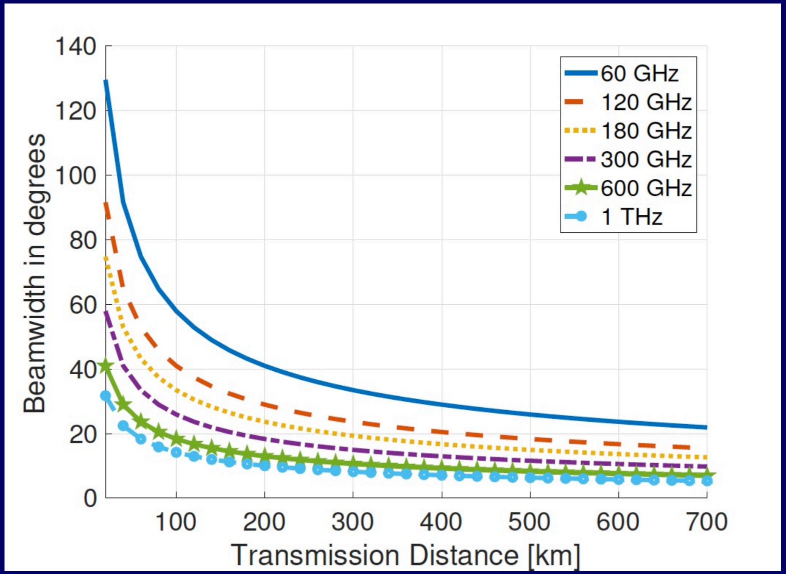
Min. required gain in ISLs at the Rx in order to maintain a 10 dB SNR

No molecular absorption!!

LINK BUDGET ANALYSIS – ISL

Parameter	Value
Transmitted Power	10 W
Bandwidth	10 MHz
Temperature	1500 Kelvin
Transmission Distance	10 km min. 700 km max.

$$G = P_t - P_r - FSPL$$
$$P_r = P_n + SNR$$
$$Beamwidth = \sqrt{\frac{4\pi}{G}}$$



Max. antenna beamwidth required at Rx in ISLs to maintain a 10 dB SNR

LESSONS LEARNED

- Higher gains are needed when increasing the transmission frequency, even in the absence of atmospheric losses.
- For the 500 MHz BW, since the channel is symmetrical, the gain at each tx end is always under 50 dB, which can be achievable with the antenna technologies
- Increasing the channel BW by an order of magnitude would increase the required gain by 10 dB.
- Distance between CubeSats not only influences the coverage of the Earth's surface, but also affects the achievable data rates.

GROUND-SATELLITE LINKS (GSL)

C-band (3.4–6.4 GHz)
X-band (8–9 GHz)
Ku-band (12–18 GHz)
Ka-band (23–27 GHz)
Mm-wave (30 – 300 GHz)
THz frequency band (0.3 – 1 THz)

- Hybrid frequency bands from microwave to mm-wave
- Propagation distance: 500 km minimum

- Atmospheric attenuation and molecular absorption need to be counted → highly directional high-gain antennas

- Modulation and Coding schemes based on service type
  - To ground stations can use mm-wave with simpler MCS since BW is large
  - To ground sensors can use lower frequency bands with more complicated MCS

LINK BUDGET ANALYSIS – GSL

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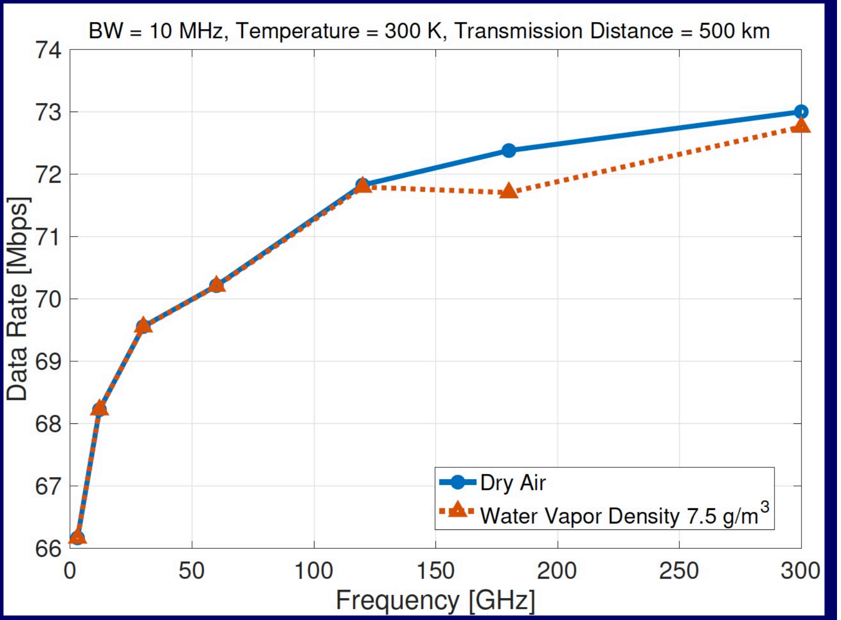
- Tx distance to CubeSats in orbit at 500 km
- Atmospheric attenuation and water molecular absorption need to be considered
  - Stronger attenuation with increased frequency
- Data rates increase as frequency increases
  - Higher SNR with higher antenna gains at mm-wave
- Data rate is expressed as

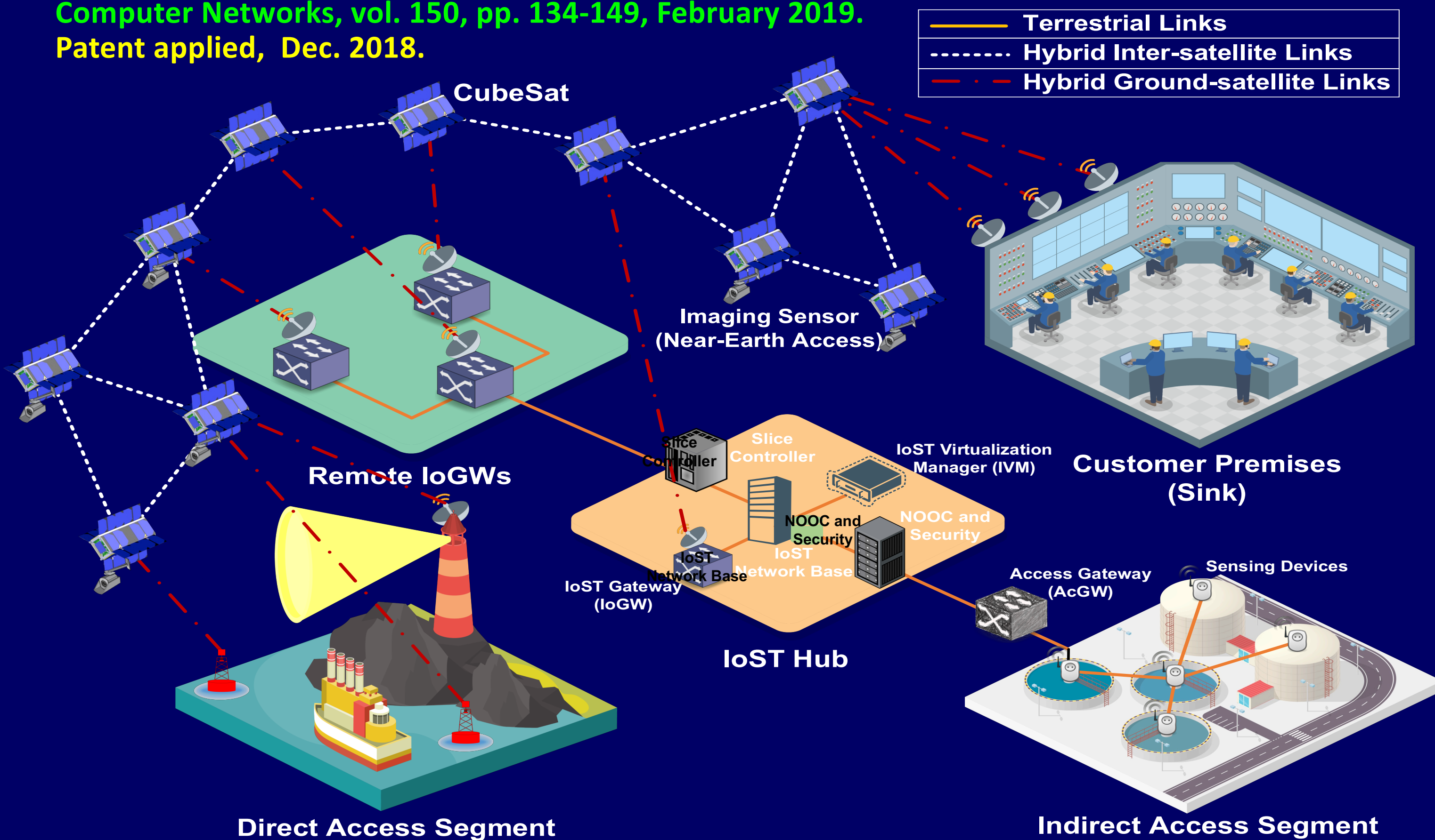
$$B\log_2(1+SNR) = \log_2(1+\frac{P_r}{P_n})$$



Achievable data rates at different frequencies in dry air and with water vapor

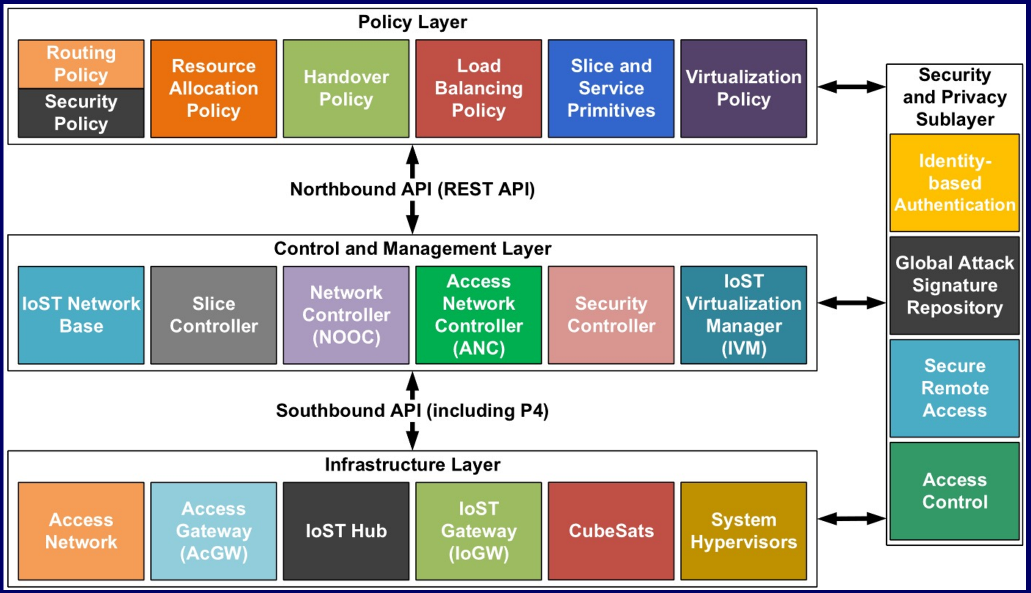
SDN AND NFV-BASED SYSTEM ARCHITECTURE

I. F. Akyildiz and A. Kak,
"The Internet of Space Things/CubeSats: A ubiquitous cyber-physical system for the connected world",
Computer Networks, vol. 150, pp. 134-149, February 2019.
Patent applied, Dec. 2018.



SDN AND NFV-BASED SYSTEM ARCHITECTURE: LAYERED APPROACH

- Infrastructure Layer
- Management and Control Layer
- Policy and Orchestration Layer
- Security and Privacy Sublayer

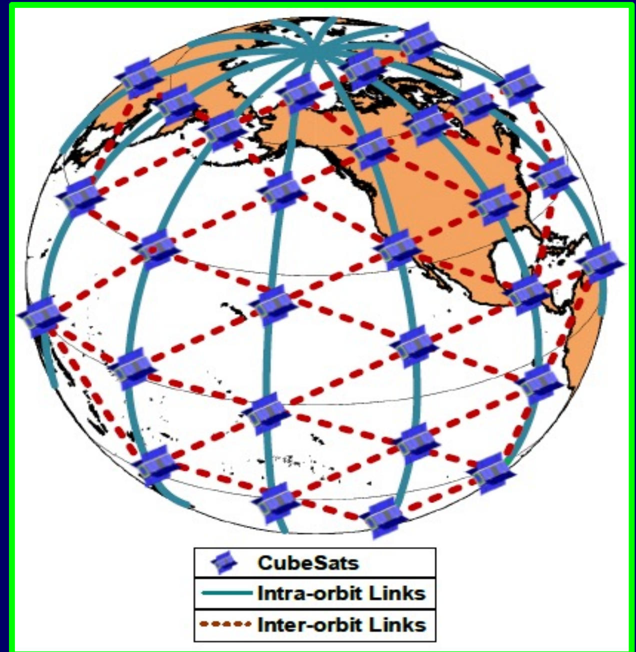


DESIGNING LARGE-SCALE CONSTELLATIONS FOR CUBESATS

A. Kak and I. F. Akyildiz
"Designing Large-scale Constellations for the Internet of Space Things",
IEEE Internet of Things Journal, 2020.

PATENT APLIED, SUMMER 2020.

- Based on the design of uniform constellations with circular orbits, i.e., Walker constellations.
- Consists of four modules:
  - Orbit Propagation Subsystem
  - Coverage Estimation Subsystem
  - Connectivity Estimation Subsystem
  - Design Optimization Framework



CONCLUSION

- IoST expands traditional IoT through
  - Always-available satellite backhaul
  - Real-time information sensing
  - Holistic integration of on-ground data and aerial information

- IoST is enabled by
  - Next generation CubeSat design
    - Multi-frequency front-ends
    - Multi-frequency antenna systems
  - Novel network orchestration and control architecture
    - SDN/NFV-based approach
  - Artificial intelligence for smart resource allocation strategies
    - Deep neural networks