Orbital Edge Computing: Nanosatellite Constellations as a New Class of Computer System

By Bradley Denby & Brandon Lucia

presented by, Kirtan Shetty

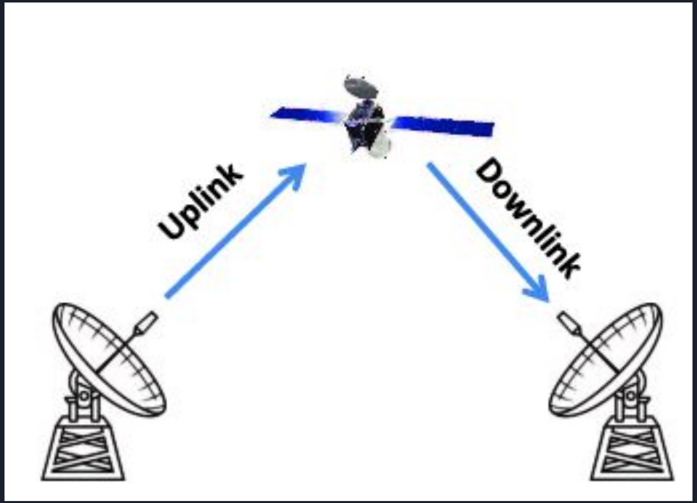
Content (27 slides)

Introduction: Contributions

- Demonstrate the limitations of bent pipes using a novel, physics-based simulator.
- Characterize the physical design space of an OEC device
- Propose and evaluate computational nanosatellite pipelines.
- Present a runtime service deployed to each nanosatellite and ground station.

Introduction: Bent pipe communication

Image source: google.com



Introduction: Resurgence in the space industry

1. Standardization of nanosatellite form factors.
2. Declining cost of access to space.
3. A massive constellations of low Earth orbit (LEO) nanosatellites.

Introduction: Nanosatellites

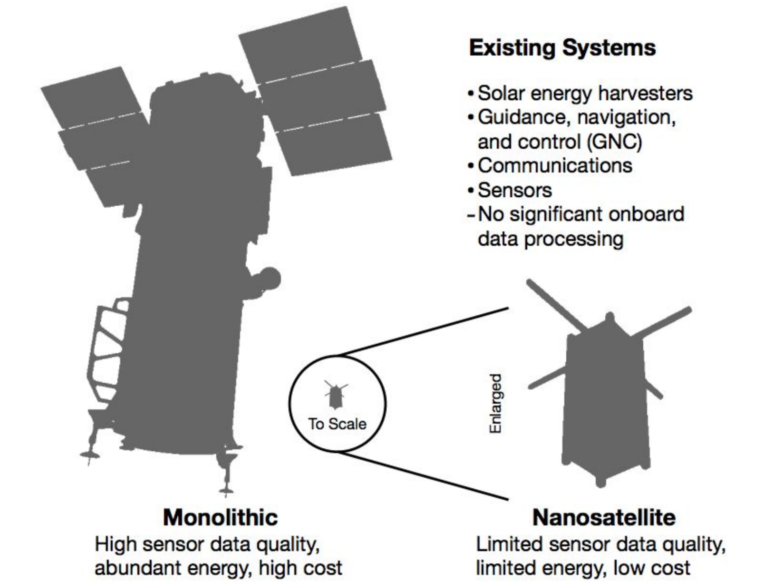


Figure 1. A comparison between a monolithic satellite and a nanosatellite. We propose augmenting existing systems by incorporating onboard visual processing components.

Introduction: Nanosatellites

1U CubeSat is 10 cm × 10 cm × 11.35 cm. (1.33 kg per 1U)

2U CubeSat is 10 cm × 10 cm × 22.70 cm.

6U CubeSat is 20 cm × 10 cm × 34.05 cm.

12U CubeSat is 20 cm × 20 cm × 34.05 cm.

Introduction: Nanosatellites Challenges

1. Data Quality is Physically Constrained.
    a. High Ground sample distance (GSD) upto 3m per pixel.
    b. Sensor size (4096 × 3072 pixel), Orbit altitude (325 km and 825 km LEO), Focal length.
    c. Energy generation and consumption.
2. Data Rate Depends on Orbit Parameters.
    a. Optimal Ground track frame rate (GTFR inverse of GTFP).
3. Bitrate Bottlenecks Constraints Constellations.
    a. Low bandwidth in Bent Pipeline.
    b. High reconfiguration time.
    c. Many ground stations.

Introduction: Nanosatellites Challenges

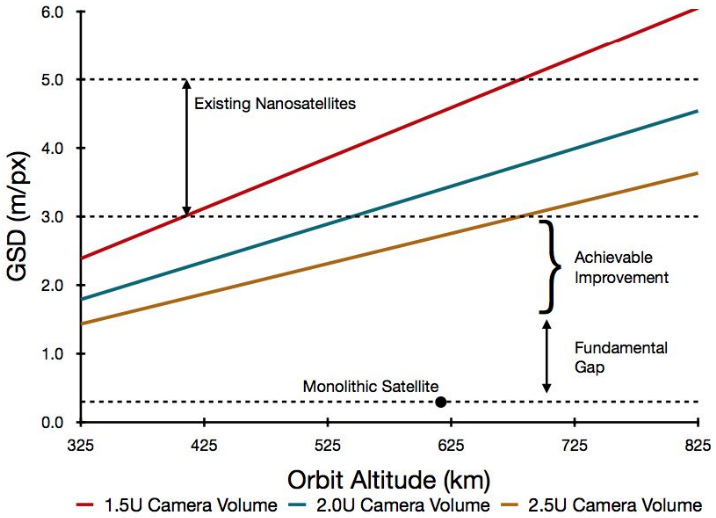


Figure 2. A 3U cubesat camera design space, assuming the smallest commercially available pixel sensor size (1.1 um)

Introduction: Nanosatellites Challenges

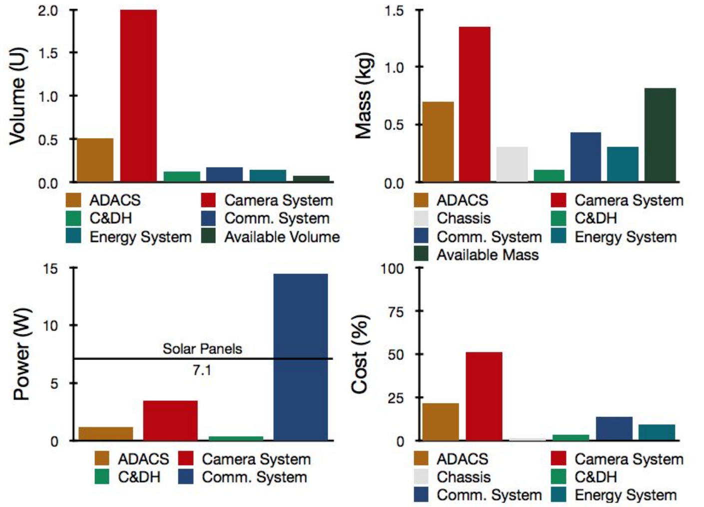


Figure 3. The volume, mass, power, and cost of an Earth-observing, 3U cubesat. These nanosatellites are constrained in volume and power, but not in mass or cost.

OEC - Orbital Edge Computing

1. Computational Nanosatellites.
    a. Jetson TX2 industrial module.
    b. Chassis-mounted solar cell.
    c. Supercapacitors.
    d. Local Image Processing.
2. Computational Nanosatellite Pipeline.
    a. Distributed frame and tile processing is among satellites.
    b. Formation Flying.
    c. Propulsion systems.
    d. Parallel processing.

OEC - Computational Nanosatellite Pipeline.

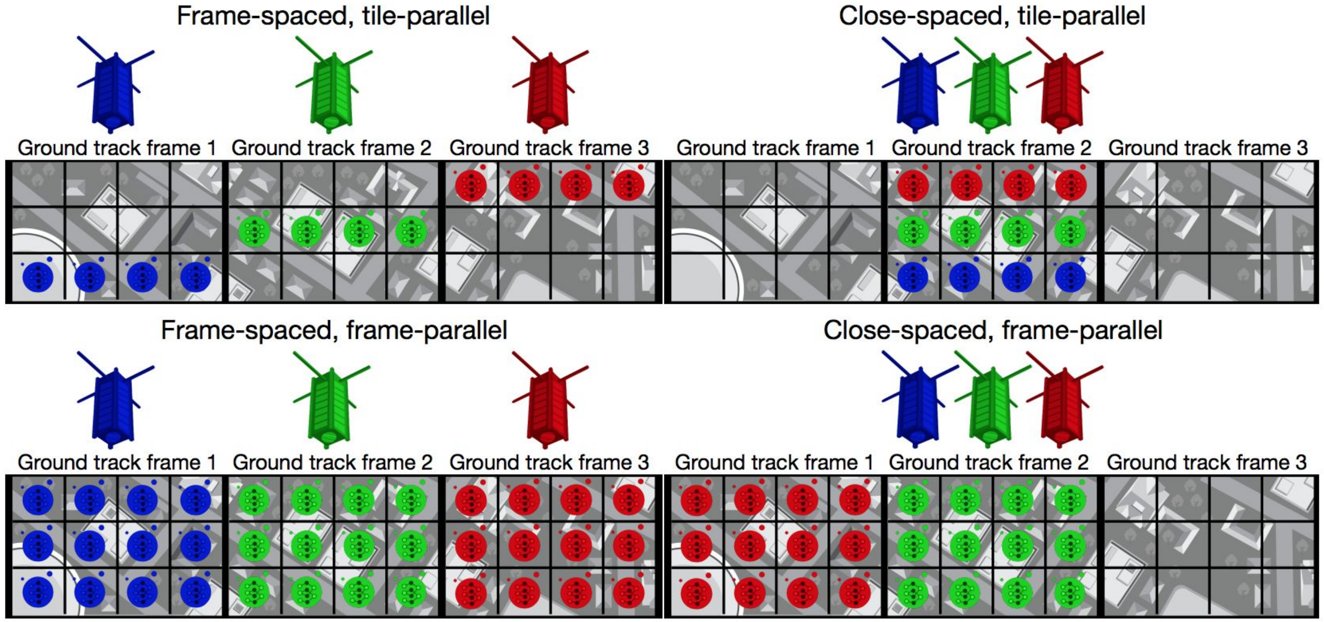


Figure 5. Four modes of operation for computational nanosatellite pipelines. Each of the four graphics depicts a snapshot in time. In the next time step, each satellite will have progressed one ground track frame to the right.

OEC - Computational Nanosatellite Pipeline.

1. Pipeline depth increases the aggregate parallel work performed and the aggregate energy collected.
2. Pipeline depth does not affect total data per revolution.
3. If Aggregate energy harvested == Aggregate energy required to process all data, full coverage is achieved.
4. Pipeline may still fall short of full coverage due to processing latency.

cote - A Model for Design and Control

cote-sim - Pre-mission simulation.

1. Provides offline simulation of OEC systems
2. Helps in mission design, planning, and analysis
3. Supports modeling.
4. Supports interactions between energy-constrained, intermittent computing, CNP configurations, data collection at the GTFR, and communication.

cote-lib - Online, autonomous control.

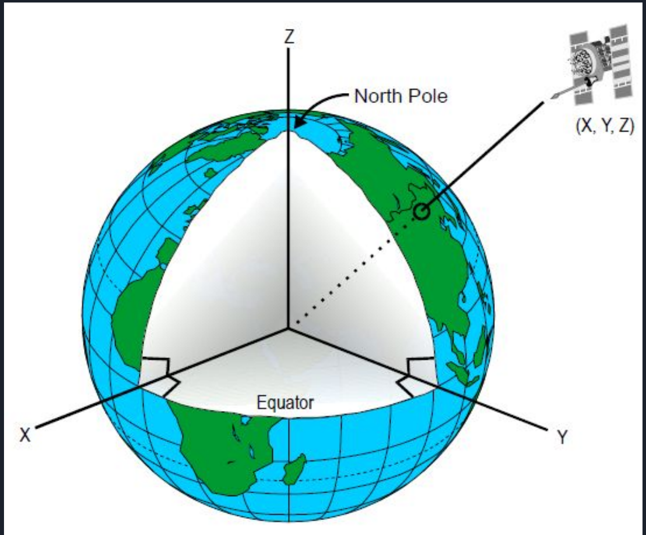
1. Continuously runs on each device in an OEC system.
2. Supports Interaction between astrodynamics and intermittent computing to autonomously decide where to compute.

cote - Time

1. UT1 measures the rotation of Earth relative to distant astronomical objects.
2. UTC is a civil time system.
3. The precise value of (UT1−UTC) and the approximate difference (DUT1) are published by the International Earth Rotation and Reference Systems Service (IERS) in Bulletins A and D, respectively.
4. If (UT1−UTC) > 0.9 s, it announces a leap second via Bulletin C.

cote - Frame

1. Earth-centered, inertial (ECI) frame.
2. Latitude, Longitude, and Height above the ellipsoid (LLH) frame.
3. South, East, Z (SEZ) frame.



cote - Orbital Mechanics

The state of a satellite relative to a rotating Earth is simulated using SGP4.

The Simplified General Perturbations (SGP4) propagator is used with two-line mean element (TLE) sets. It considers secular and periodic variations due to Earth oblateness, solar and lunar gravitational effects, gravitational resonance effects, and orbital decay using a drag model. *(source: https://help.agi.com/)*

cote - Communication

- C - Received signal power
- P - Transmit power
- Ll - The line loss factor
- Gt - The transmitter gain parallel to the separation vector
- Gr - The receiver gain parallel to the separation vector
- λ - The center frequency of the channel
- S - The magnitude of the separation vector

$$C = PL_l G_t G_r \left(\frac{\lambda}{4\pi S} \right)^2, \qquad (1)$$

cote - Communication

- R_{max} - Maximum bitrate
- B - the channel bandwidth
- C - the received signal power
- N - the received noise power
- k - the Boltzmann constant
- T - the system noise temperature

$$R_{\max} = B \log_2 (1 + C/N), \tag{2}$$

cote - Energy

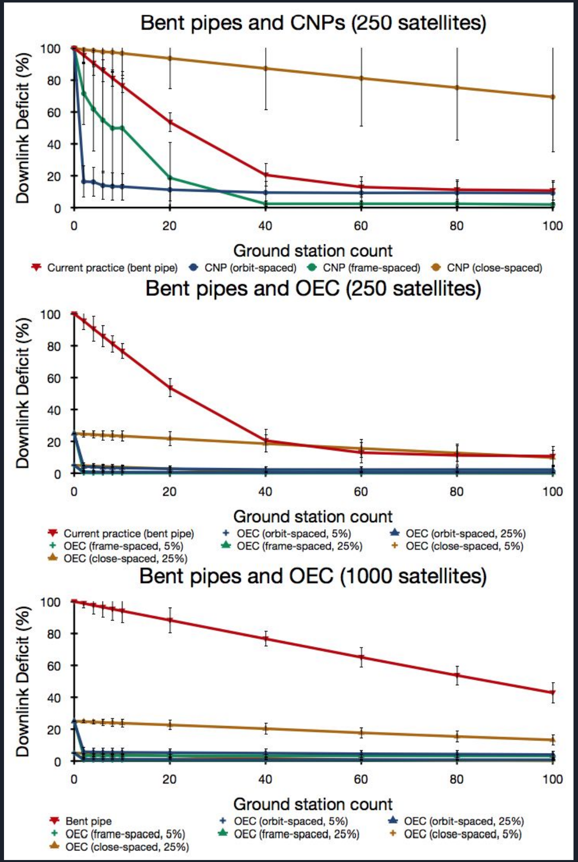
- v(t) - node voltage equation
- q(t) - charge held in the capacitor bank at time t
- C - total capacitance of the capacitor bank
- Is - instantaneous current provided by the solar panel
- Resr - equivalent series resistance of the capacitor bank
- Pmode - instantaneous power draw of all energy-consuming devices

$$v(t) = \frac{\frac{q(t)}{C} + I_S R_{ESR} + \sqrt{(\frac{q(t)}{C} + I_S R_{ESR})^2 - 4P_{MODE}R_{ESR}}}{2}. \quad (3)$$

Methodology

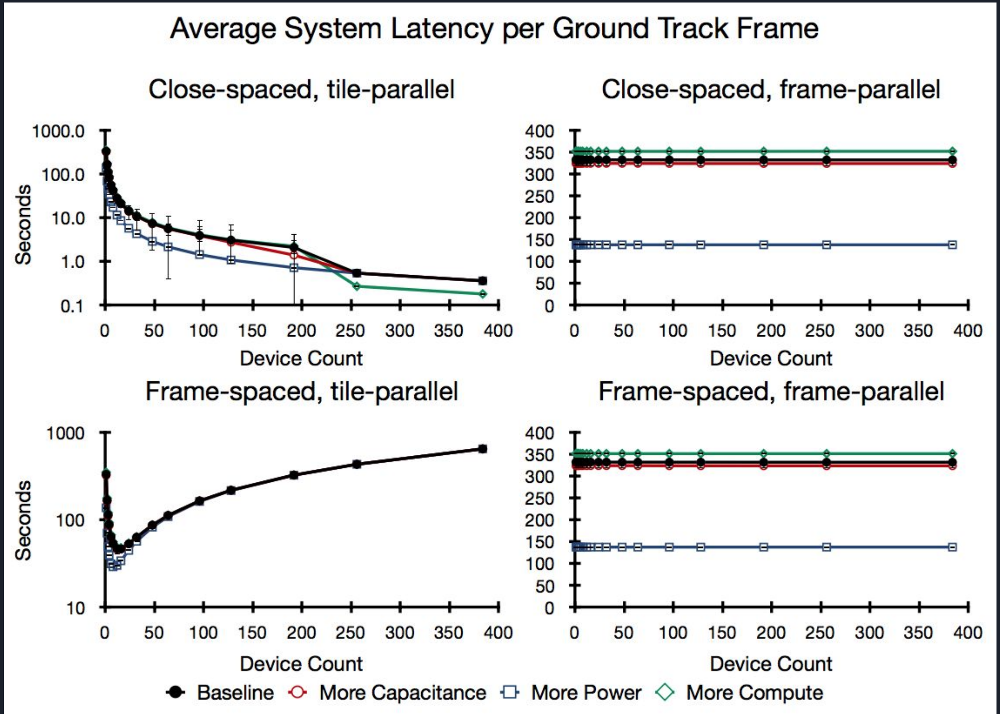
- Jetson TX2 module (256-core NVIDIA Pascal™ GPU architecture with 256 NVIDIA CUDA cores, Dual-Core NVIDIA Denver 2 64-Bit CPU, 8GB 128-bit LPDDR4 Memory, 32GB eMMC 5.1, 7.5W / 15W)
- Building footprint detection for the remote sensing application.
- Train DetectNet CNN on satellite images and ground-truth labels from the SpaceNet dataset.
- Measure power with multimeters.
- Polar ground segment consisting of two rings of ground stations, one at 87°N and one at 87°S.
- Frequency 8.15 GHz with a bandwidth of 20.0 MHz.
- Nanosatellite patch antennas with a peak gain of 6.0 dB
- Ground station receiving dishes with a peak gain of 44.1 dB

Evaluation



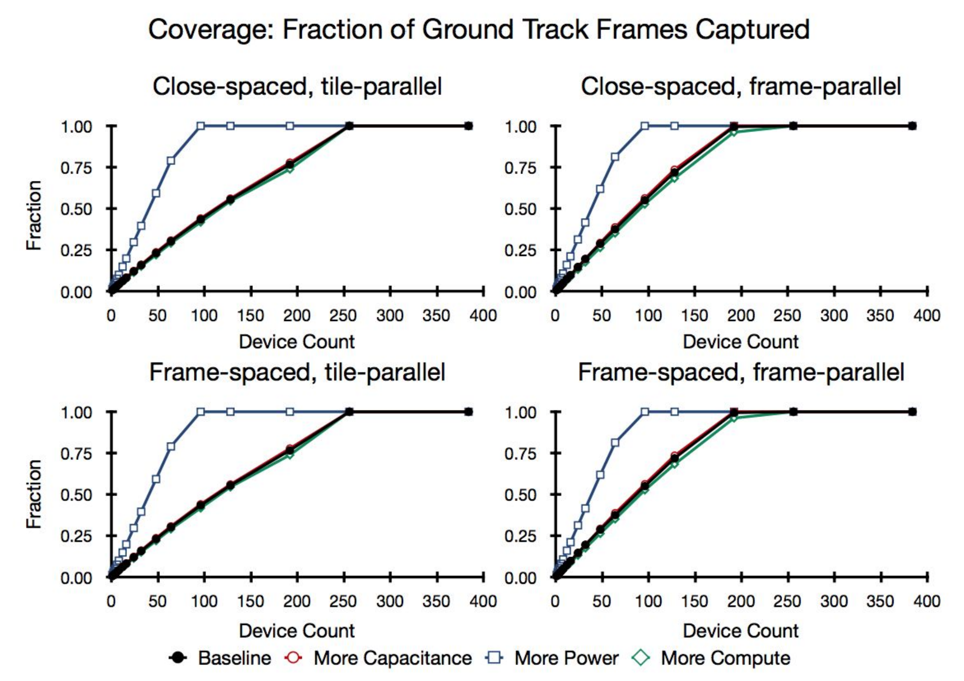
Bent pipes and CNPs (250 satellites)
Downlink Deficit (%)
Ground station count
Current practice (bent pipe)
CNP (orbit-spaced)
CNP (frame-spaced)
CNP (close-spaced)
Bent pipes and OEC (250 satellites)
Downlink Deficit (%)
Ground station count
Current practice (bent pipe)
OEC (orbit-spaced, 5%)
OEC (orbit-spaced, 25%)
OEC (frame-spaced, 5%)
OEC (frame-spaced, 25%)
OEC (close-spaced, 5%)
OEC (close-spaced, 25%)
Bent pipes and OEC (1000 satellites)
Downlink Deficit (%)
Ground station count
Bent pipe
OEC (orbit-spaced, 5%)
OEC (orbit-spaced, 25%)
OEC (frame-spaced, 5%)
OEC (frame-spaced, 25%)
OEC (close-spaced, 5%)
OEC (close-spaced, 25%)

Evaluation

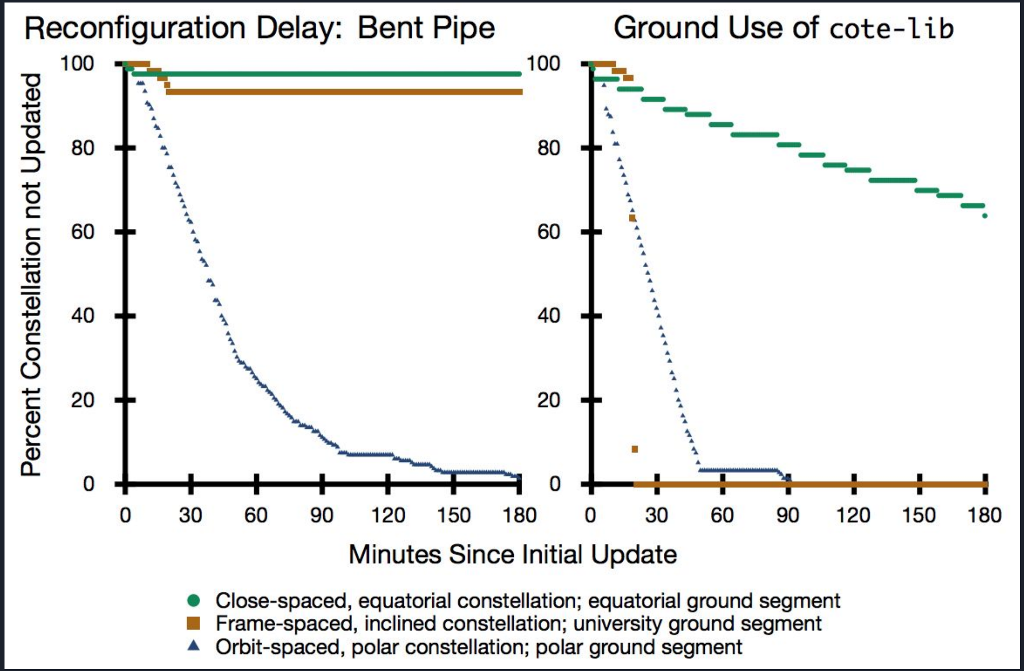


Average System Latency per Ground Track Frame
Close-spaced, tile-parallel
Close-spaced, frame-parallel
Frame-spaced, tile-parallel
Frame-spaced, frame-parallel
Seconds
1000.0
100.0
10.0
1.0
0.1
1000
100
10
400
350
300
250
200
150
100
50
0
0 50 100 150 200 250 300 350 400
Device Count
Baseline
More Capacitance
More Power
More Compute

Evaluation


Coverage: Fraction of Ground Track Frames Captured
Close-spaced, tile-parallel
Close-spaced, frame-parallel
Frame-spaced, tile-parallel
Frame-spaced, frame-parallel
Fraction
1.00
0.75
0.50
0.25
0.00
0
50
100
150
200
250
300
350
400
Device Count
Baseline
More Capacitance
More Power
More Compute

Evaluation


Reconfiguration Delay: Bent Pipe
Ground Use of cote-lib
Percent Constellation not Updated
100
80
60
40
20
0
0 30 60 90 120 150 180
Minutes Since Initial Update
Close-spaced, equatorial constellation; equatorial ground segment
Frame-spaced, inclined constellation; university ground segment
Orbit-spaced, polar constellation; polar ground segment

Conclusion & Future Work

- Orbital edge computing provides responsiveness, reliability, and scalability benefits.
- Applications of this emerging technology are impeded by existing, bent-pipe architectures.
- Future work should study energy collection and storage for orbital edge computing
- Future work may investigate heterogeneous systems and heterogeneous workloads.
- OEC for Chip-scale or gramscale satellites (“chipsats”).

Thank you.