Emulating Space Computing Networks with RHONE

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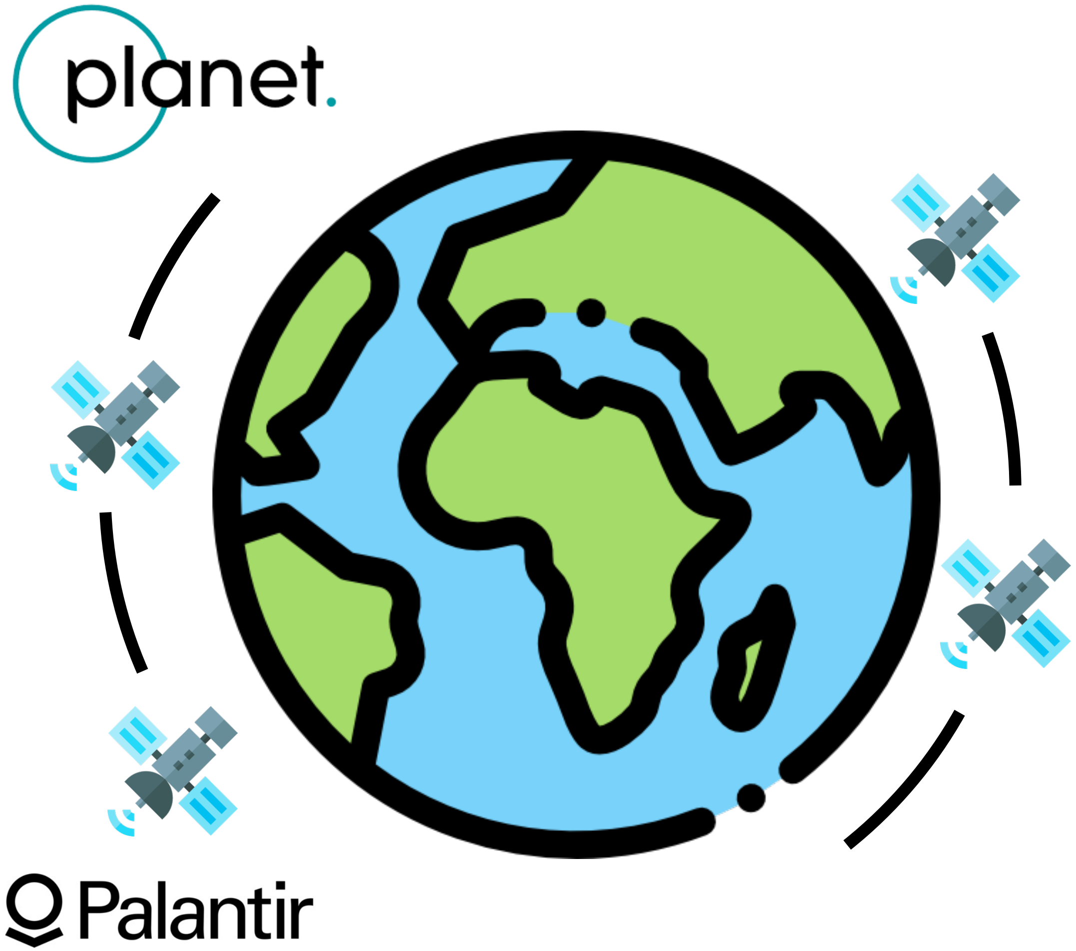
Donghao Zhang, Shangguang Wang, Xuanzhe Liu, Chenren Xu

北京大學 PEKING UNIVERSITY
北京郵電大學 BEIJING UNIVERSITY OF POSTS AND TELECOMMUNICATIONS

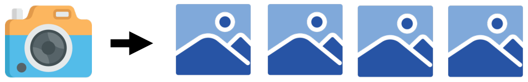
From Satellites to Space Computing Networks (SCNs)

From Satellites to Space Computing Networks

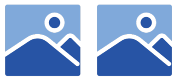


From Satellites to Space Computing Networks

- **Earth Observation**
  - Capture



  - Filter / Compress



  - Transmit

planet.

Palantir

From Satellites to Space Computing Networks

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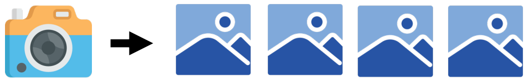

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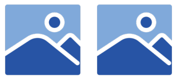

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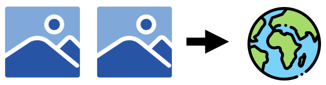

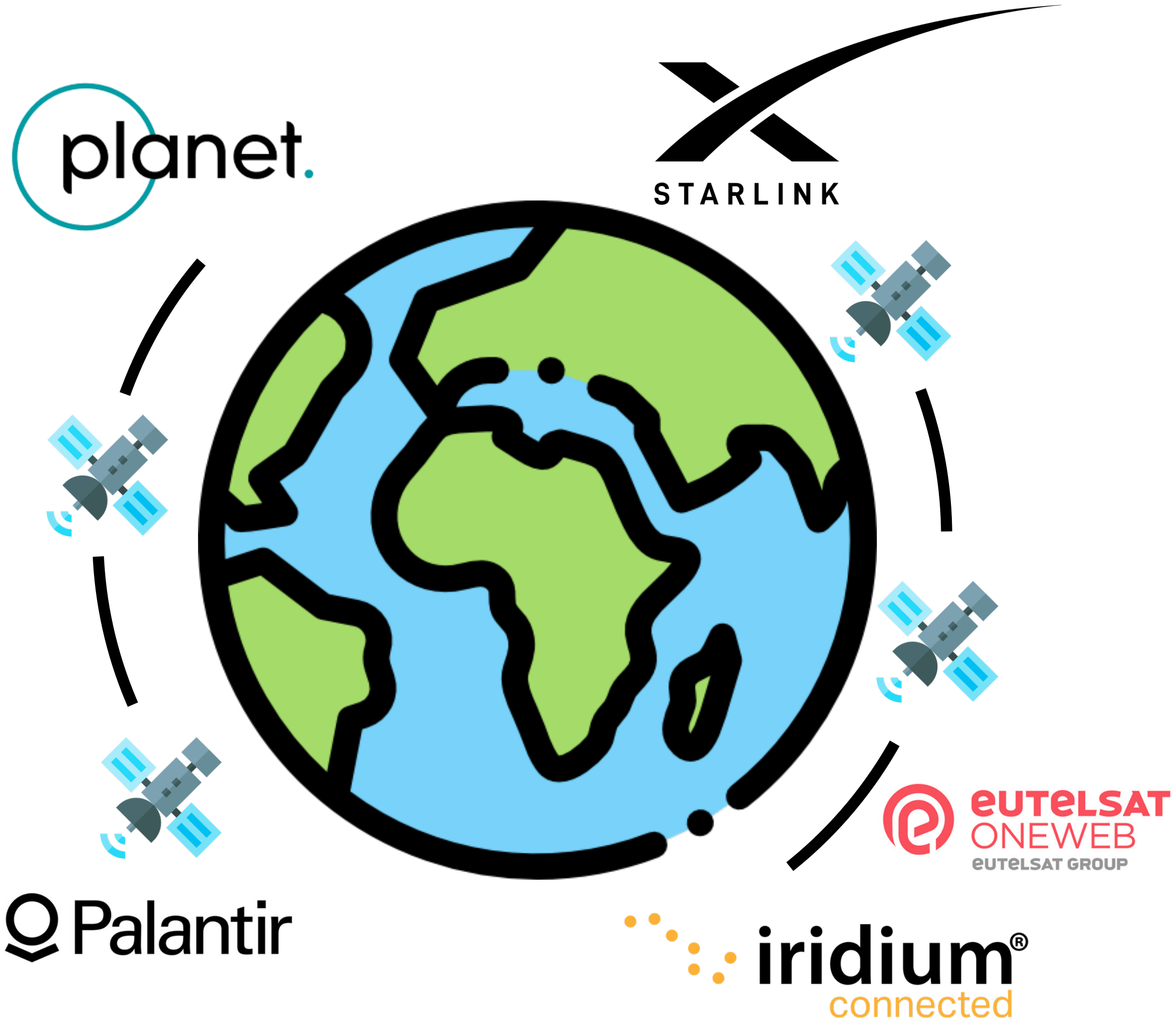

From Satellites to Space Computing Networks

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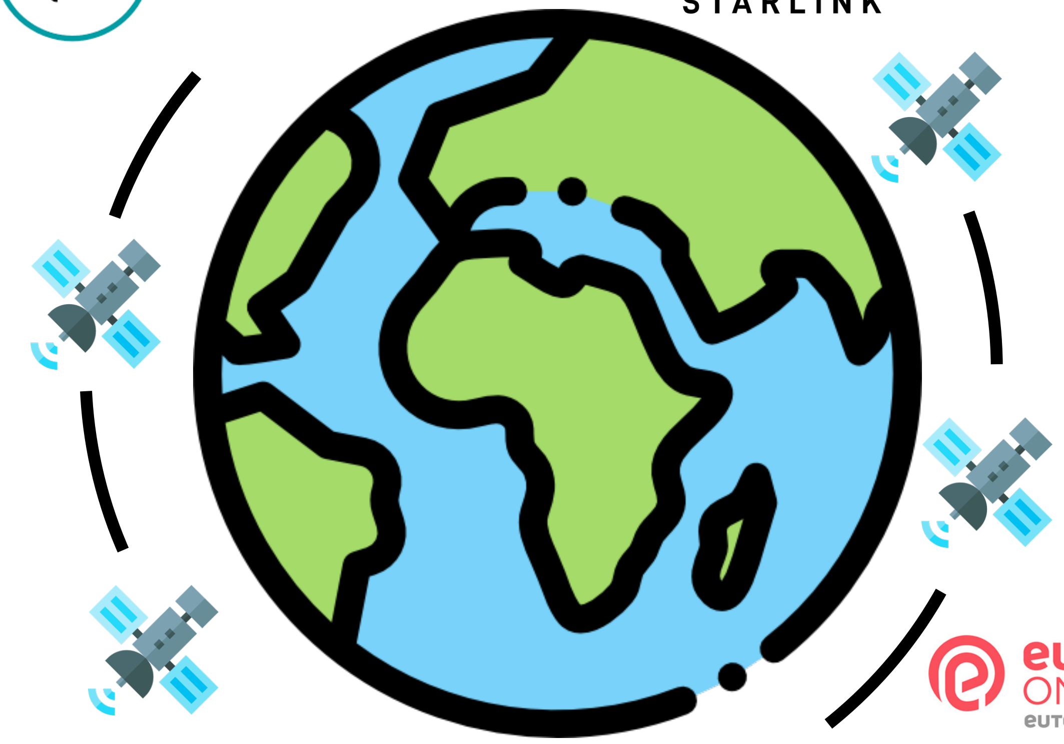

- **Global Networking**
  - Applications
  - Topology & Routing
  - Security

From Satellites to Space Computing Networks

- Earth Observation
  - Capture
  - Filter / Compress
  - Transmit

- Global Networking
  - Applications
  - Topology & Routing
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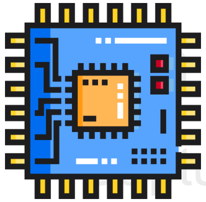
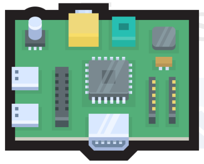
Space Computing Networks: Technological Trends

- **COTS chips in Space**



EnduroSat OBC
- $10, 000
- CPU 216MHz
- 64MB RAM
- 256MB Flash

↓



Commercial-off-the-shelf (COTS) chip
(e.g., Raspberry Pi 4B on BUPT-1 satellite)
- $40-100
- CPU 1.4GHz
- 1GB RAM
- microSD cards

- **Constellation Networking**

STARLINK

planet.

iridium® connected

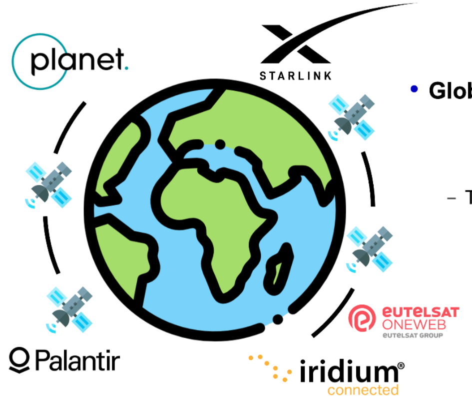
Palantir

eutelsat ONEWEB eutelsat GROUP

Designing SCN Applications

YES,

- **Earth Observation**
  - Capture
  - Filter / Compress
  - Transmit



- **Global Networking**
  - Applications
    NETFLIX
  - Topology & Routing
  - Security

- **COTS chips in Space**

EnduroSat OBC
- Radiation-hardened
- $10, 000
- CPU 216MHz
- 64MB RAM
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Commercial-off-the-shelf (COTS) chip
(e.g., Raspberry Pi 4B on BUPT-1 satellite)
- Non-radiation-hardened
- $40-100
- CPU 1.4GHz
- 1GB RAM
- microSD cards

- **Constellation Networking**

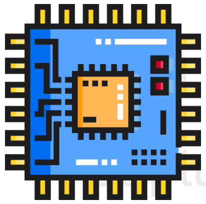
STARLINK planet. iridium connected Palantir eutelsat ONEWEB eutelsat group

BUT

- I want to design, build and evaluate new applications 🙂
- Not so easy 🤔

Designing SCN Applications

- **COTS chips in Space**



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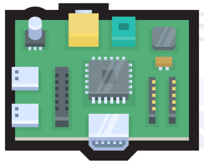
- $10, 000 ❌
- CPU 216MHz ❌
- 64MB RAM ❌
- 256MB Flash ❌

↓



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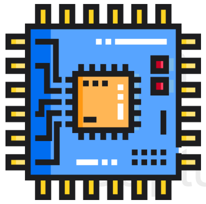
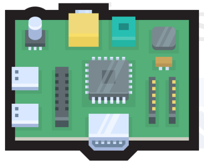
Designing SCN Applications

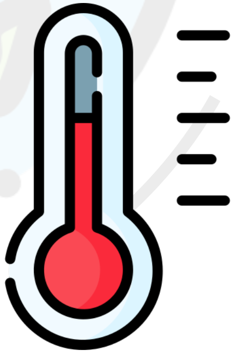
- **COTS chips in Space**



EnduroSat OBC
- Low power ✅
- Carefully designed thermal management ✅

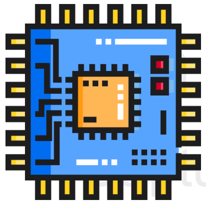


Commercial-off-the-shelf (COTS) chip
(e.g., Raspberry Pi 4B on BUPT-1 satellite)
- High power ❌
- Easily gets overheated ❌
- Performance degradation under overheat ❌



Designing SCN Applications

- **COTS chips in Space**



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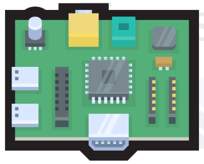

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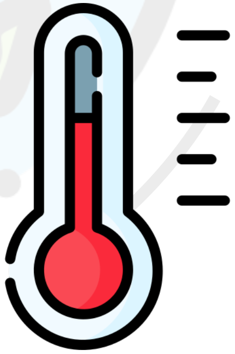
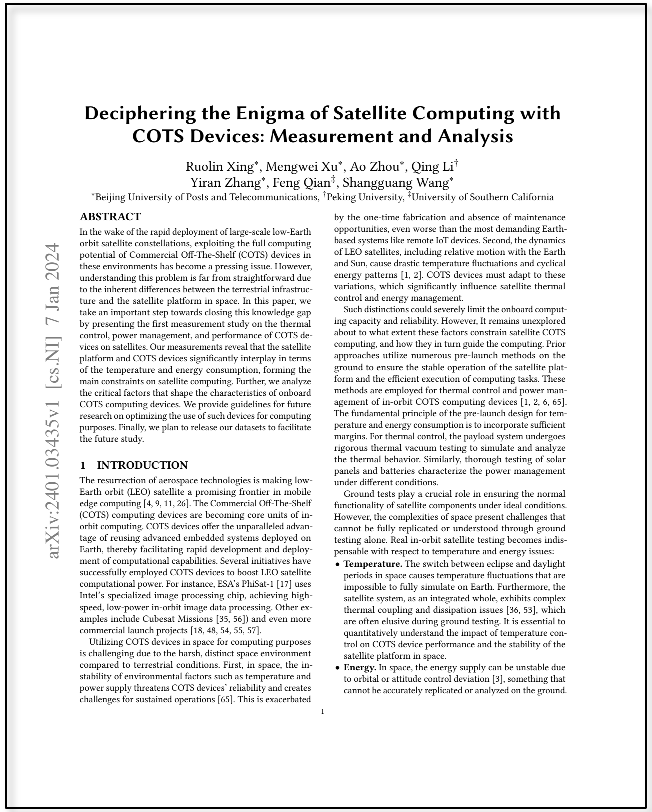




arXiv:2401.03435v1 [cs.NI] 7 Jan 2024

Deciphering the Enigma of Satellite Computing with COTS Devices: Measurement and Analysis

Ruolin Xing*, Mengwei Xu*, Ao Zhou*, Qing Li†
Yiran Zhang*, Feng Qian‡, Shangguang Wang*
*Beijing University of Posts and Telecommunications, †Peking University, ‡University of Southern California

ABSTRACT

In the wake of the rapid deployment of large-scale low-Earth orbit satellite constellations, exploiting the full computing potential of Commercial Off-The-Shelf (COTS) devices in these environments has become a pressing issue. However, understanding this problem is far from straightforward due to the inherent differences between the terrestrial infrastructure and the satellite platform in space. In this paper, we take an important step towards closing this knowledge gap by presenting the first measurement study on the thermal control, power management, and performance of COTS devices on satellites. Our measurements reveal that the satellite platform and COTS devices significantly interplay in terms of the temperature and energy consumption, forming the main constraints on satellite computing. Further, we analyze the critical factors that shape the characteristics of onboard COTS computing devices. We provide guidelines for future research on optimizing the use of such devices for computing purposes. Finally, we plan to release our datasets to facilitate the future study.

1 INTRODUCTION

The resurrection of aerospace technologies is making low-Earth orbit (LEO) satellite a promising frontier in mobile edge computing [4, 9, 11, 26]. The Commercial Off-The-Shelf (COTS) computing devices are becoming core units of in-orbit computing. COTS devices offer the unparalleled advantage of reusing advanced embedded systems deployed on Earth, thereby facilitating rapid development and deployment of computational capabilities. Several initiatives have successfully employed COTS devices to boost LEO satellite computational power. For instance, ESA's PhiSat-1 [17] uses Intel's specialized image processing chip, achieving high-speed, low-power in-orbit image data processing. Other examples include Cubesat Missions [35, 56]) and even more commercial launch projects [18, 48, 54, 55, 57].

Utilizing COTS devices in space for computing purposes is challenging due to the harsh, distinct space environment compared to terrestrial conditions. First, in space, the instability of environmental factors such as temperature and power supply threatens COTS devices' reliability and creates challenges for sustained operations [65]. This is exacerbated by the one-time fabrication and absence of maintenance opportunities, even worse than the most demanding Earth-based systems like remote IoT devices. Second, the dynamics of LEO satellites, including relative motion with the Earth and Sun, cause drastic temperature fluctuations and cyclical energy patterns [1, 2]. COTS devices must adapt to these variations, which significantly influence satellite thermal control and energy management.

Such distinctions could severely limit the onboard computing capacity and reliability. However, It remains unexplored about to what extent these factors constrain satellite COTS computing, and how they in turn guide the computing. Prior approaches utilize numerous pre-launch methods on the ground to ensure the stable operation of the satellite platform and the efficient execution of computing tasks. These methods are employed for thermal control and power management of in-orbit COTS computing devices [1, 2, 6, 65]. The fundamental principle of the pre-launch design for temperature and energy consumption is to incorporate sufficient margins. For thermal control, the payload system undergoes rigorous thermal vacuum testing to simulate and analyze the thermal behavior. Similarly, thorough testing of solar panels and batteries characterize the power management under different conditions.

Ground tests play a crucial role in ensuring the normal functionality of satellite components under ideal conditions. However, the complexities of space present challenges that cannot be fully replicated or understood through ground testing alone. Real in-orbit satellite testing becomes indispensable with respect to temperature and energy issues:

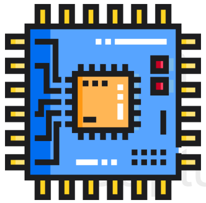
- **Temperature.** The switch between eclipse and daylight periods in space causes temperature fluctuations that are impossible to fully simulate on Earth. Furthermore, the satellite system, as an integrated whole, exhibits complex thermal coupling and dissipation issues [36, 53], which are often elusive during ground testing. It is essential to quantitatively understand the impact of temperature control on COTS device performance and the stability of the satellite platform in space.
- **Energy.** In space, the energy supply can be unstable due to orbital or attitude control deviation [3], something that cannot be accurately replicated or analyzed on the ground.

1

Check our MobiCom'24 paper for detailed measurement results on our **real in-orbit satellite**!

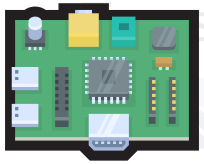
Designing SCN Applications

- **COTS chips in Space**



EnduroSat OBC
- Low power ✅
- Carefully designed thermal management ✅

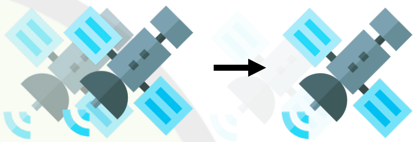
↓



Commercial-off-the-shelf (COTS) chip
(e.g., Raspberry Pi 4B on BUPT-1 satellite)
- High power ❌
- Easily gets overheated ❌
- Performance degradation under overheat ❌

- **Constellation Networking**

Extreme mobility
- 7.9km/s for LEO satellites

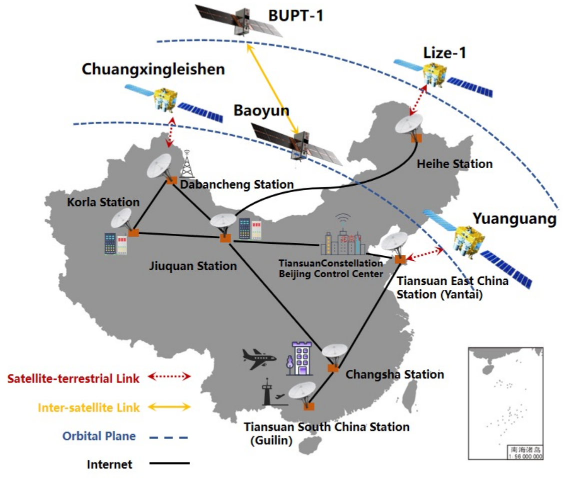


Frequent node failure

=> <u>Highly dynamic topology</u>

Designing SCN Applications

	Real satellites
Satellite-Level Fidelity	✅
Constellation-Level Fidelity	❌
Usability	



STARLINK

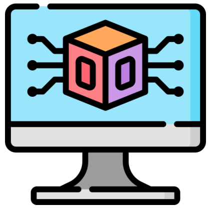
planet.

❌ I don't have a satellite!

…

❌ At least I don't have a constellation

Designing SCN Applications

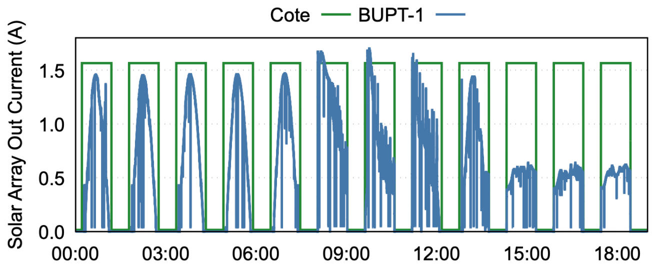



	Real satellites	Simulators
Satellite-Level Fidelity	✅	❌
Constellation-Level Fidelity	❌	❌
Usability		✅

CMUAbstract / **cote**

snkas / **hypatia**

❌ No software stack / network stack (Lai et al.)



😭 Inaccurate power modeling
😭 No temperature modeling

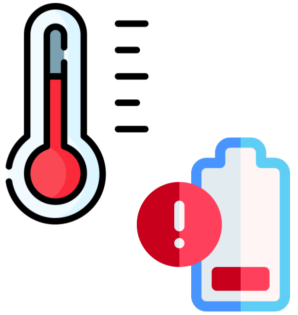
Designing SCN Applications

	Real satellites	Simulators	Emulators
Satellite-Level Fidelity	✅	❌	❌
Constellation-Level Fidelity	❌	❌	✅
Usability		✅	✅

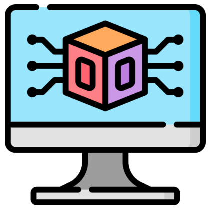
SpaceNetLab / StarryNet

··· / celestial

❌ Not enough consideration of operation environment

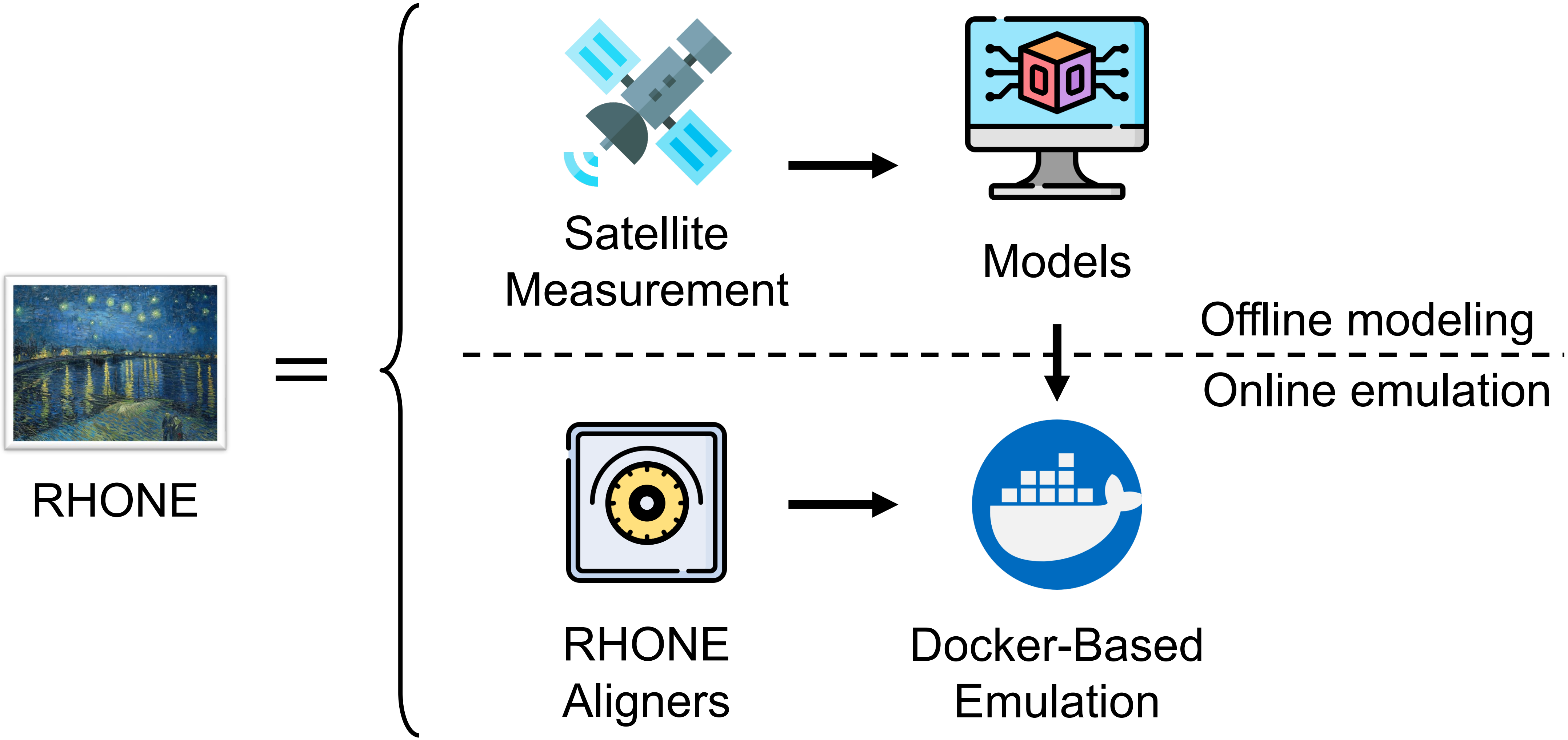


Designing SCN Applications

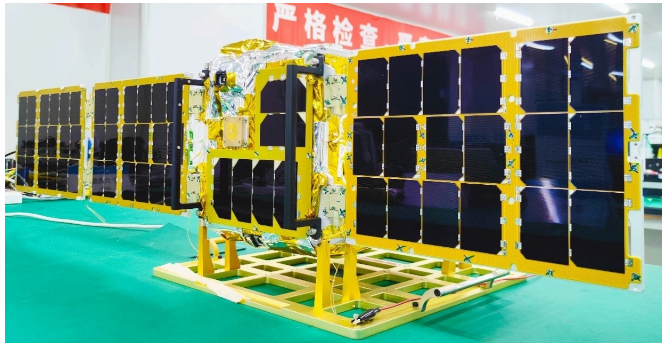

<table>
<tr><th></th><th>Real satellites</th><th>Simulators</th><th>Emulators</th><th>RHONE</th></tr>
<tr><td>Satellite-Level Fidelity</td><td>✅</td><td>❌</td><td>❌</td><td>✅</td></tr>
<tr><td>Constellation-Level Fidelity</td><td rowspan="2">❌</td><td>❌</td><td>✅</td><td>✅</td></tr>
<tr><td>Usability</td><td>✅</td><td>✅</td><td>✅</td></tr>
</table>

Our solution: RHONE



RHONE – Part I: Offline Modeling

- Modeling based on **real satellite measurement**

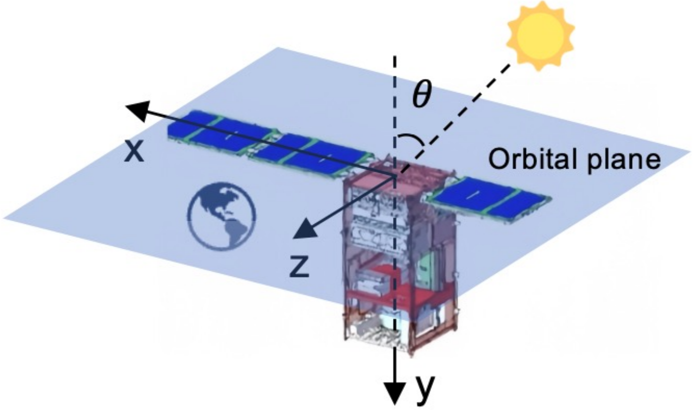


🛰 A real in-orbit satellite

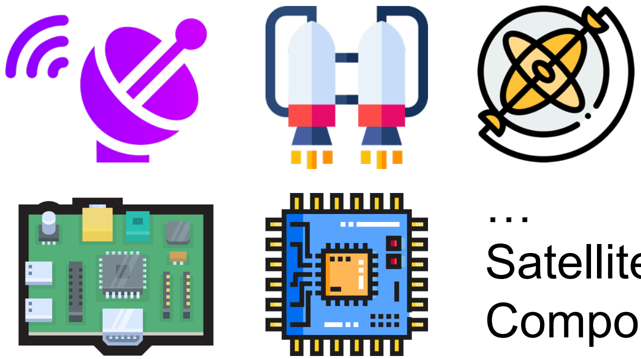
📝 800000 timestamped entries

📅 December 23, 2021 to July 14, 2022

1 Power modeling



Power harvesting



…
Satellite Components

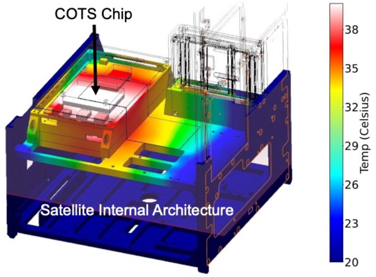
Power consuming

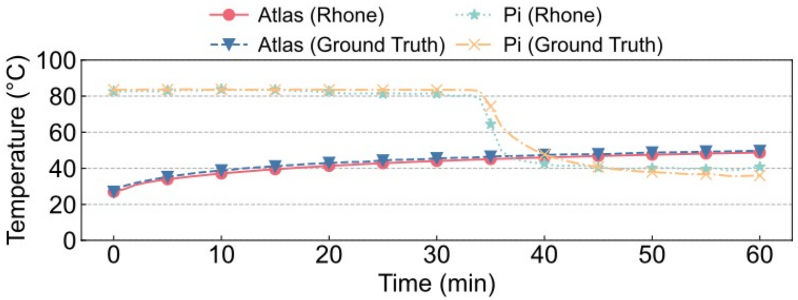
📊 Our data is available at https://github.com/TiansuanConstellation/ATC25-RHONE-Data

RHONE – Part I: Offline Modeling

- Modeling based on **real satellite measurement**

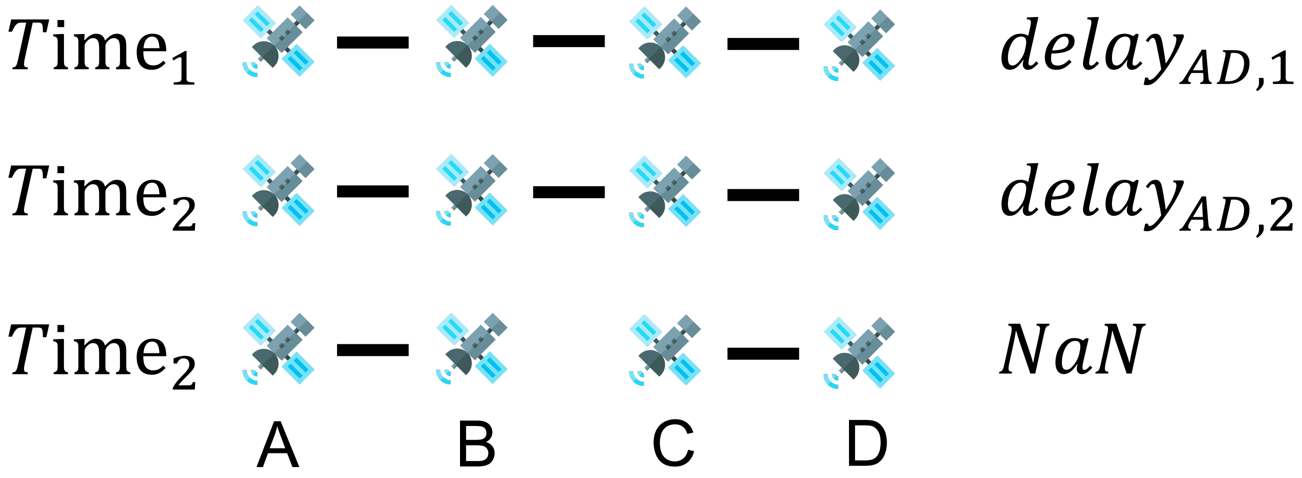
2 Thermal modeling





3 Orbit modeling

4 Network modeling

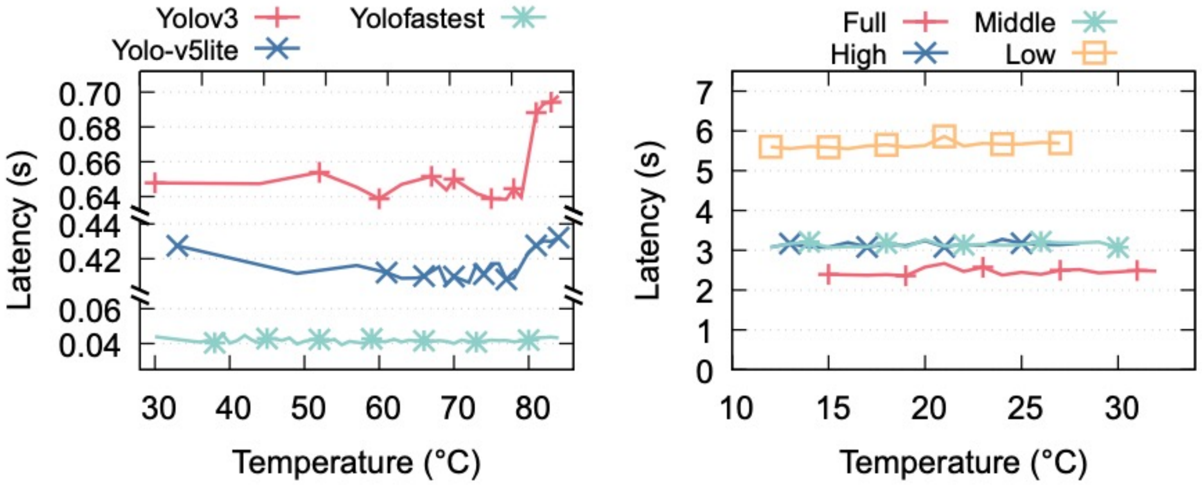


RHONE – Part I: Offline Modeling

- Modeling based on **real satellite measurement**

5 Computation modeling

- Actually it is really hard…



(a) Raspberry Pi (b) Atlas 200 DK

Varying temperature

Different chips → Performance

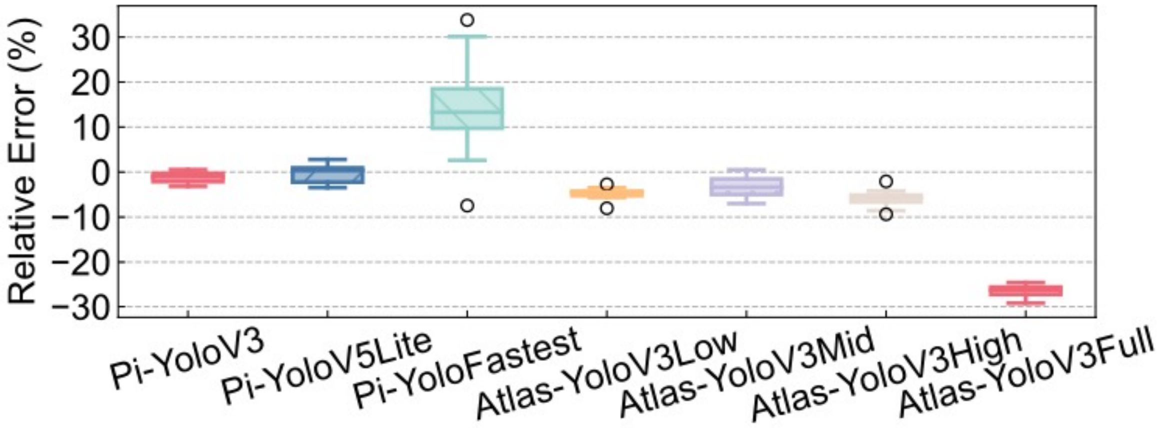
Different applications

RHONE – Part I: Offline Modeling

- Modeling based on **real satellite measurement**

5 Computation modeling

- There is a chance.



For most applications, the degradation due to overheating can be mimicked on the ground!

Remark

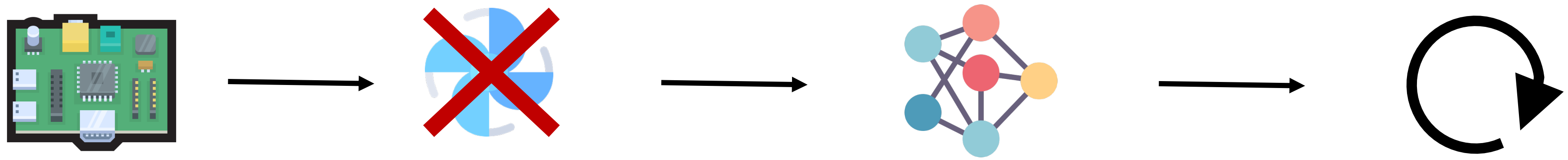
- We focus on short-duration tasks which are typical for satellite computing

RHONE – Part I: Offline Modeling

- Modeling based on **real satellite measurement**

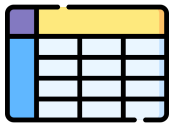
5 Computation modeling

- RHONE performs ground-based mirror-chip profiling



COTS chip → Fan removed → Application → Repeated execution

Results →



SatPerf Table

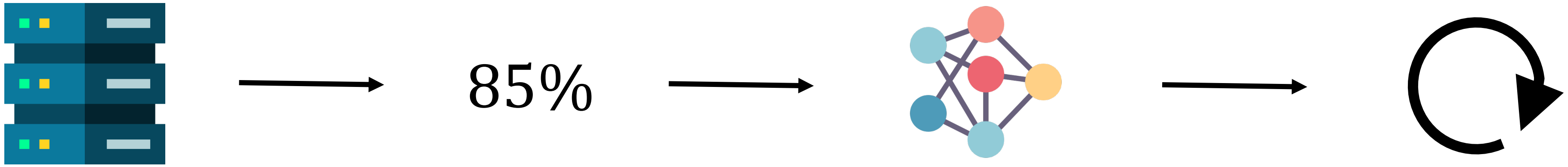
$Chip_A$	App_1	15 °C	3.0 s
		...	
		50 °C	4.6 s
...			

RHONE – Part I: Offline Modeling

- Modeling based on **real satellite measurement**

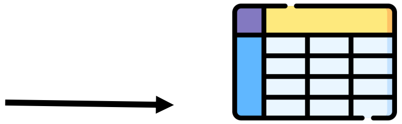
5 Computation modeling

- RHONE also profiles the emulation physical machine



Physical node Resource limit Application Repeated execution

Results

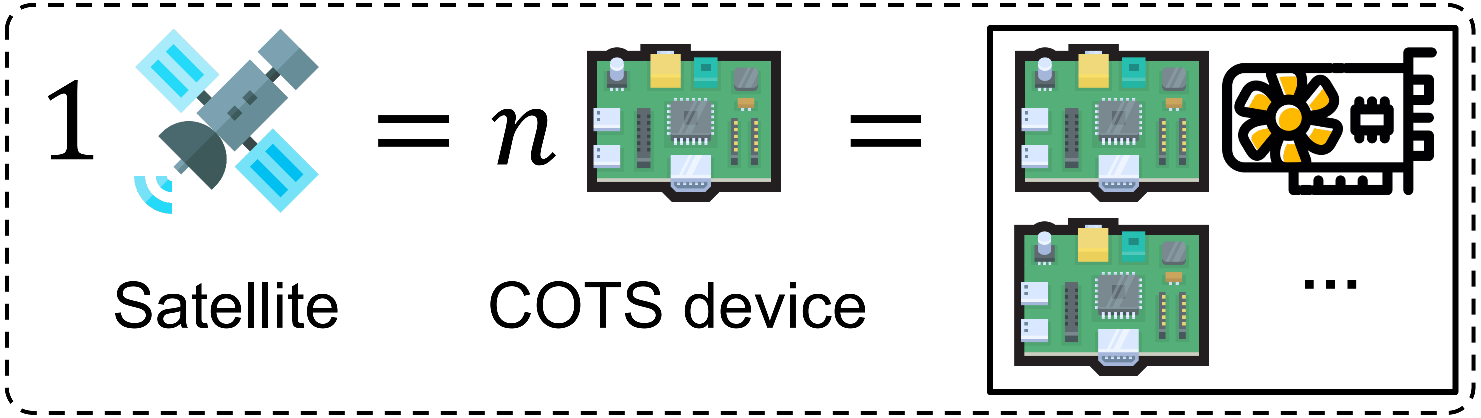


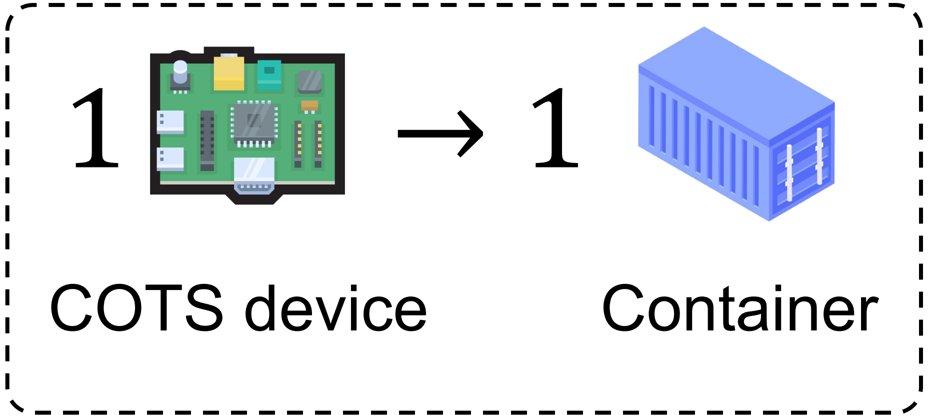
EmuPerf Table

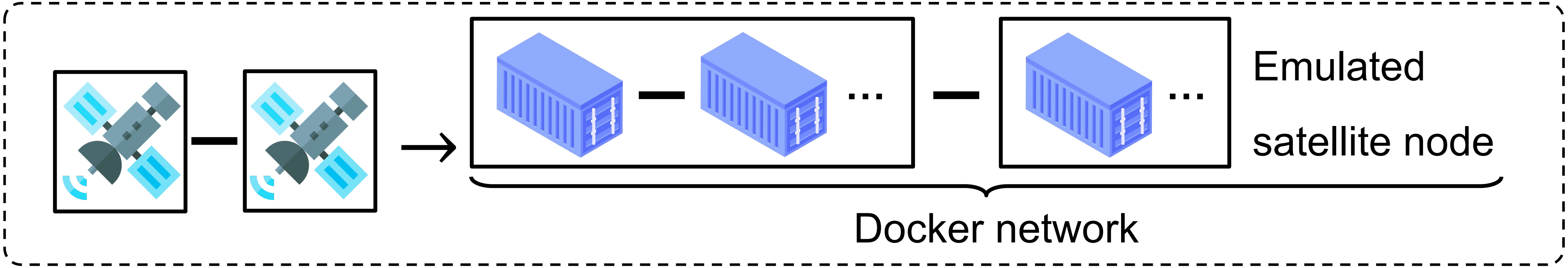
$Node_A$	App_1	10 %	9.5 s
		...	
		90 %	3.0 s
...			

RHONE – Part II: Online Emulation

- **Node representation**
  - We use containers, but not container-per-satellite

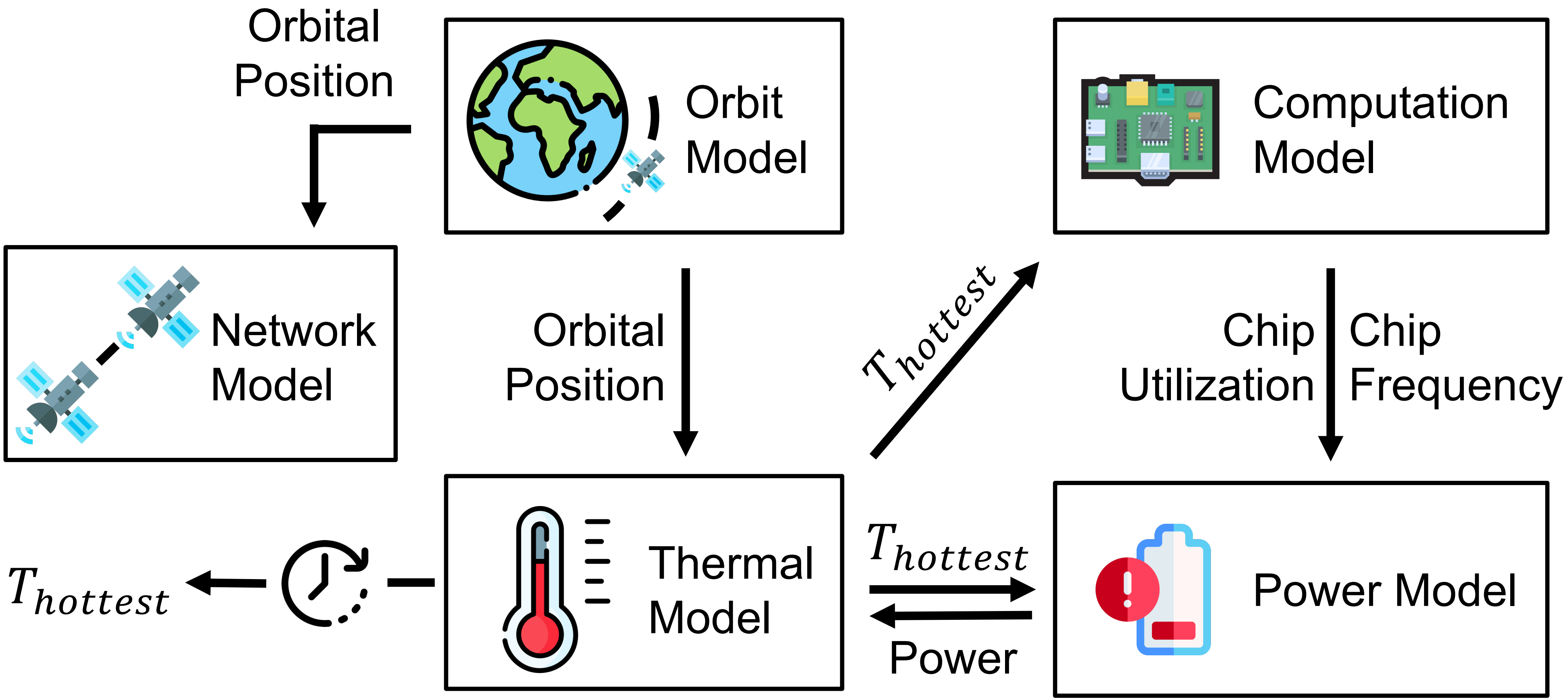






RHONE – Part II: Online Emulation

- **Model interaction**



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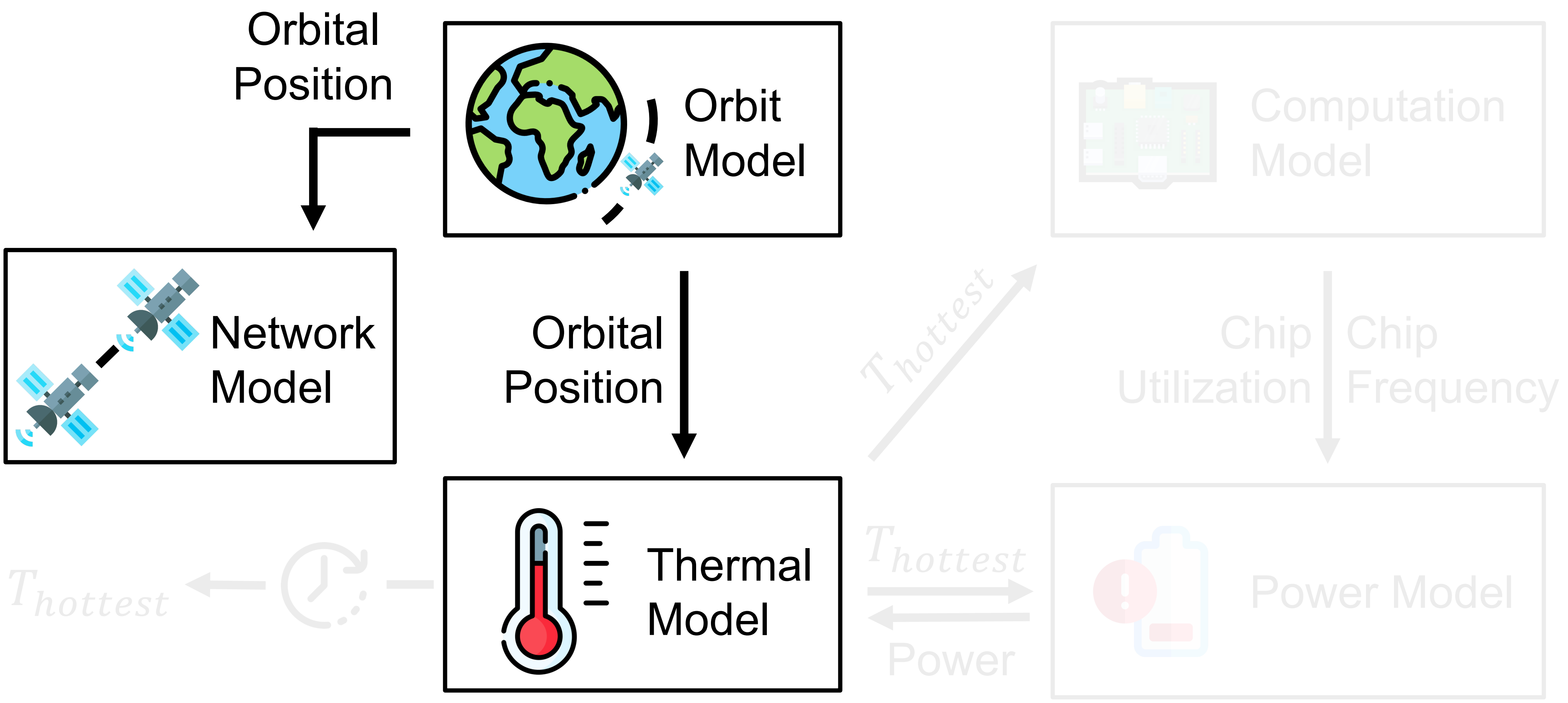
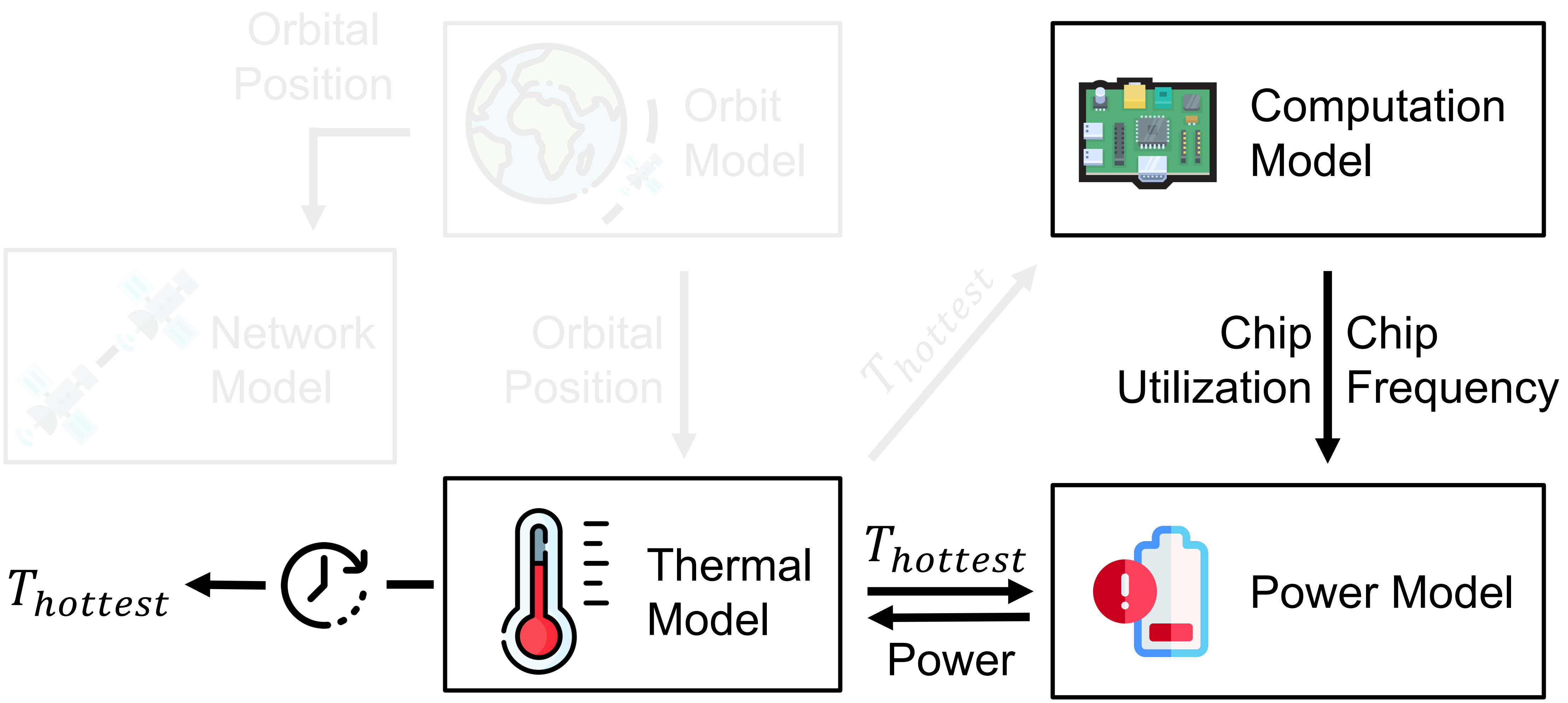


RHONE – Part II: Online Emulation

- **Model interaction**



RHONE – Part II: Online Emulation

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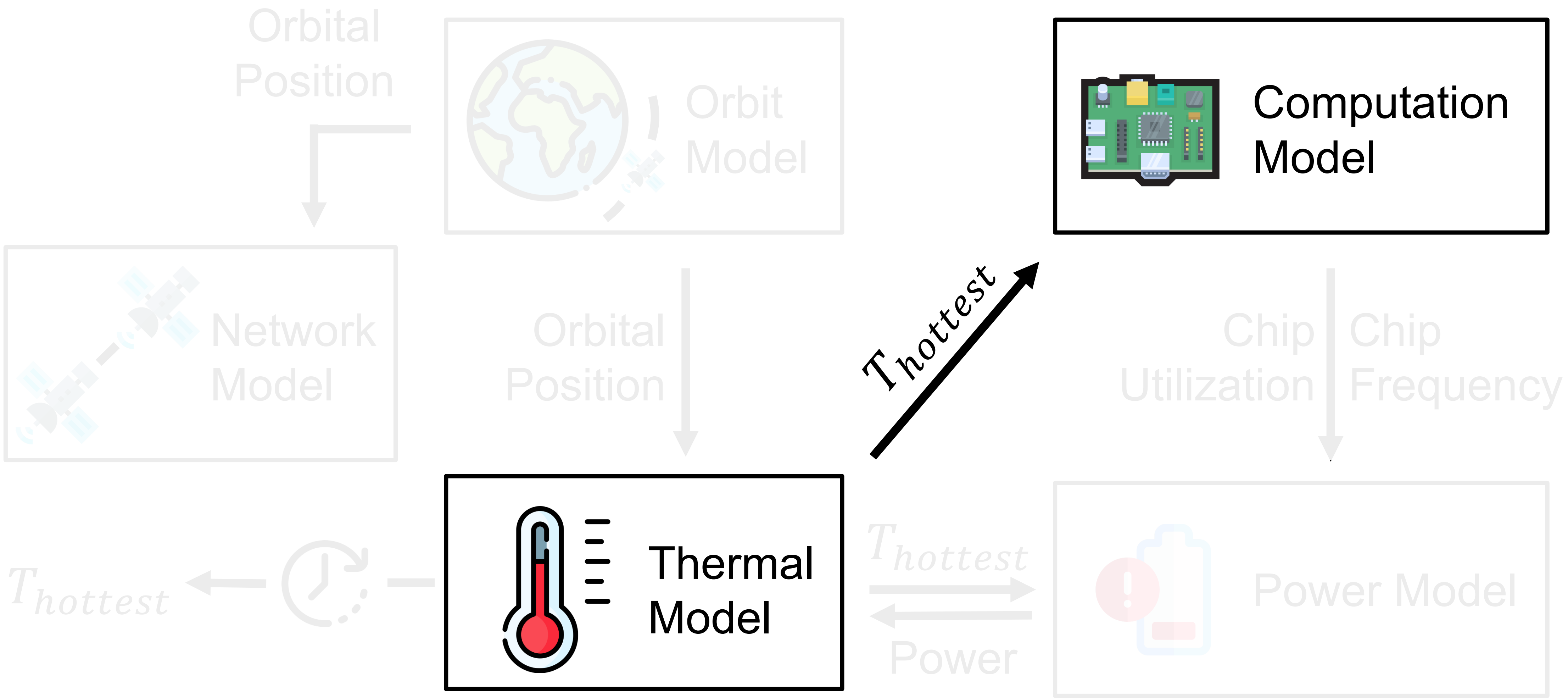

RHONE – Part II: Online Emulation

- **Satellite COTS chip aligner**
- **Satellite network aligner**

RHONE – Part II: Online Emulation

- **Satellite COTS chip aligner**
  - For "run Application 1 on Chip A" task:

- **Satellite network aligner**

RHONE – Part II: Online Emulation

- **Satellite COTS chip aligner**
  - For "run Application 1 on Chip A" task:

  - Check SatPerf Table and EmuPerf Table

$Chip_A$	App_1	15 °C	3.0 s
		…	
		50 °C	4.6 s
…			

SatPerfTable

$Chip_A$	App_1	10%	9.5 s
		…	
		90%	3.0 s
…			

EmuPerfTable

- **Satellite network aligner**

RHONE – Part II: Online Emulation

- **Satellite COTS chip aligner**
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SatPerfTable

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EmuPerfTable

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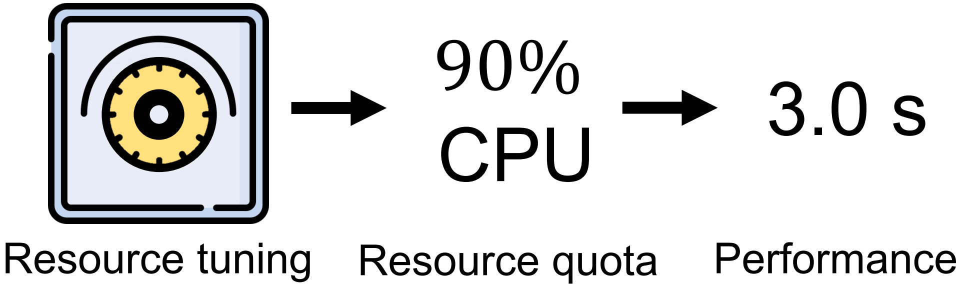
  - Tune CPU/GPU resources to align performance



- **Satellite network aligner**

RHONE – Part II: Online Emulation

- **Satellite COTS chip aligner**
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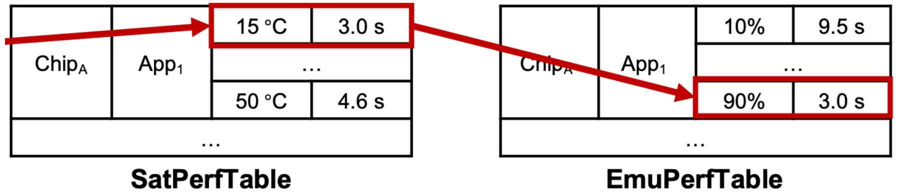

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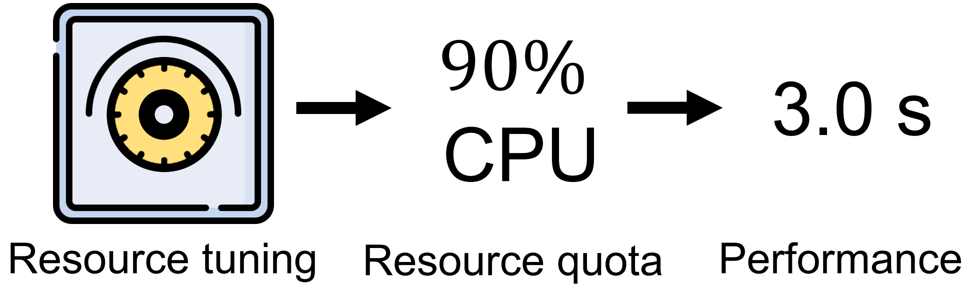
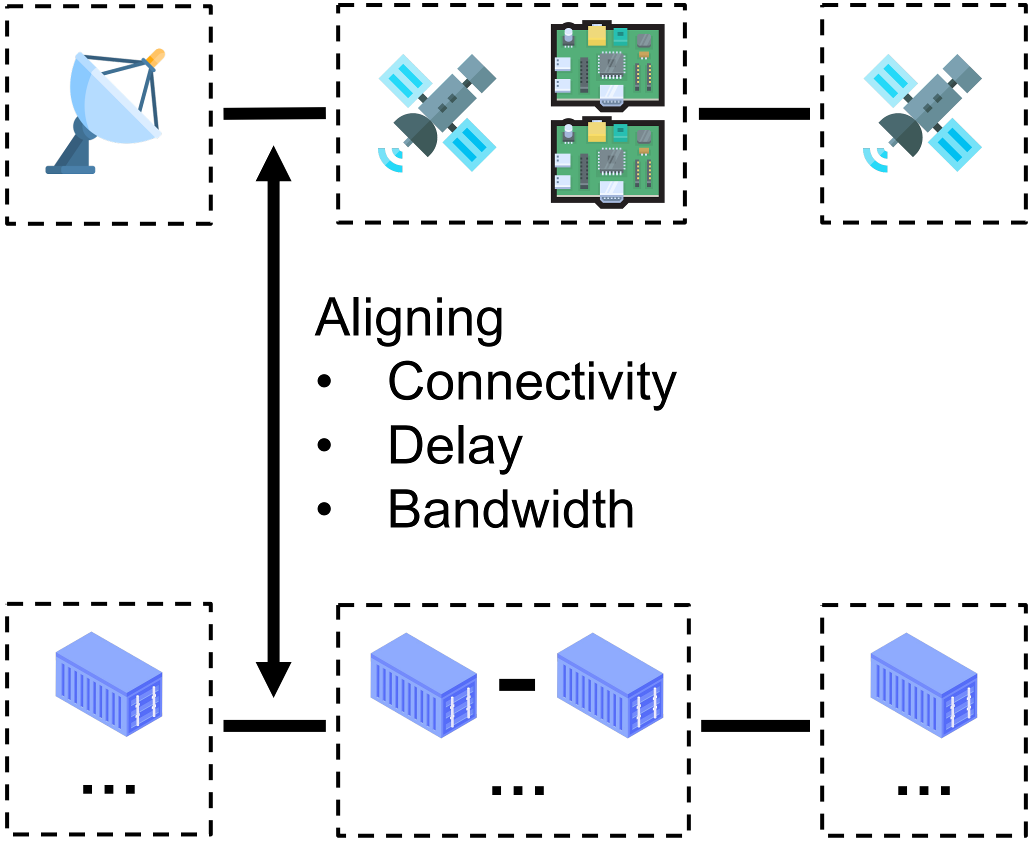


- **Satellite network aligner**
  - Align the container network to network model



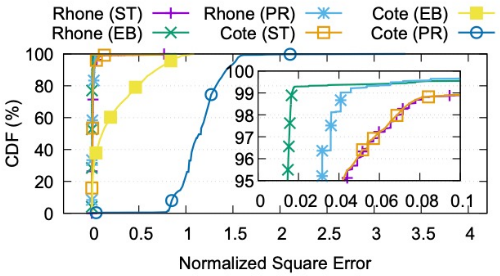
RHONE is scalable and accurate

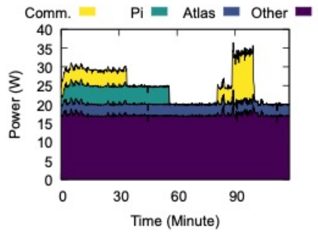
- RHONE scales ~700 satellites on a single physical node

Satellite Num.	CPU Usage Mean (%)	CPU Usage Std. Var. (%)	Memory Usage Mean (%)	Memory Usage Std. Var. (%)	Setup Time (min)
172	12.1 / 18.3	14.7 / 33.1	8.9 / 10.3	0.1 / 1.5	15.1 / 5.1
348	23.7 / 27.5	31.1 / 38.8	13.5 / 16.7	0.2 / 3.0	19.8 / 7.8
720	37.7 / 42.7	35.6 / 39.5	24.5 / 33.3	0.5 / 8.5	42.2 / 17.1

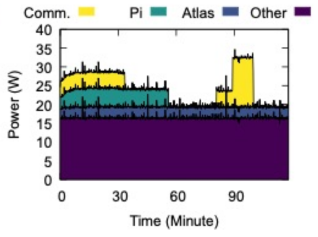
X/Y indicates the result of RHONE/StarryNet

- Power and thermal outputs are accurate

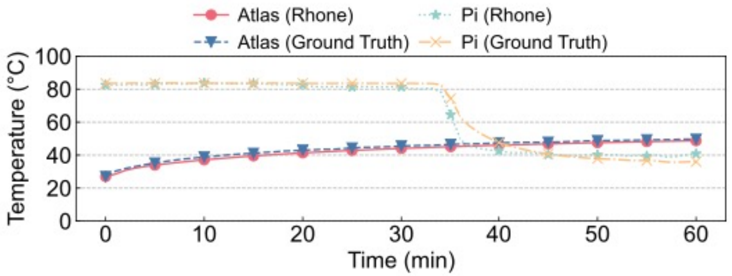




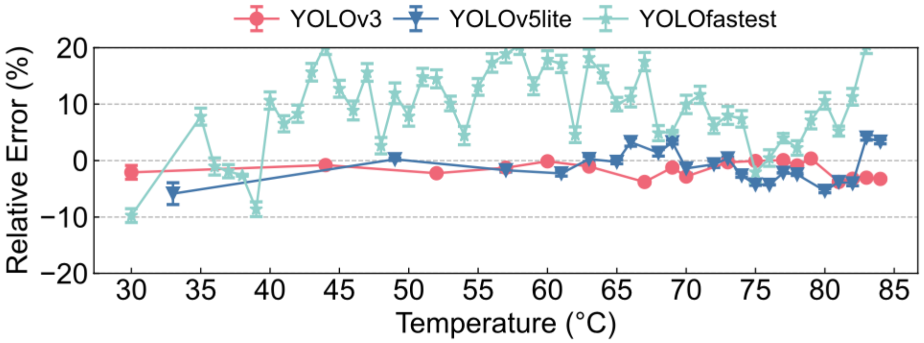
(a) Real satellite trace.



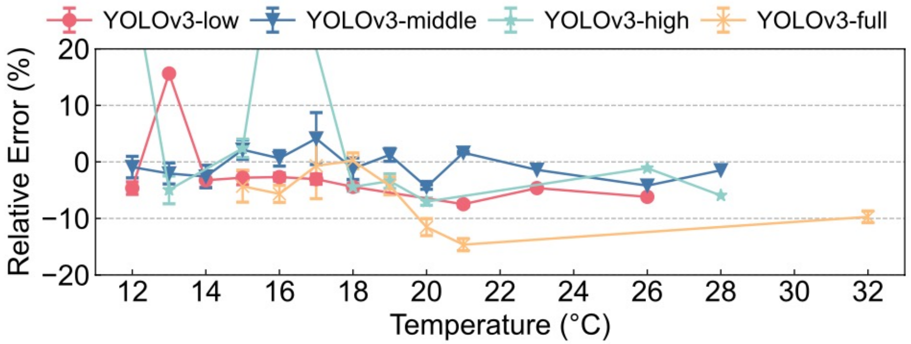
(b) RHONE generated trace.



- Emulated performance is accurate



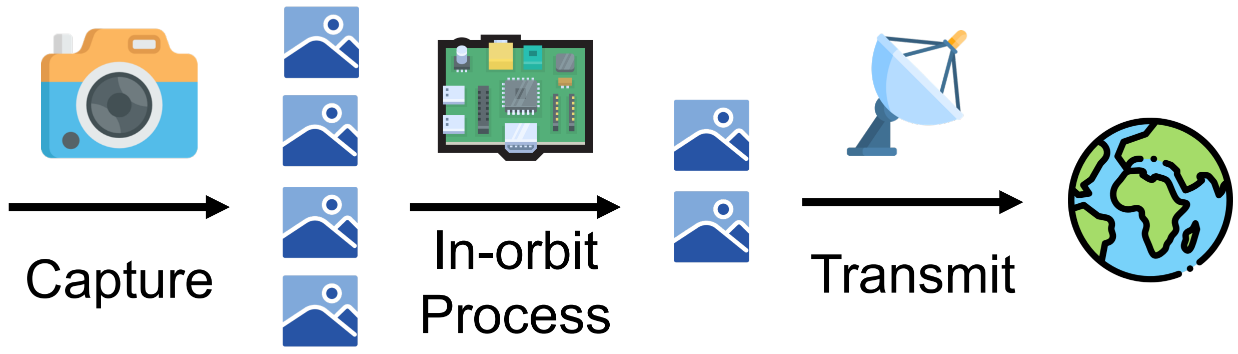
(a) Raspberry Pi



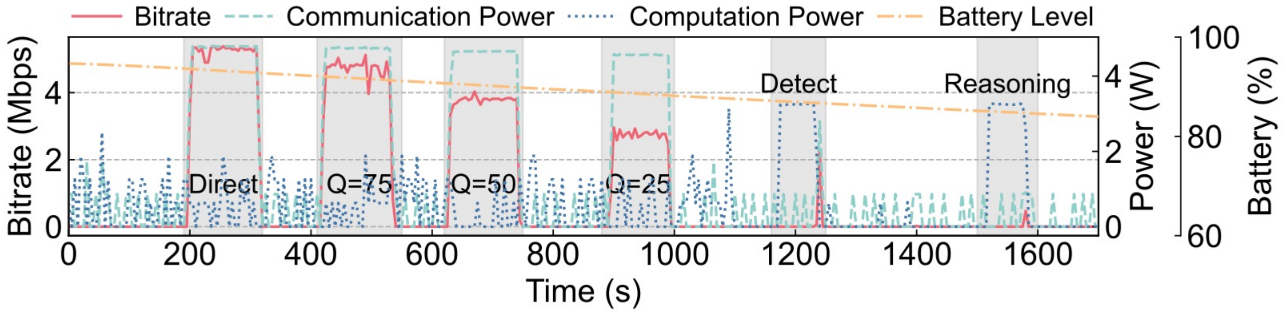
(b) Atlas 200 DK

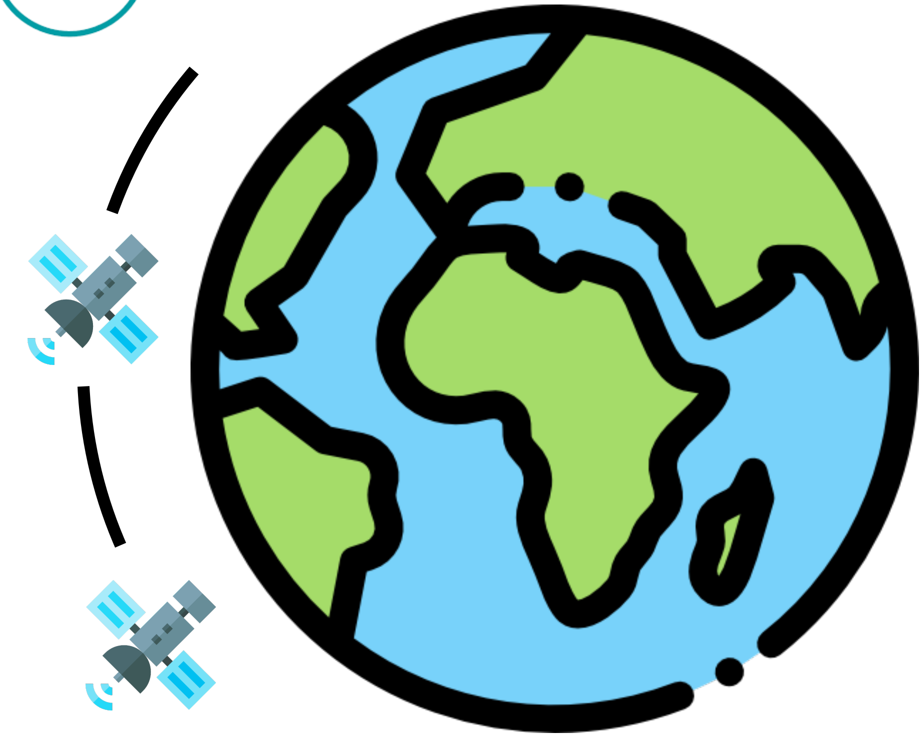
Using RHONE to design SCN applications

- **Earth Observation**
  - Pipeline



  - Using RHONE to design

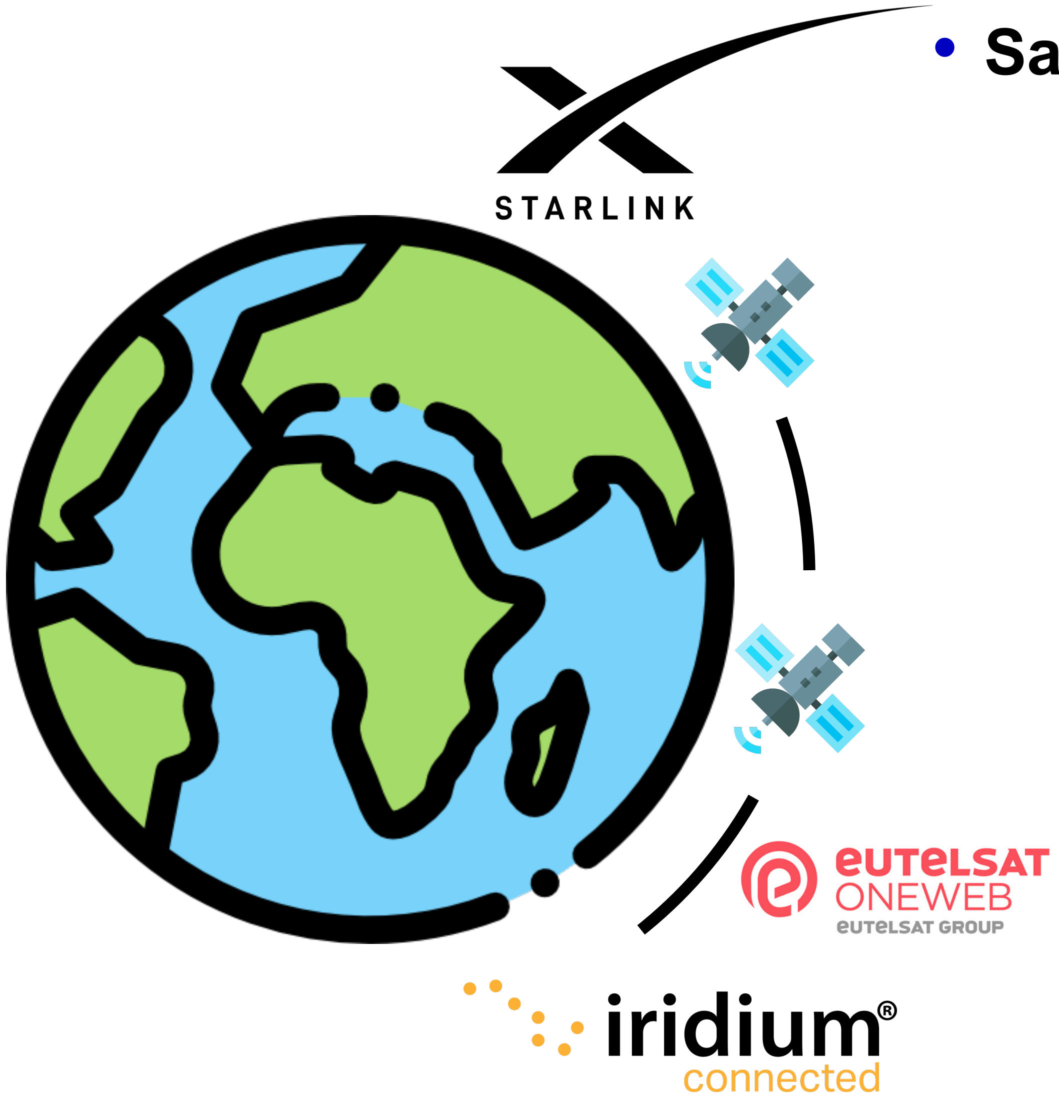




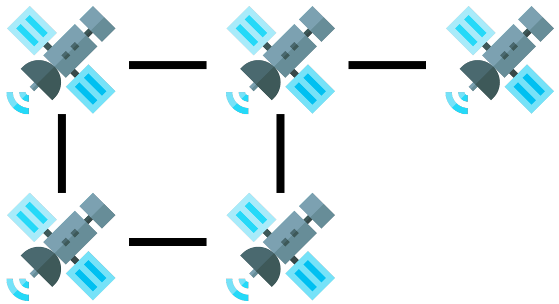
planet.

Palantir

Using RHONE to design SCN applications

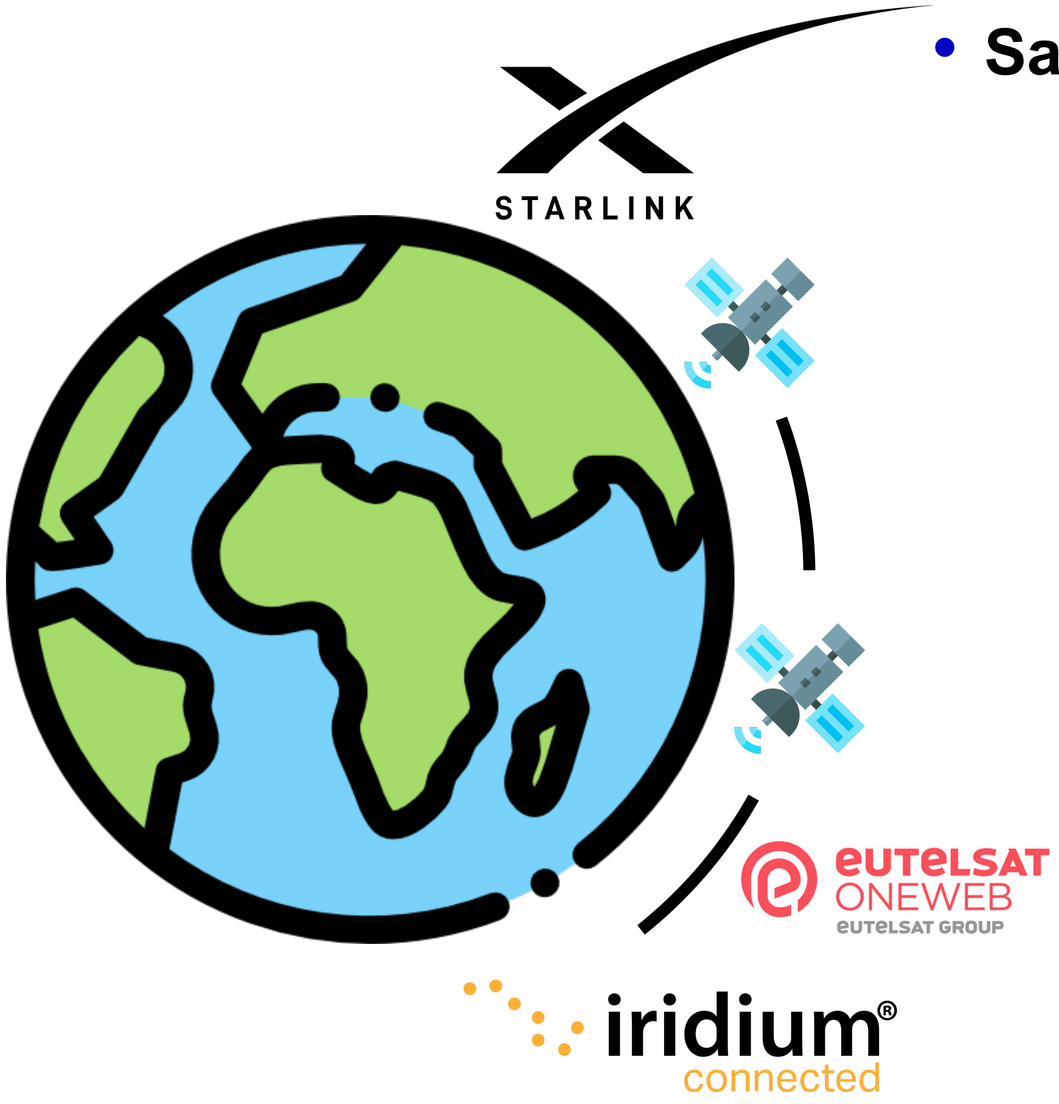


- **Satellite DDoS attacks leading to energy drain**



Predictable toplology

Using RHONE to design SCN applications



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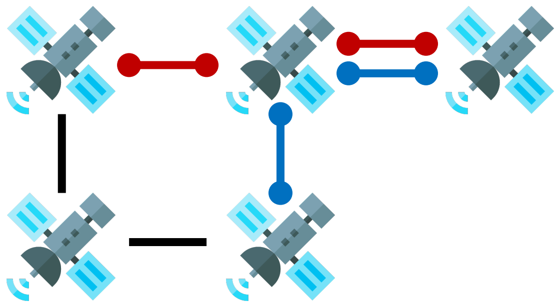
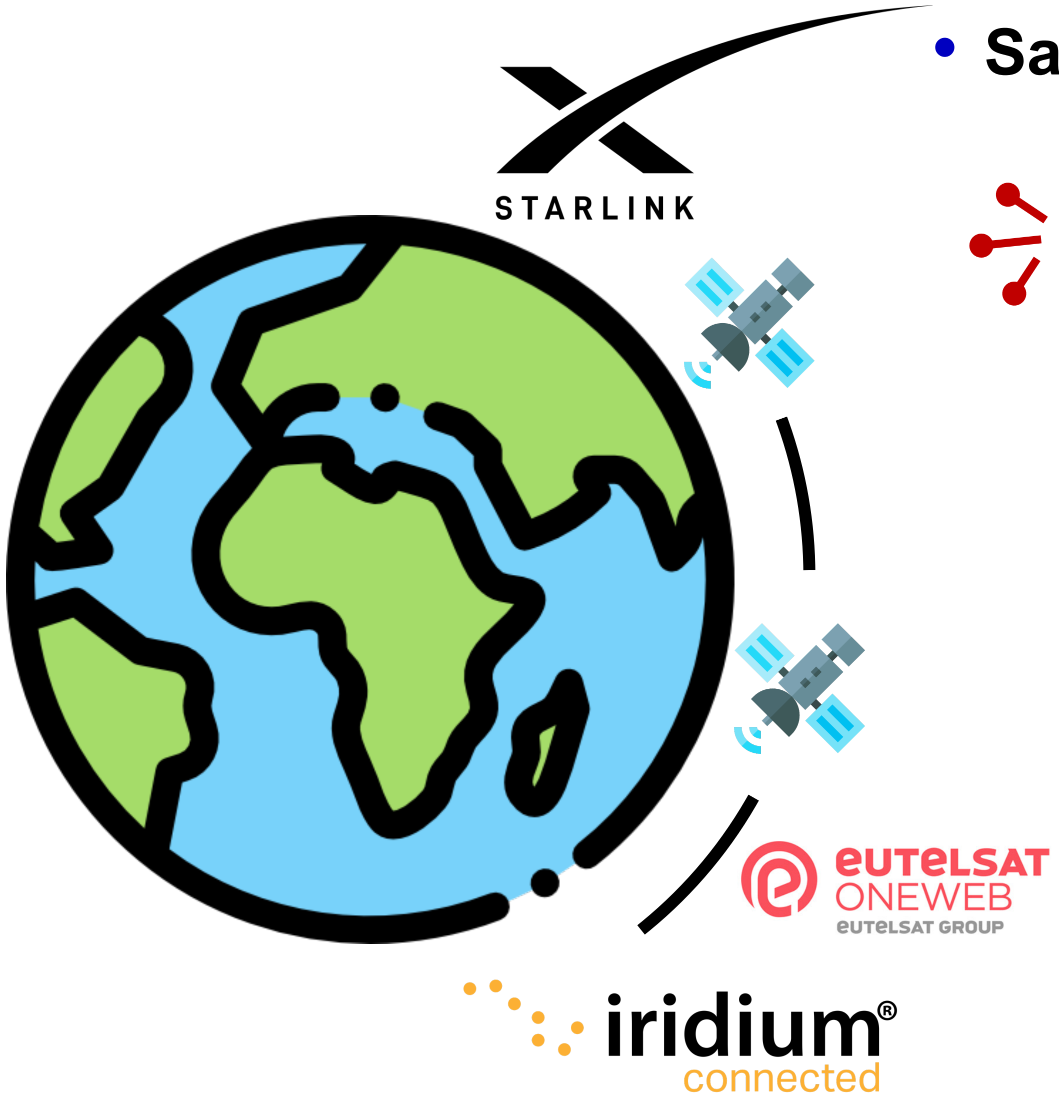


Predictable toplology

Predictable routing

Using RHONE to design SCN applications



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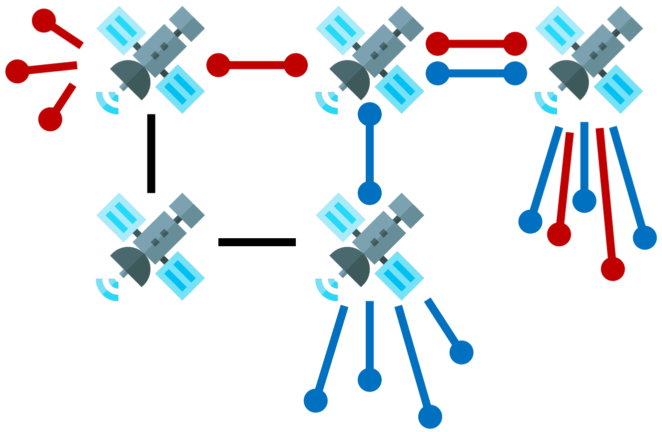
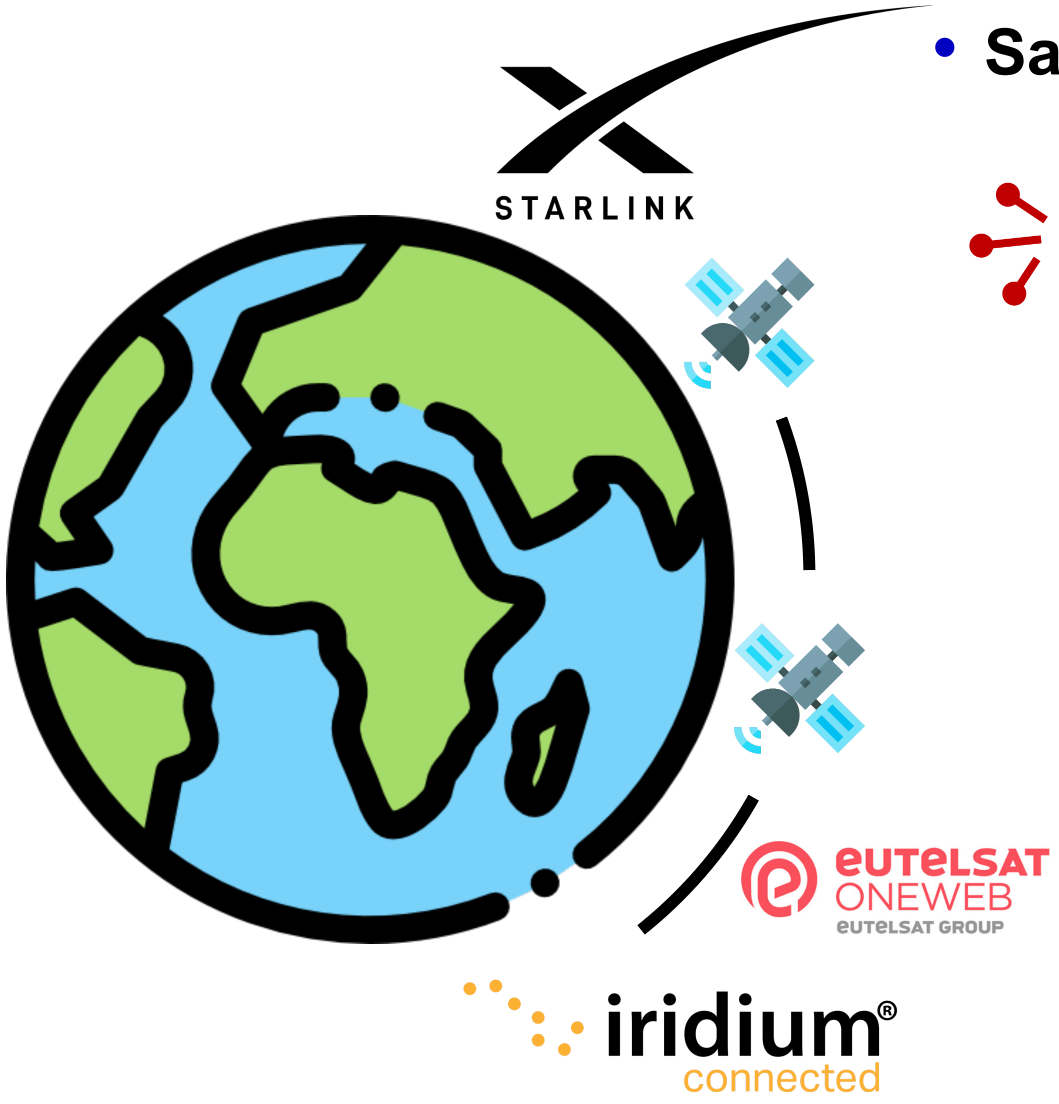


Predictable toplology

Predictable routing

DDoS attack

Using RHONE to design SCN applications



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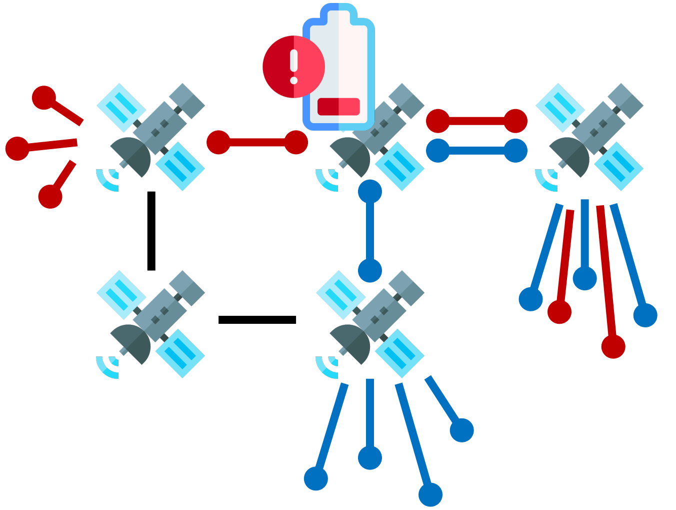


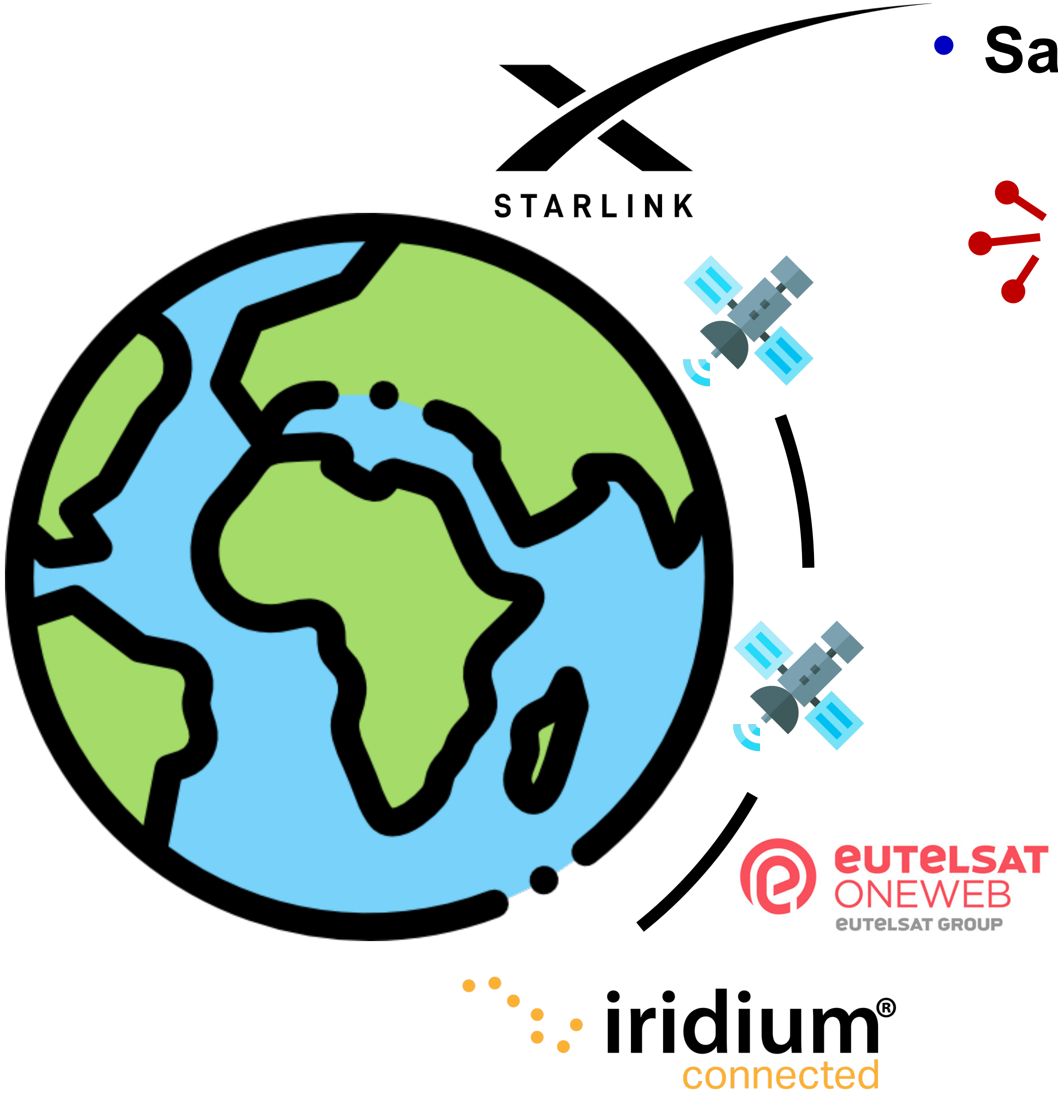
Predictable toplology

Predictable routing

DDoS attack

Energy drain

Using RHONE to design SCN applications



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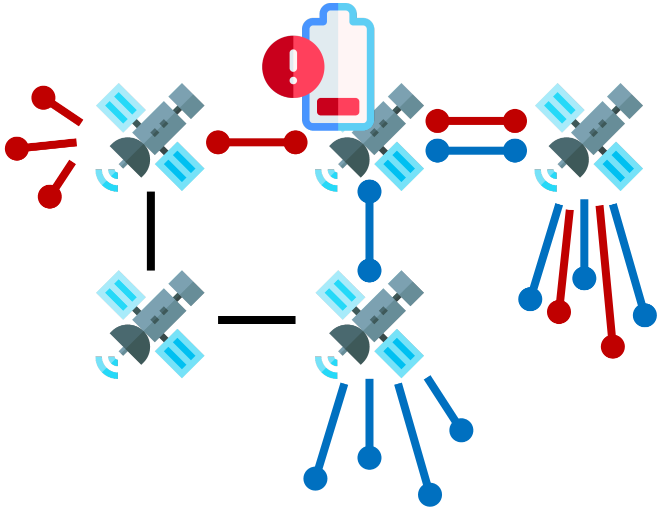

Predictable toplology

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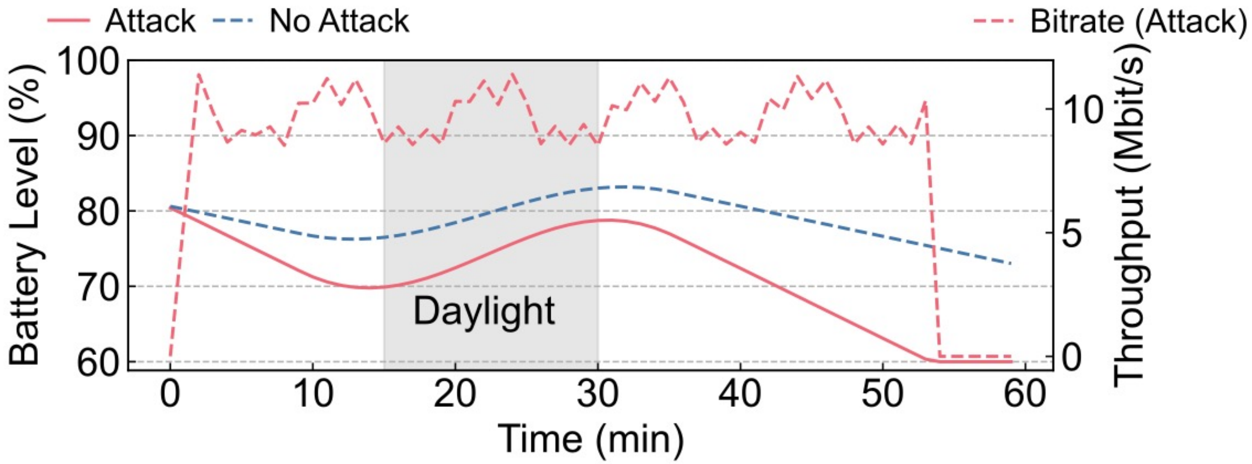

Thanks for Your Listening & Any Questions?

Acknowledgement

- Collaborators:
  - Qing Li, Yuhan Zhou, Zhaofeng Luo, Donghao Zhang, Shangguang Wang, Xuanzhe Liu, Chenren Xu