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Beyond the Edge: Cloud Native Application Management Under Extreme Network Conditions

Tobias Nöthlich and Maximilian Nitsch (D3TN GmbH)



Agenda



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- ▶ **Motivation**
- ▶ **Background**
 - Why not just use Kubernetes without any modifications?
 - What is Delay- and Disruption-tolerant Networking?
 - The DARKSOL research project
 - What could a solution look like?
- ▶ **Integrating K8s and DTN**
 - Deploying Kubernetes to satellites and space probes
 - Managing an application's Lifecycle over a DTN
 - Allowing applications to communicate over a DTN
- ▶ **Key Takeaways & Future Work**

**Who even cares about cloud native
applications in space?**

Motivation



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Google plans to put datacentres in space
to meet demand for AI

US technology company's engineers want to exploit solar
power and the falling cost of rocket launches

**... cares about cloud native
applications in space?**

Motivation



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applications ...

China joins race to develop space-based
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By Julian Dossett published February 5, 2026

Motivation



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Google plans to put datacentres in space to meet demand for AI

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applications ...

ARTIFICIAL INTELLIGENCE • LATEST NEWS

Elon Musk wants to put the data cloud into orbit, SpaceX plans data centers in space

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China

Article • Cloud & Infrastructure

Cloud in the Stars: How Space Could Solve AI's Energy Crisis

plan space-based

5, 2026

cloud into orbit, SpaceX

By Tom Chapman
January 19, 2026 • 7 mins • Bashir

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centres in space

Nebulae: Deep-Space Computing Clouds

to Solve

Google
to me August 26 - 30, 2019

US technology companies
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Cloud in the Stars.

AI's Energy Crisis

© 2026
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Technology - Pasadena, CA 91125
5, 2026

Cloud into orbit, SpaceX

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Nebulae: Deep-Space Comm

Connectivity

ReOrbit Partners With Google Cloud for Space Data Network

By Ben Ackman | February 5, 2026



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Cloud AI's Energy

cloud into orbit, SpaceX

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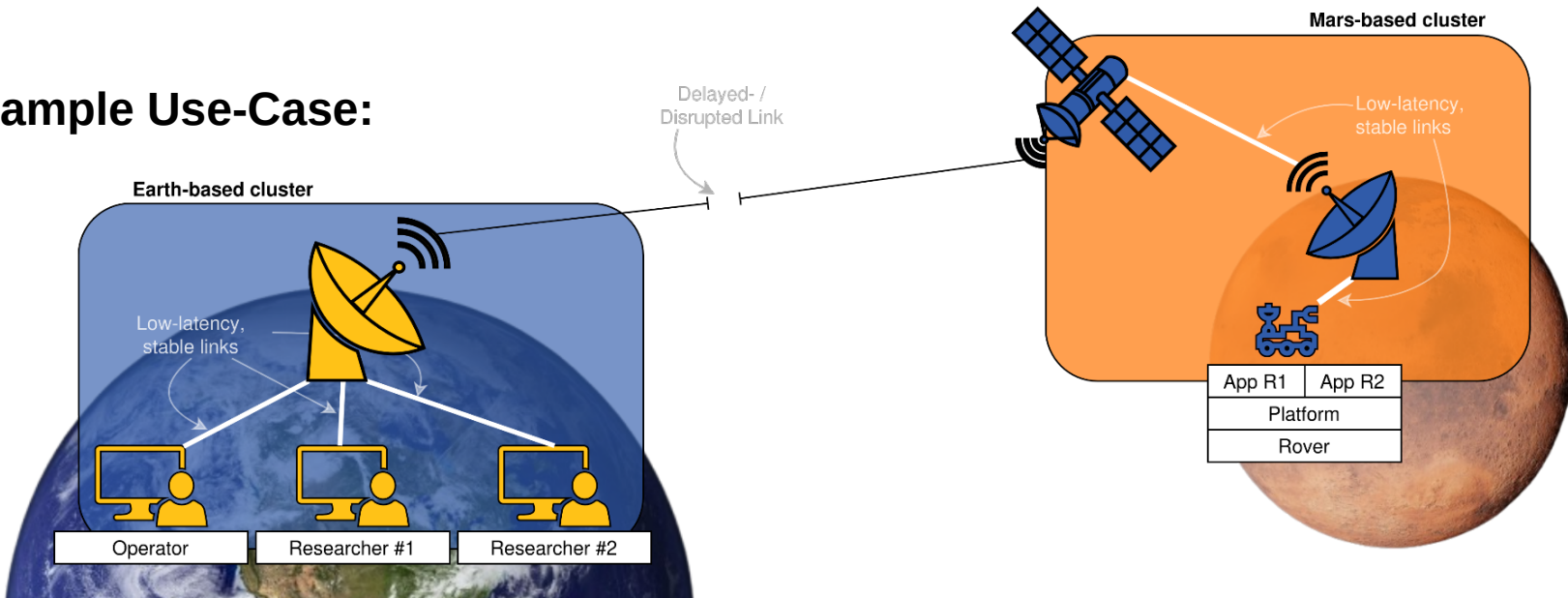


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- ▶ Turns out, quite a lot of people do!
- ▶ So why don't more people operate cloud native applications in space?
 - It seems to be harder than it sounds (especially in the deep-space context!)

Example Use-Case:



Motivation



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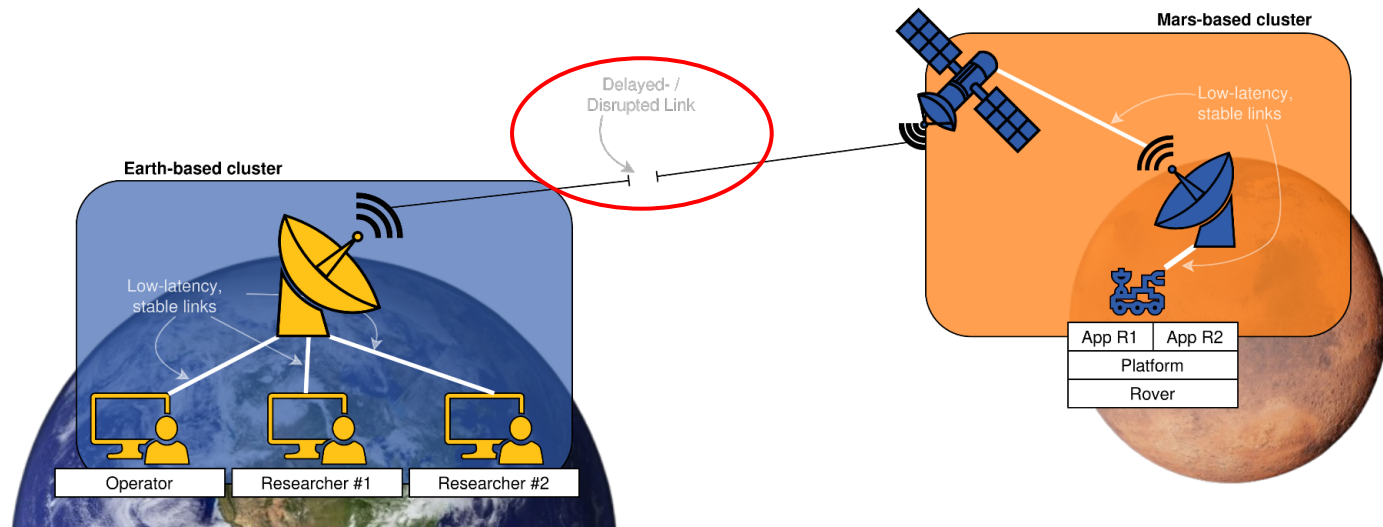


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Main Problems:

1. Deep-space **lacks the continuous network connectivity** found on Earth
2. There are **no flexible and easy-to-use cloud-native execution environments** for space agencies
3. **Tenant separation** for space hardware-software platforms is **insufficient**
4. **Deploying new software** to existing satellite/rover platforms is **done via dedicated toolchains**



Motivation



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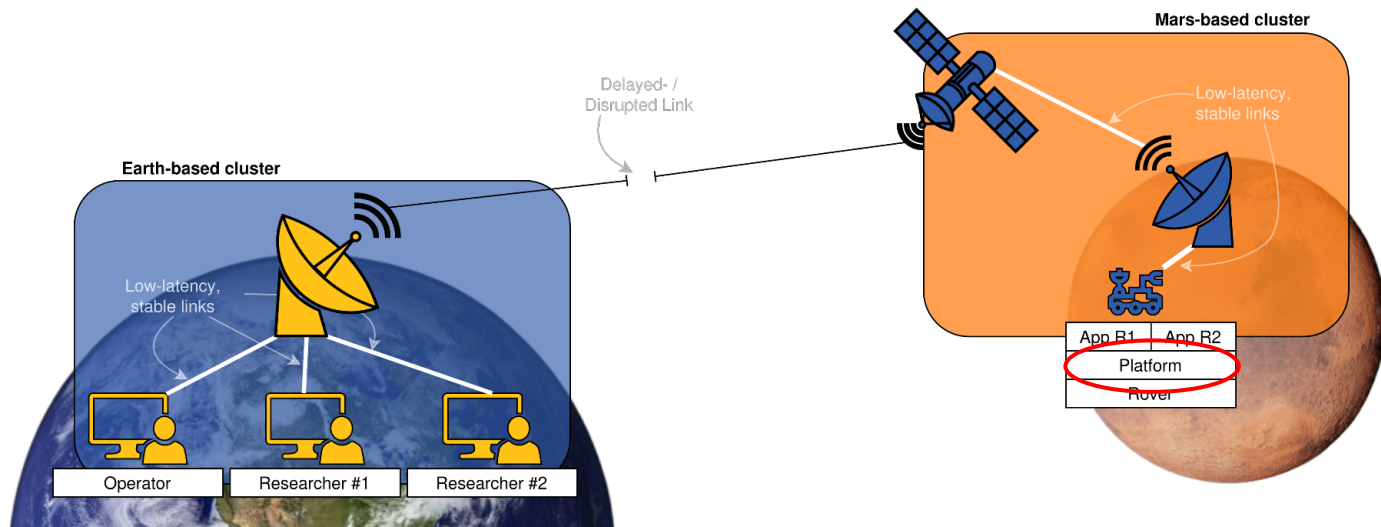


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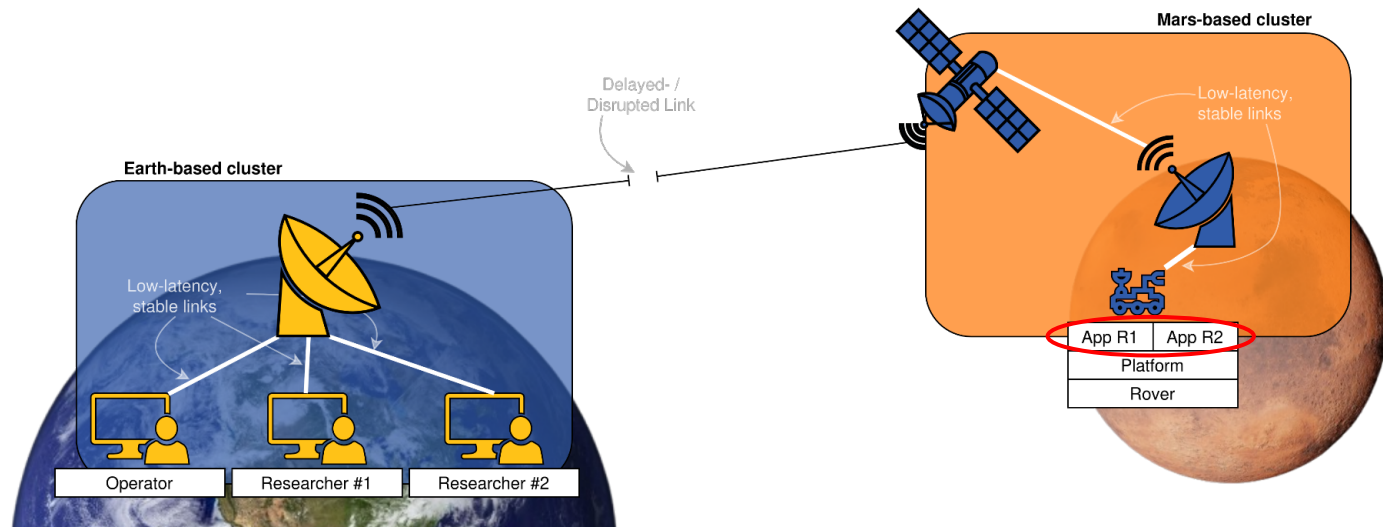


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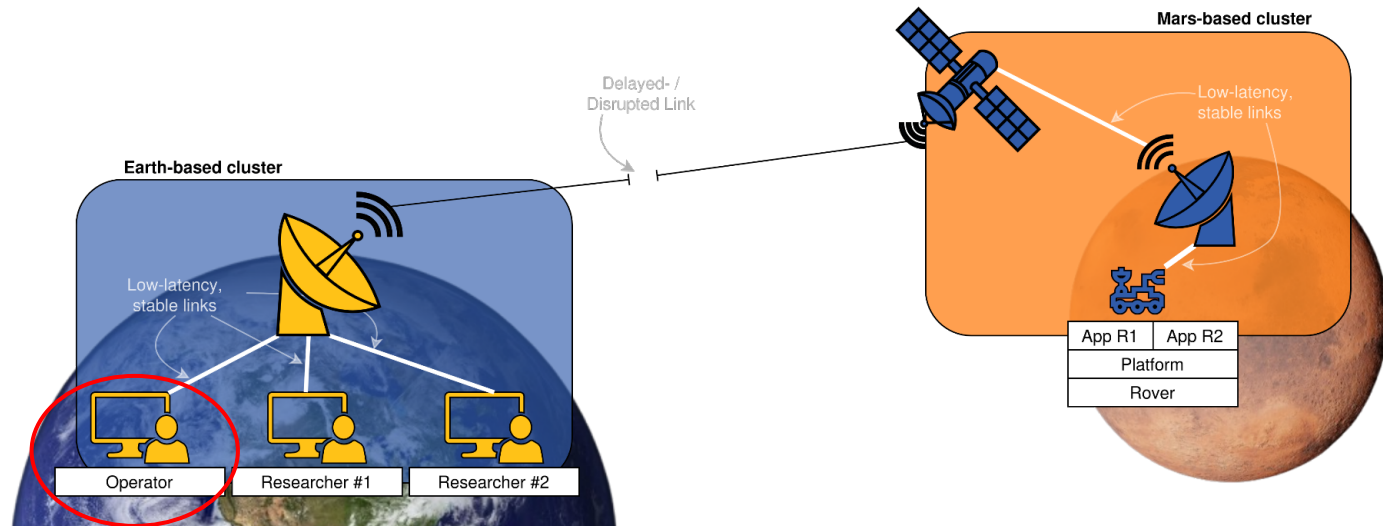


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Background

Why not just use Kubernetes without any modifications?



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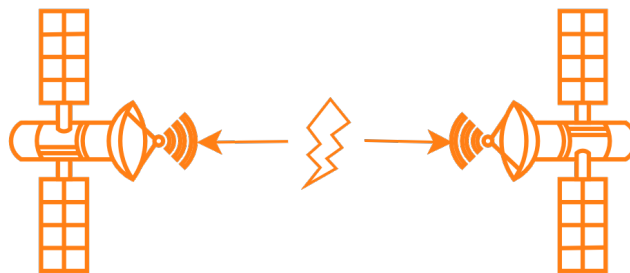
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- ▶ Built for terrestrial use-cases:
 - Optimized for stable, low-latency networks
 - Image pulls (e.g. after a deployment) require a stable network connection
 - Application data flows assume uninterrupted connectivity
- ▶ Rather easy to realize in a datacenter, very hard to do on satellites or space probes due to:



Delays

and



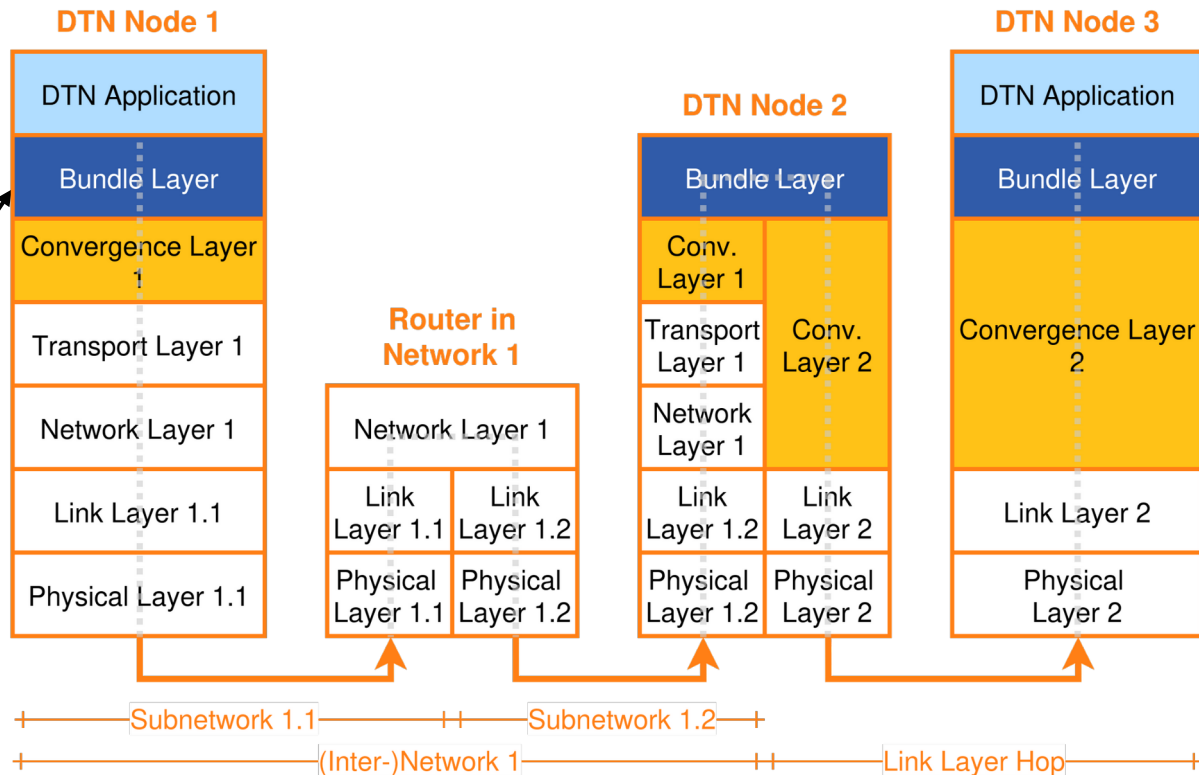
Disruptions

Background

What is Delay- and Disruption-tolerant Networking?

- ▶ Hop-by-hop data transmission incl. physical movement
- ▶ Nodes buffer data in memory or in persistent storage for a potentially arbitrary amount of time

Overlay network by introducing the “Bundle Layer” (RFC 9171)

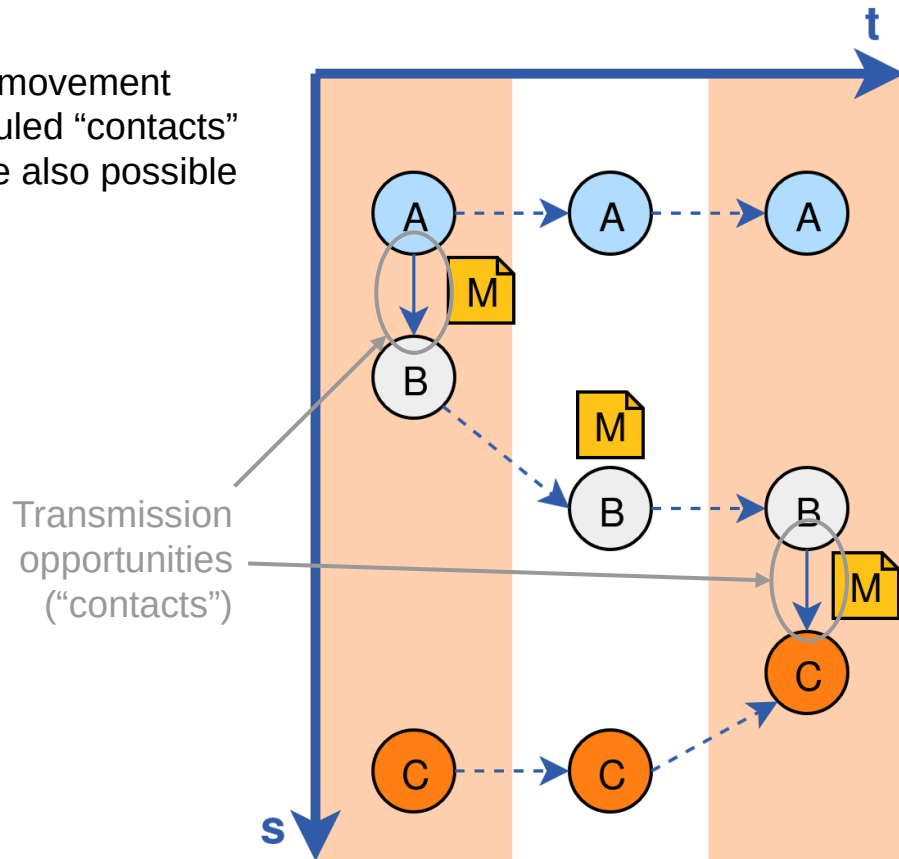


Data Transmission in DTN:

- ▶ Hop-by-hop data transmission incl. physical movement
- ▶ Transmission is (usually) done during scheduled “contacts”
- ▶ Opportunistic discovery and transmission are also possible

Example:

- ▶ A wants to transmit to C, but they are never in range
- ▶ A uses B as intermediate hop, which travels closer to C and eventually transmits the message



Background

The DARKSOL research project

DARKSOL

DTN-ARchiteKturen für Space-Cloud-Operations und
Space-Cloud-Lifecycle-Management



Main research areas:

- 1) Delay- and disruption-tolerant cloud infrastructure (TU Dresden)
- 2) Secure Separation Layer for multi-tenant operation (Cyberus Technology GmbH)
- 3) Delay- and disruption-tolerant application operation (D3TN GmbH)

Background

What could a solution look like?

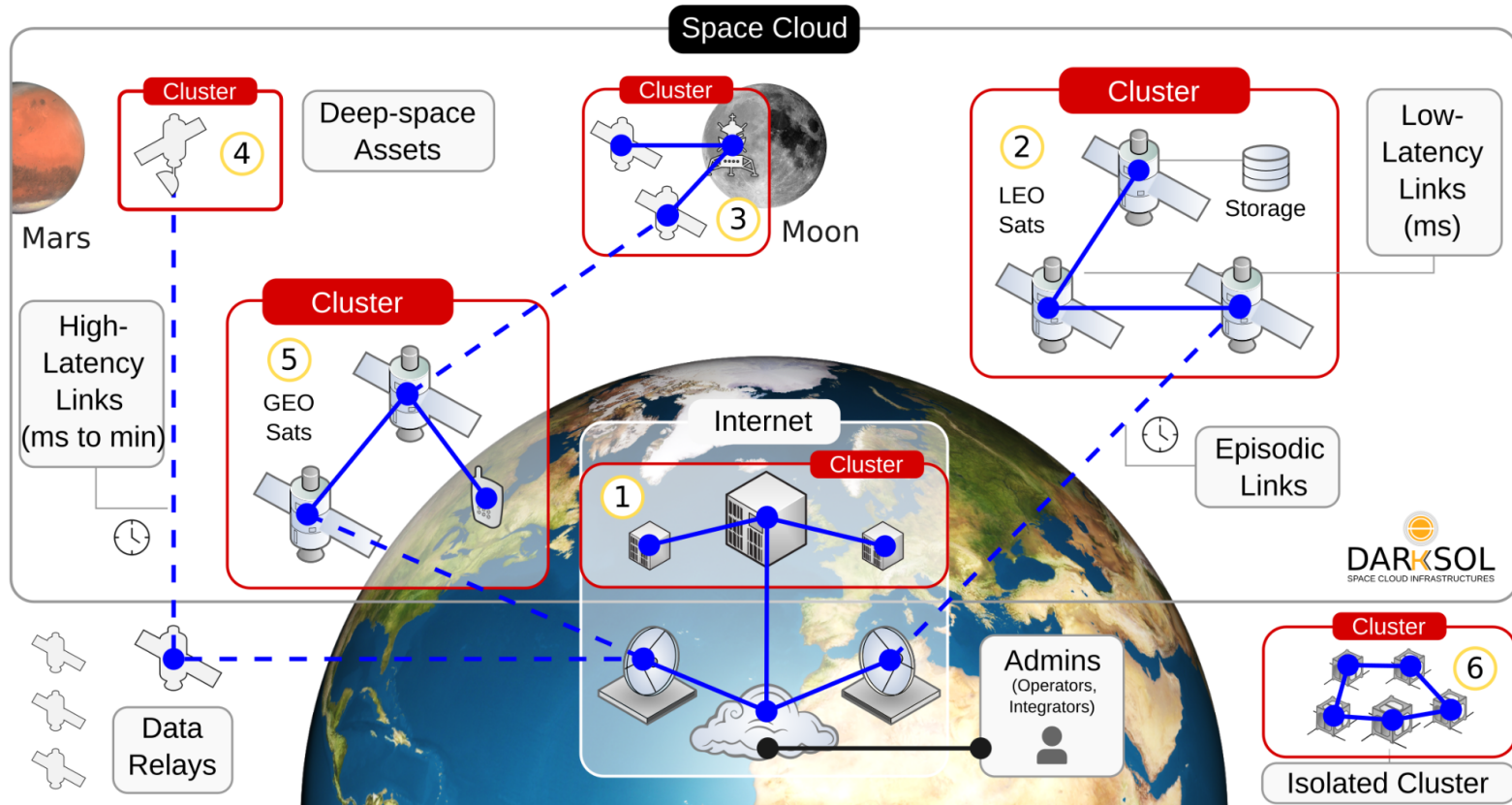


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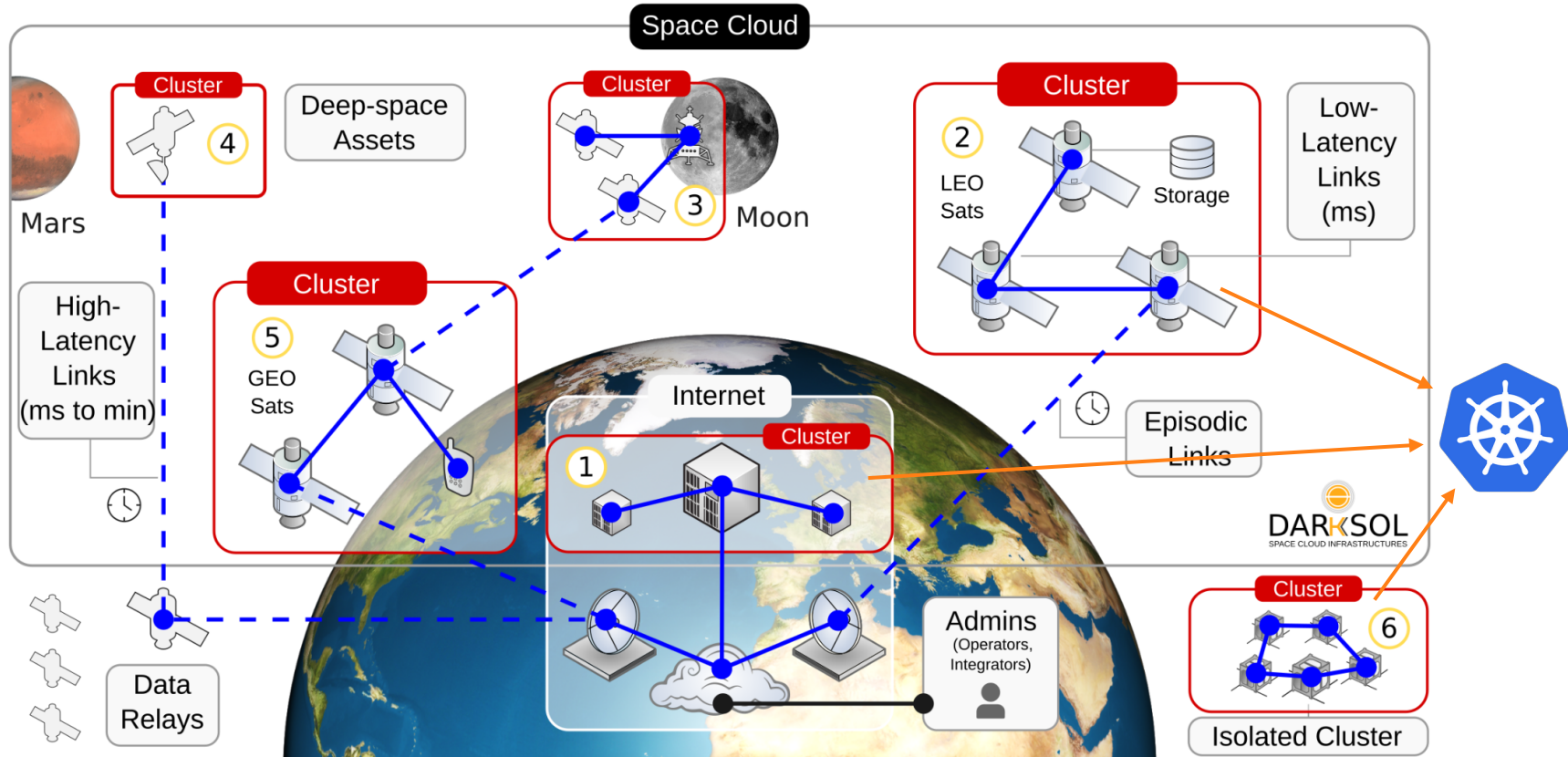


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Integrating K8s and DTN

Deploying Kubernetes to satellites and space probes

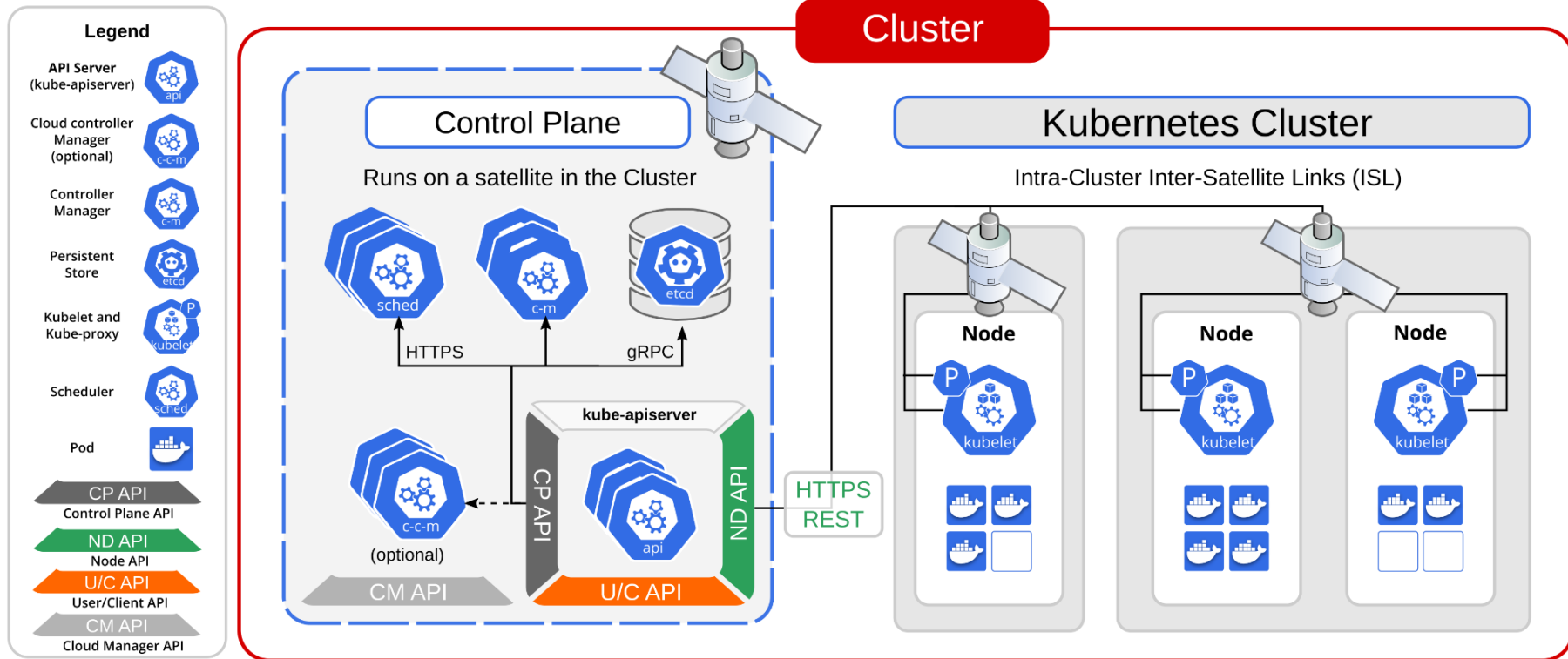


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Deploying Kubernetes to satellites and space probes



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What do we need to do?

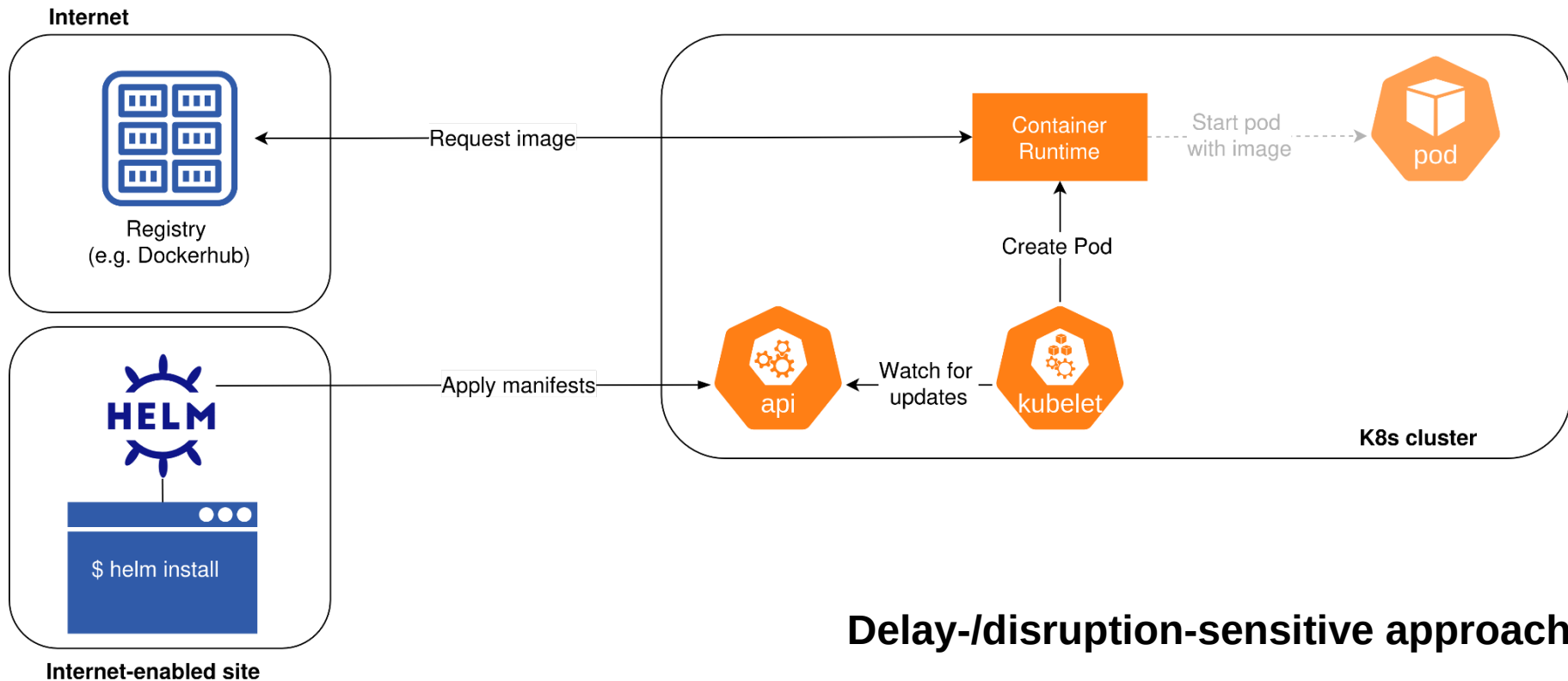
- ▶ **Build** an application
- ▶ **Deploy** it to a cluster
- ▶ **Send** application data to other clusters
- ▶ **Receive** data from other clusters

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Integrating K8s and DTN

Managing an application's lifecycle over a DTN



Integrating K8s and DTN

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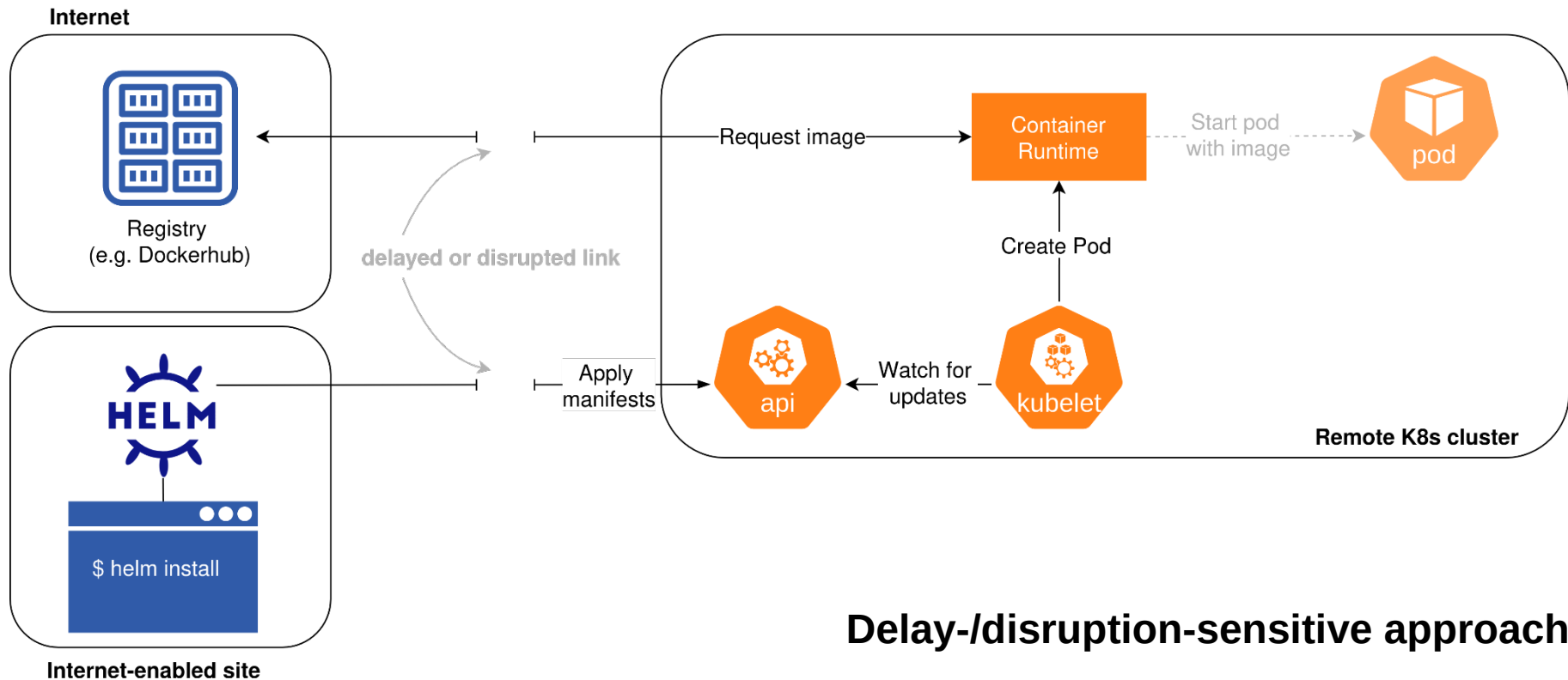


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Delay-/disruption-sensitive approach

Integrating K8s and DTN

Managing an application's lifecycle over a DTN

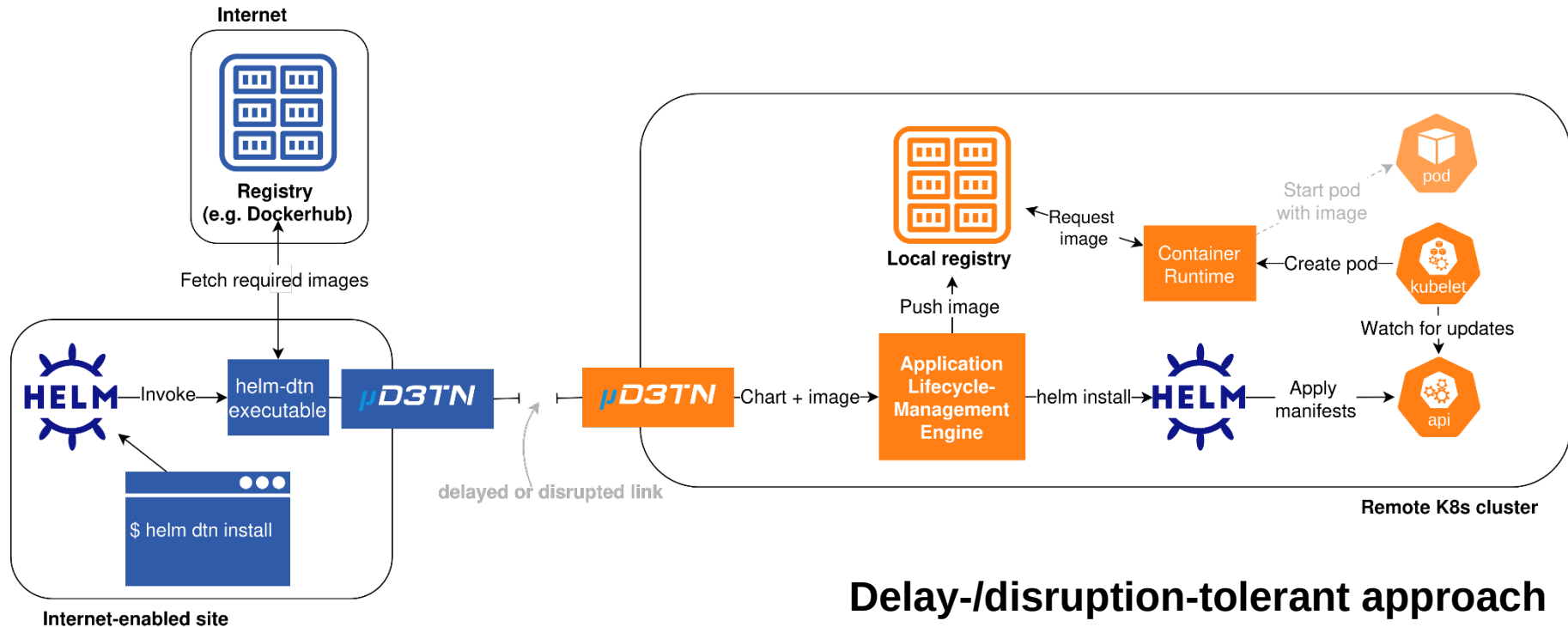


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Integrating K8s and DTN

Allowing applications to communicate over a DTN

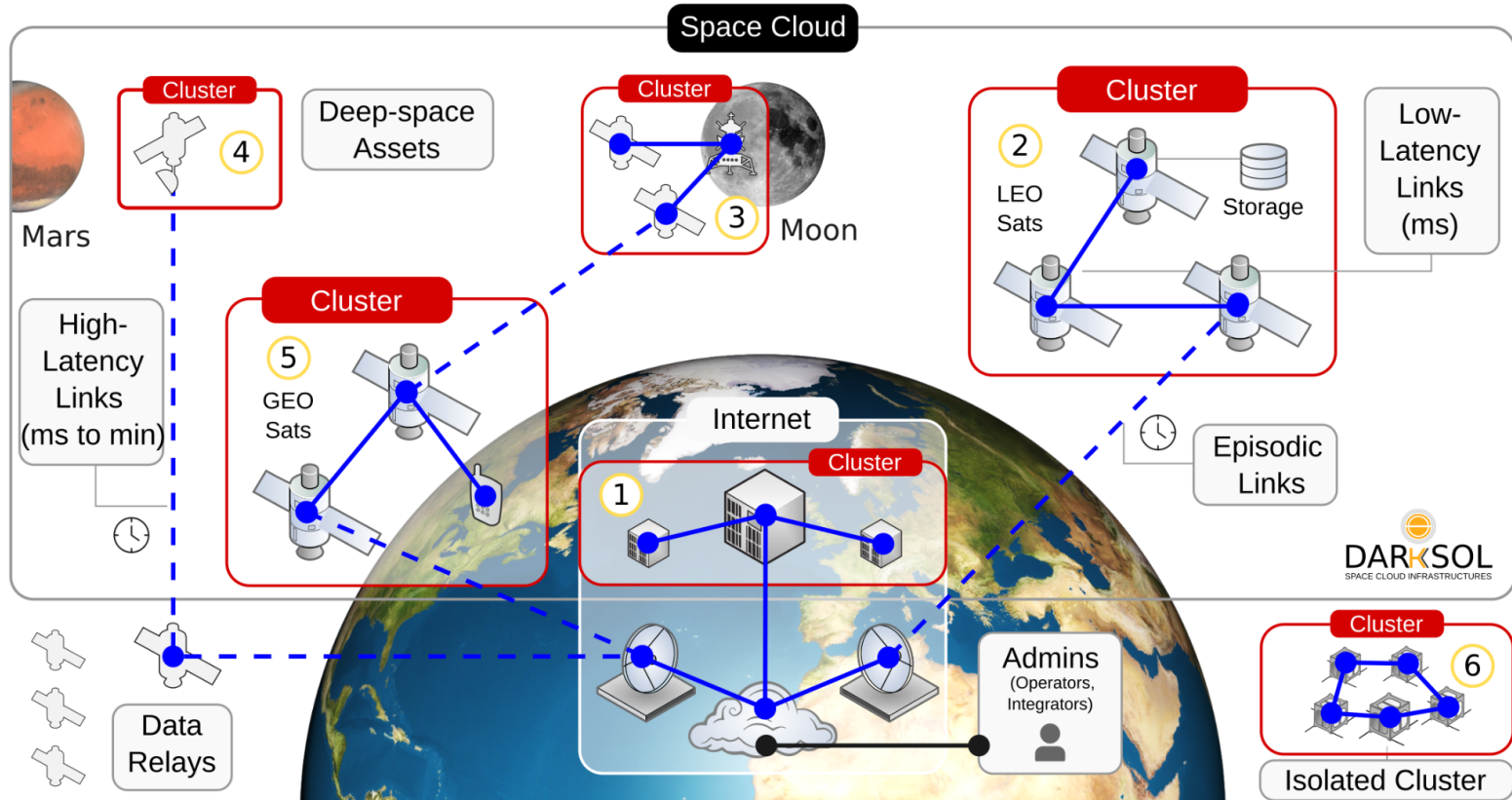


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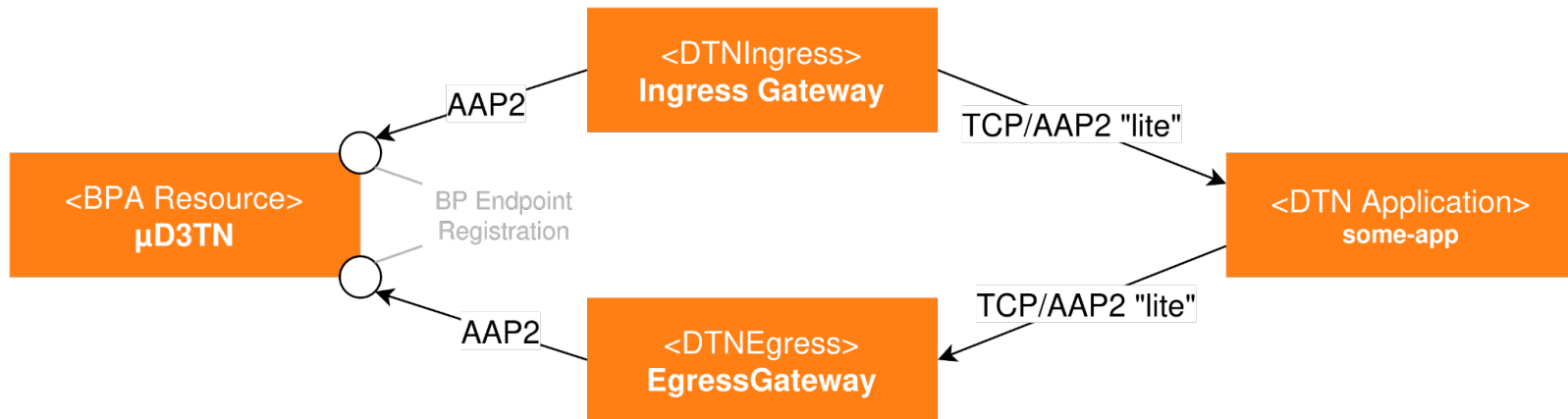


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First draft:

- ▶ **Bundle Processing Agent (BPA)** for delay-tolerant communications between clusters
- ▶ **DTN ingress** for forwarding data **to** applications
- ▶ **DTN egress** for forwarding data **from** applications
- ▶ Usage of existing protocol (**AAP2**) for connecting BPA and ingress/egress

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Allowing applications to communicate over a DTN



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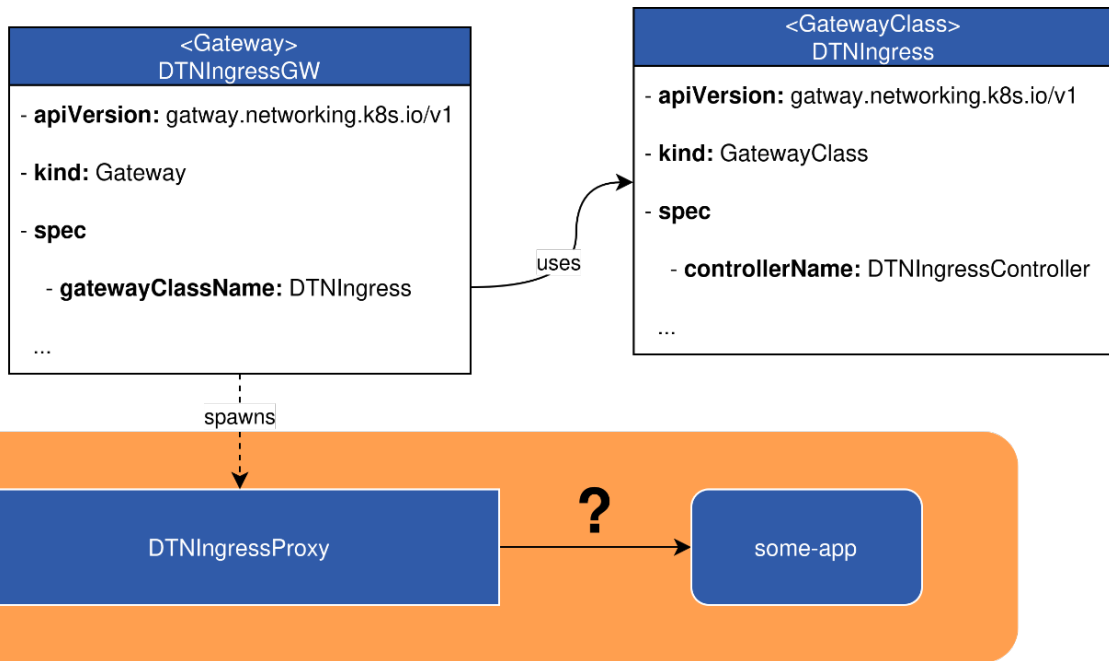


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Option 1: DTNIngressProxy = Gateway

- ▶ Corresponds to original idea
- ▶ Gateway spawns DTNIngressProxy
 - Connects to μ D3TN to register agent(s)
 - Forwards data to application(s)
 - How?



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Allowing applications to communicate over a DTN



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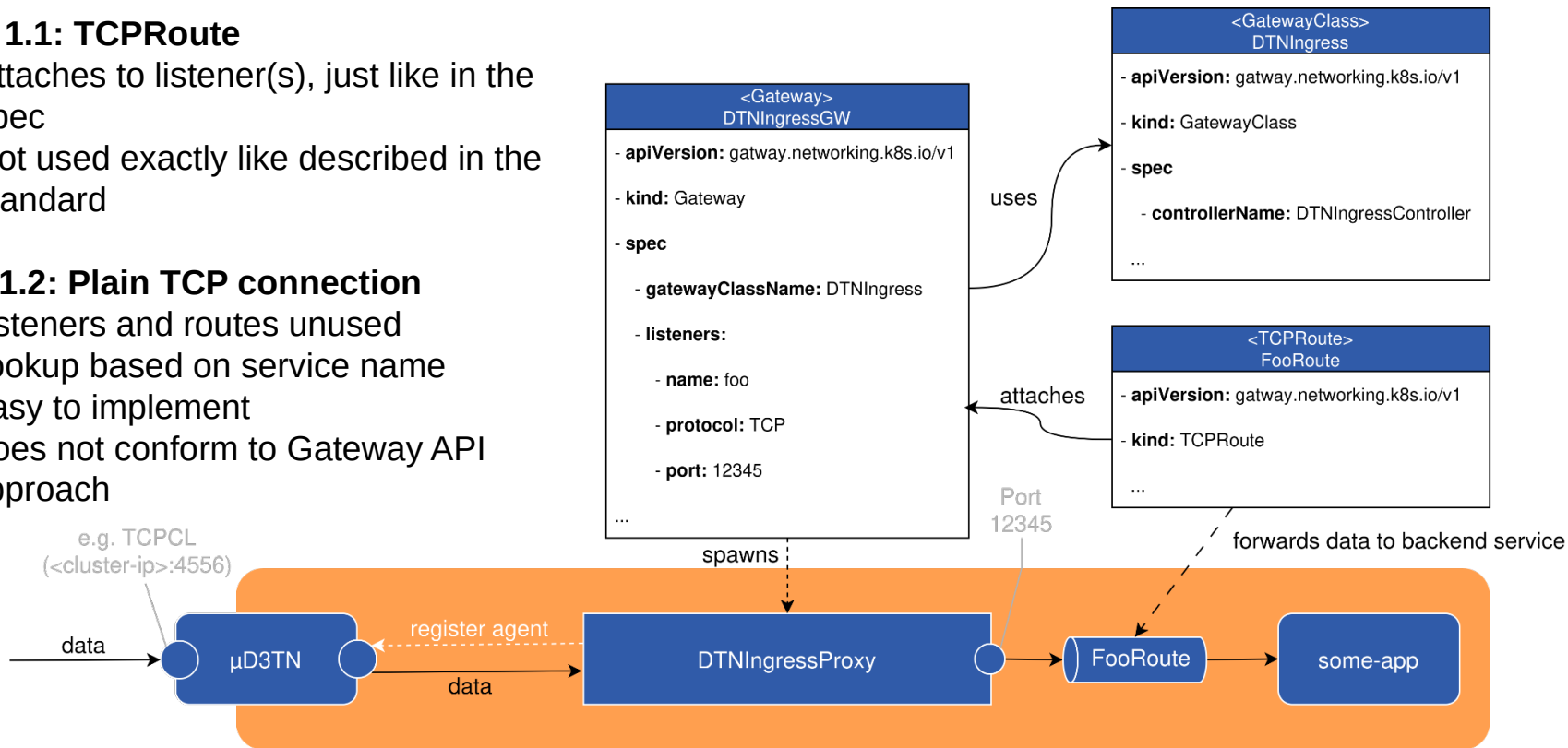
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Option 1.1: TCPRoute

- ▶ Attaches to listener(s), just like in the spec
- ▶ Not used exactly like described in the standard

Option 1.2: Plain TCP connection

- ▶ Listeners and routes unused
- ▶ Lookup based on service name
- ▶ Easy to implement
- ▶ Does not conform to Gateway API approach



Integrating K8s and DTN



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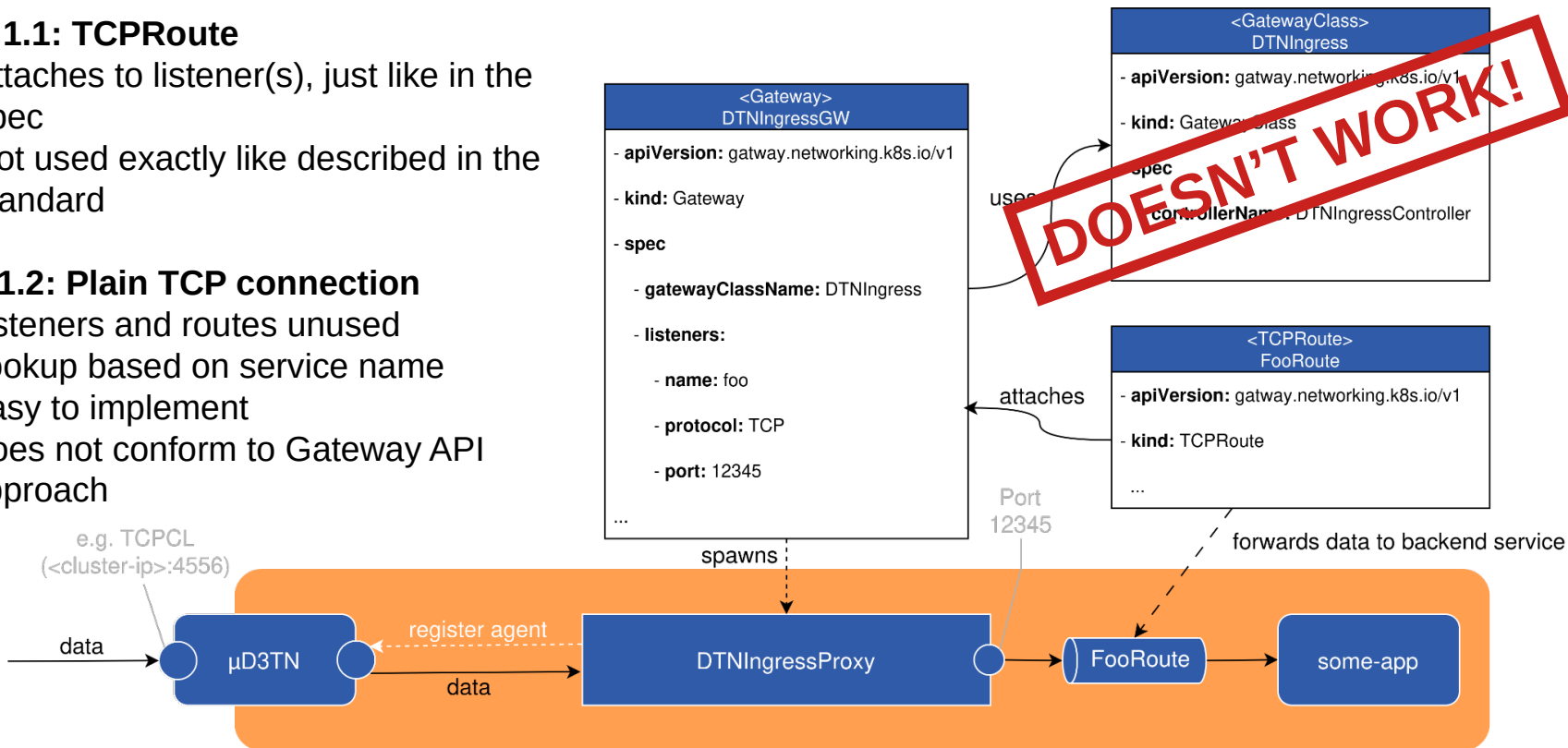
Allowing applications to communicate over a DTN

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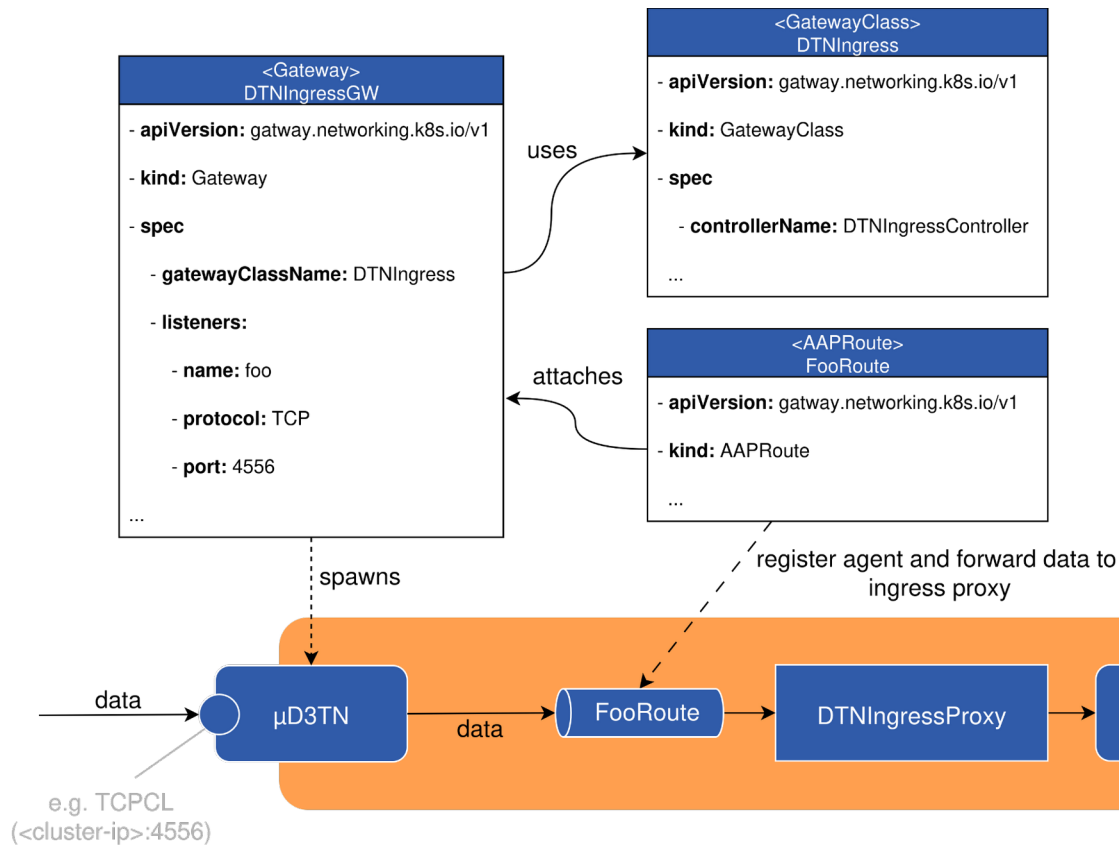
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Allowing applications to communicate over a DTN



Option 2: μD3TN = Gateway

- ▶ Gateway spawns μD3TN
- ▶ Listeners used correctly
- ▶ No support for DTN protocols
- ▶ Requires custom route type (AAPRoute)

Integrating K8s and DTN

Allowing applications to communicate over a DTN

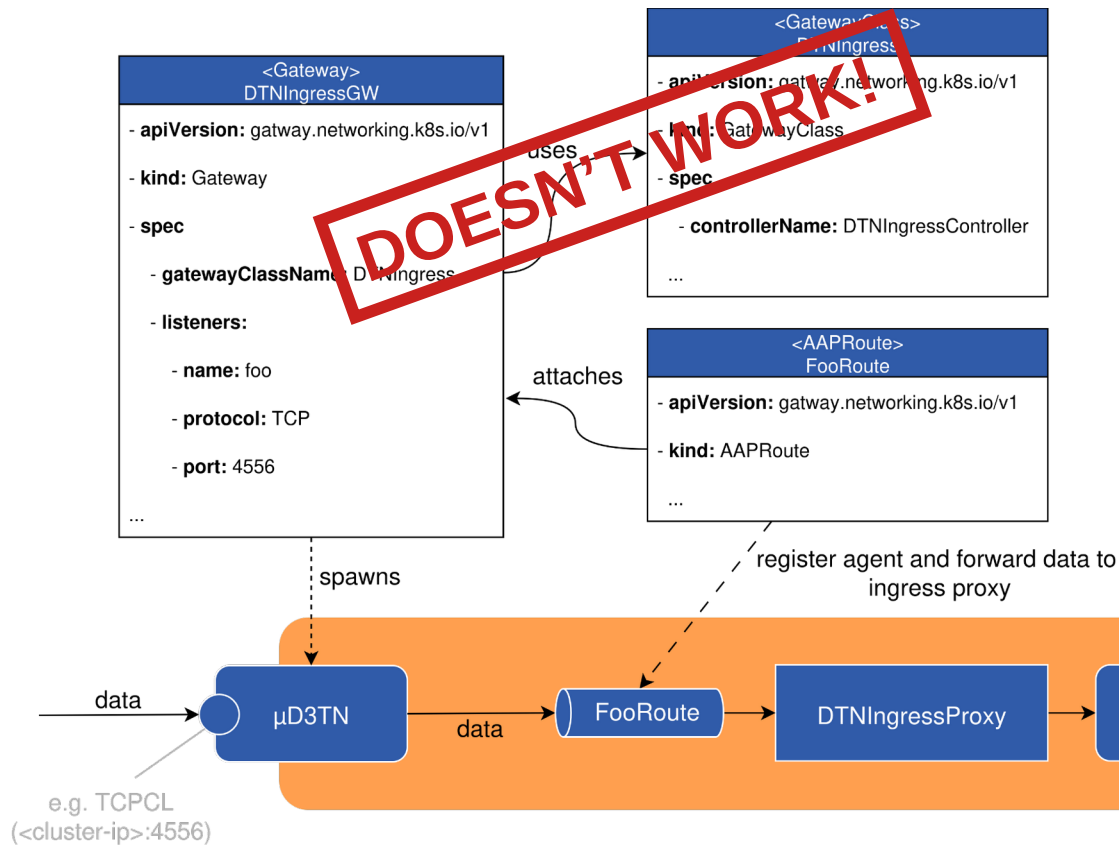


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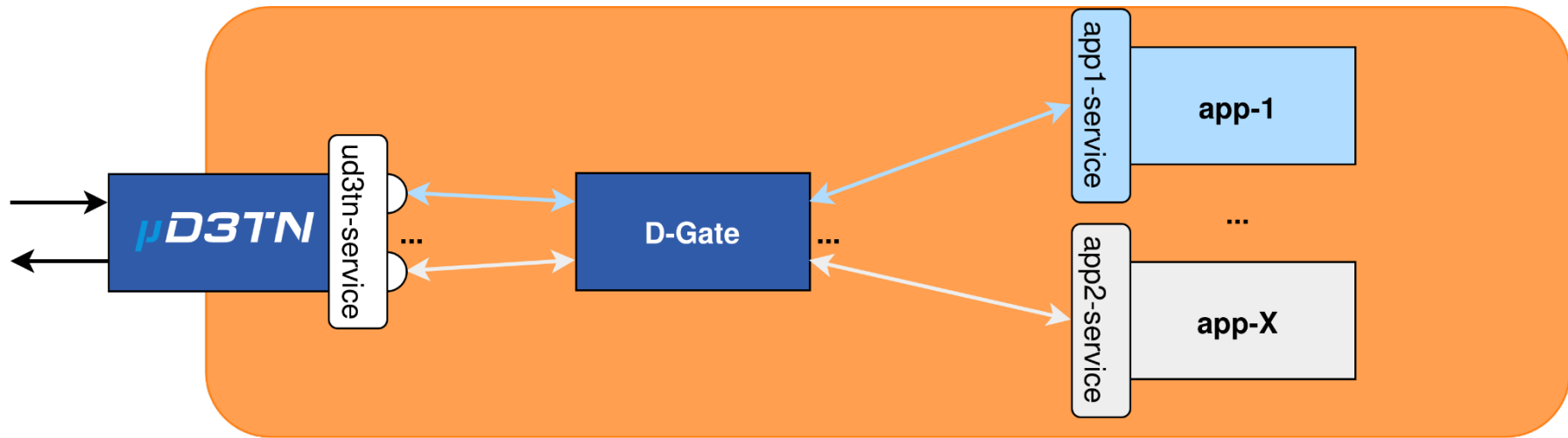


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Option 3: D-Gate (DARKSOL-Gateway)

- ▶ CRD providing an ingress/egress solution
- ▶ Registers agents with μ D3TN and forwards data received at these agents to the correct backend applications
- ▶ Applications can use the same connection to send data back out

Link to a previous Tech-Talk going into more detail about the predecessor of the D-Gate —→



Integrating K8s and DTN

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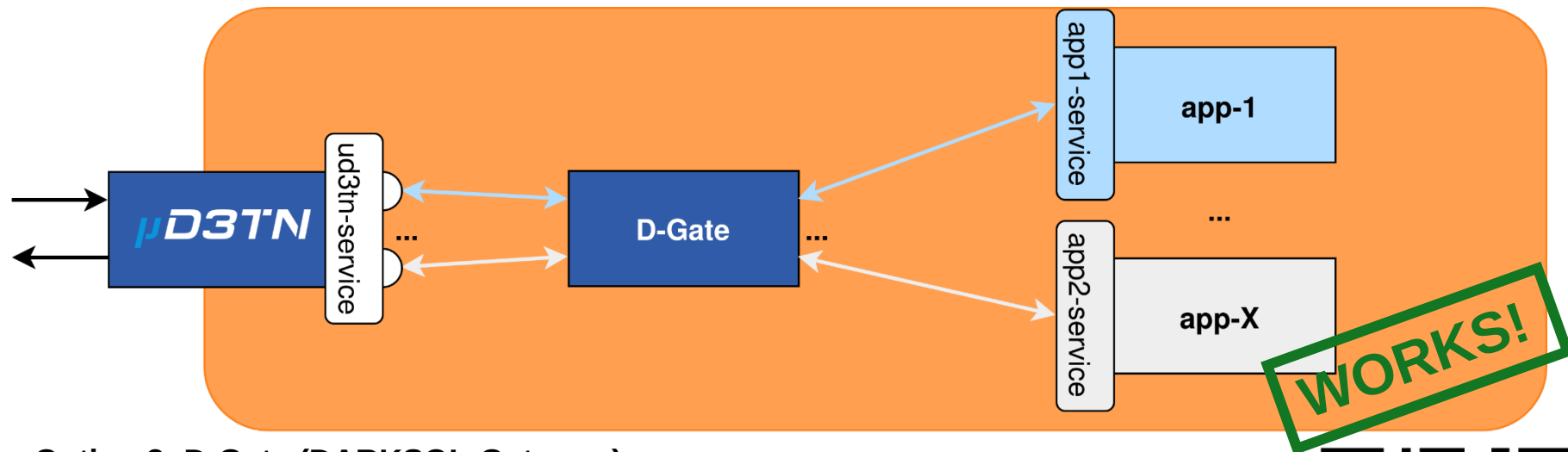


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Key Takeaways & Future Work



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Key takeaways:

- ▶ Networking in space poses challenges not usually encountered on Earth
- ▶ Addressing these challenges through the use of DTN opens up possibilities for cloud-native application deployment even in deep space
- ▶ However, clusters spanning multiple planets remain impossible due to tight coupling of K8s components and the need for timely responses (e.g. heartbeats)

Future work:

- ▶ **Platform-related work:** Autonomous deployment and upgrades of the Kubernetes environment
- ▶ **Security-related work:** Strong tenant separation, node & workload attestation
- ▶ **DTN-related work:** Opportunistic discovery of clusters
- ▶ **Practical exploration:** Exploration of project components in space-terrestrial internetworking scenarios using satellites deployed and operated by ESA to gain further insights into the overall applicability



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