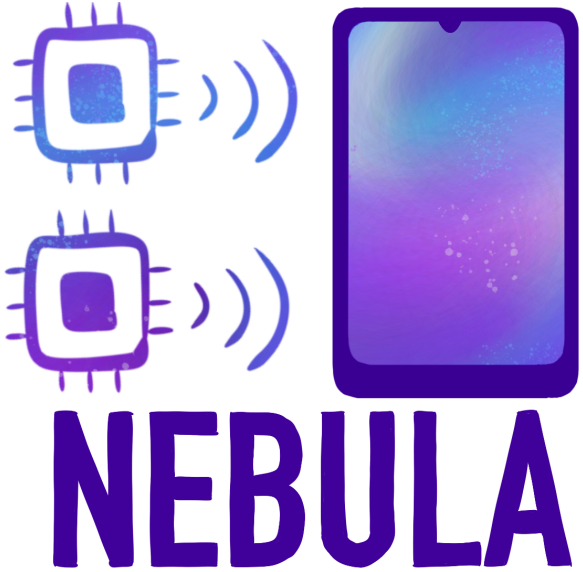
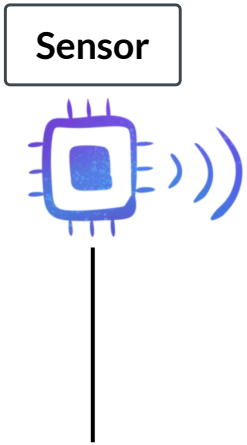


A Privacy-First Platform for Data Backhaul

Jean-Luc Watson, Tess Despres, Alvin Tan, Shishir Patil
Prabal Dutta, Raluca Ada Popa

UC Berkeley

Goal: enable sensor deployments **at large scale**



Air quality measurement **on every block**
Public infrastructure use **throughout a city**
Wildlife counting **over square miles**
Package tracking **at every stop**

Problem: data backhaul for useful applications

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Scientific studies
City planners
Conservation agency
Shipping customers

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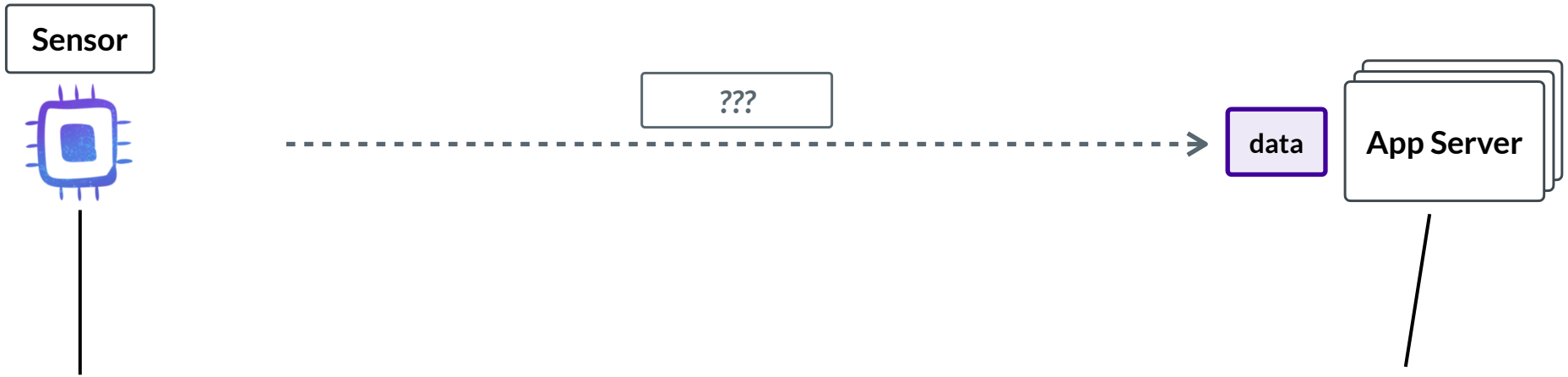

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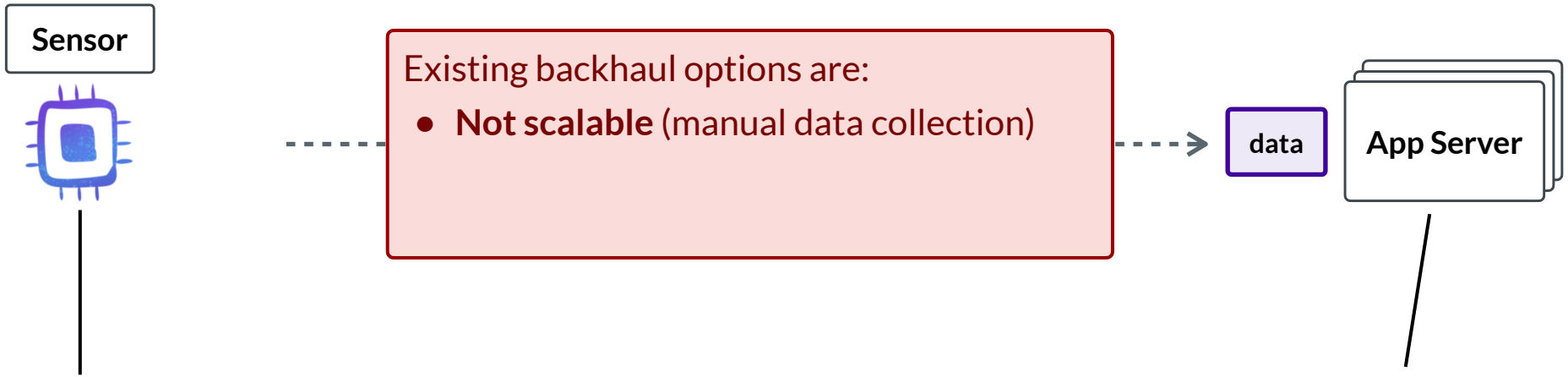

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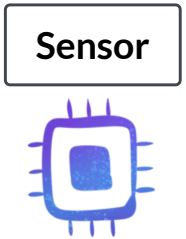

Existing backhaul options are:

- **Not scalable** (manual data collection)
- **Expensive** (app-specific base stations)

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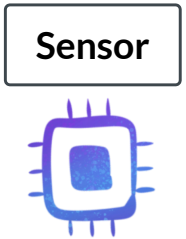

Existing backhaul options are:

- **Not scalable** (manual data collection)
- **Expensive** (app-specific base stations)
- **Power-hungry** (cellular radios)

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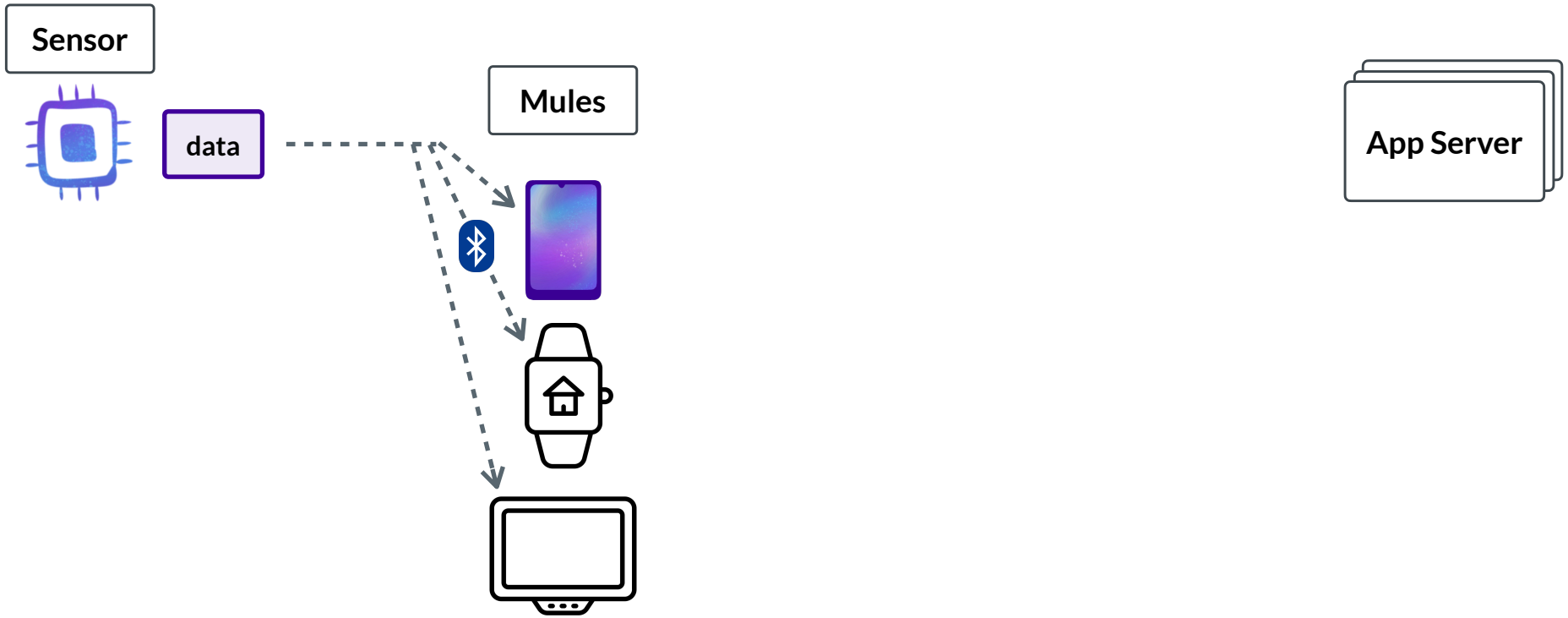
Instead, 'mules' in close proximity could gather data



[icons by Icons Field from Noun Project]

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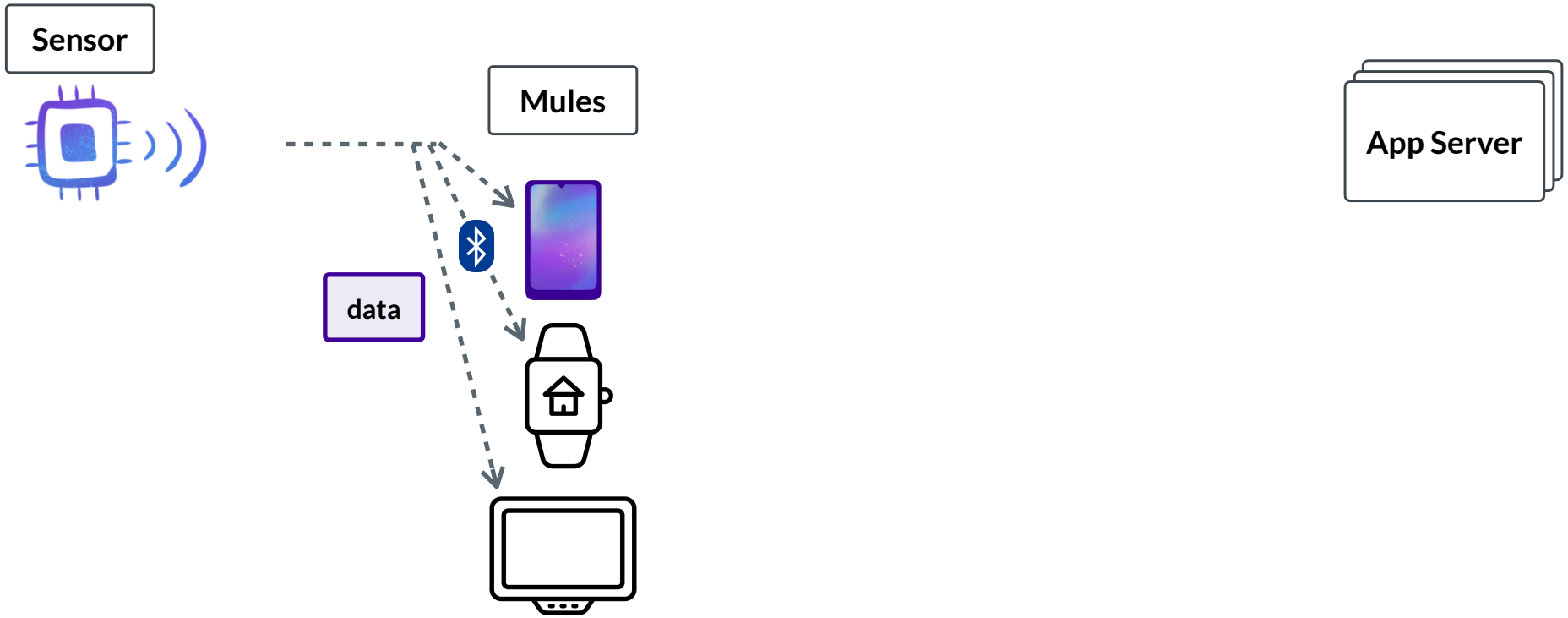
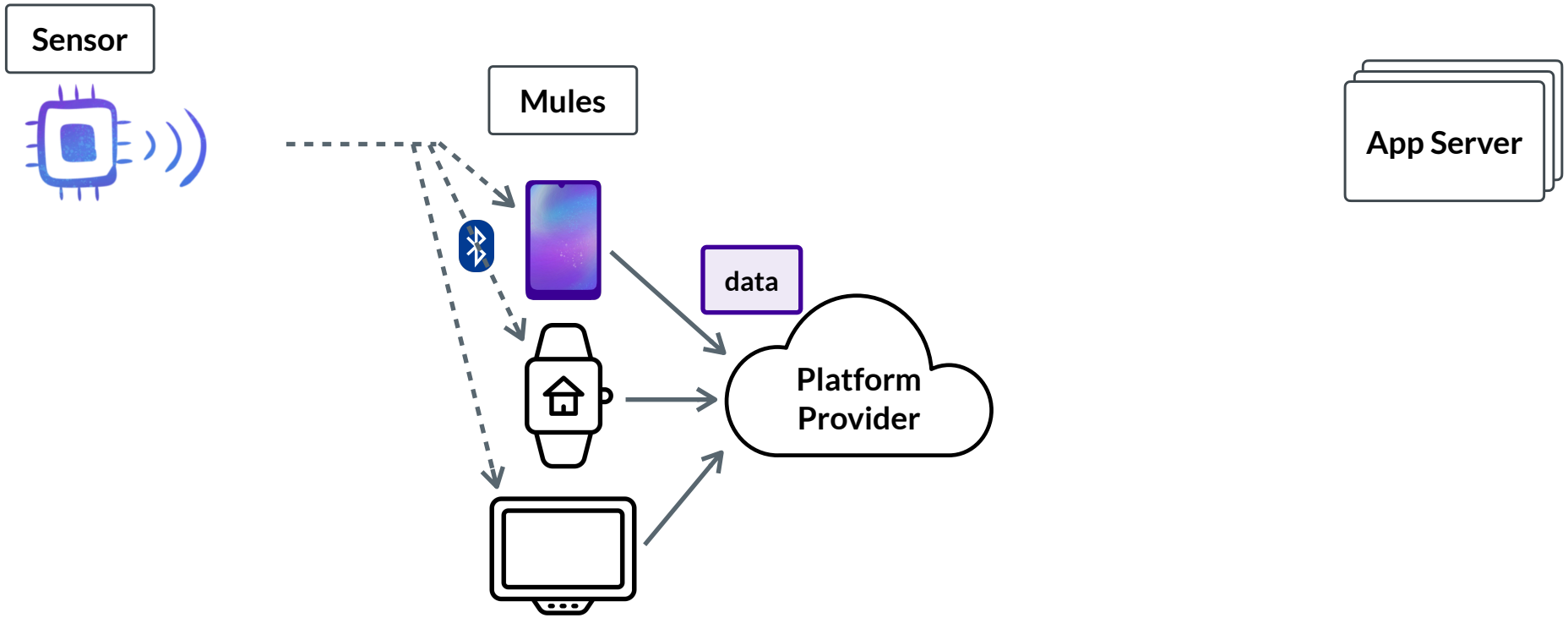


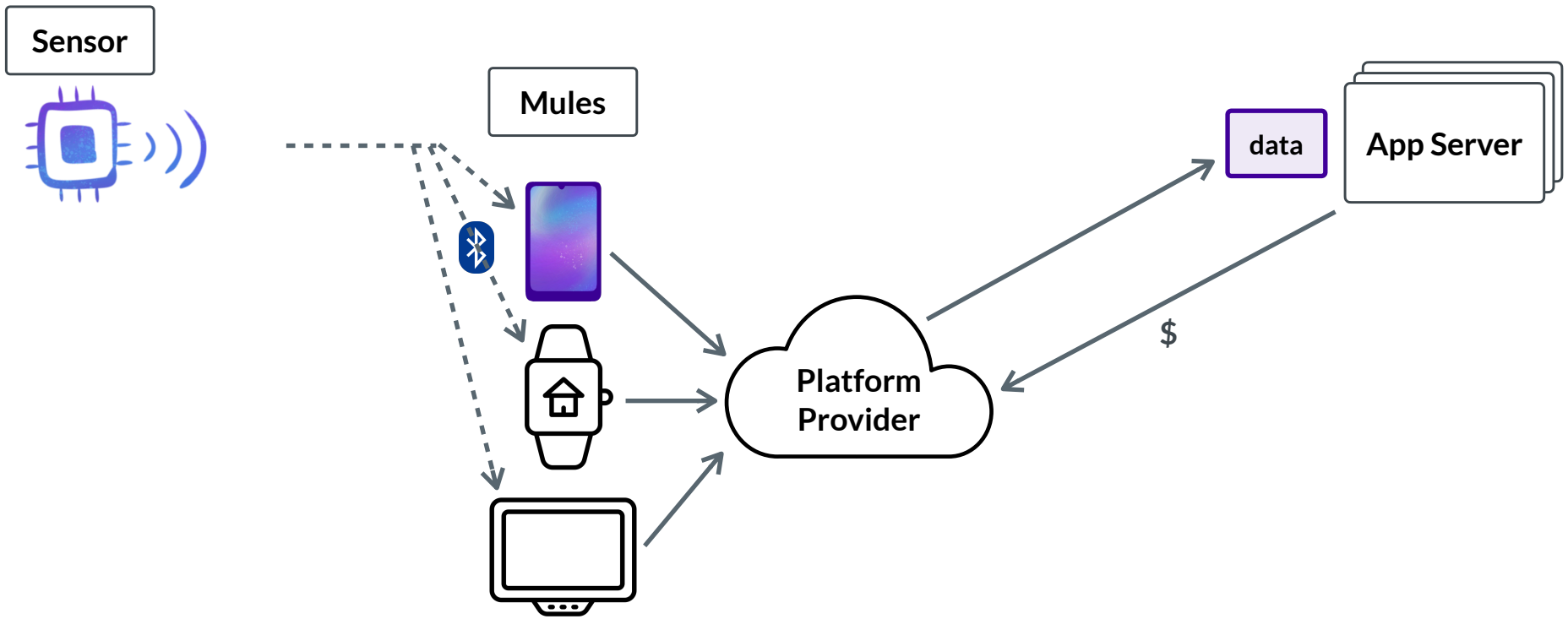
[icons by Icons Field from Noun Project]

Mules send data to a backhaul provider



[icons by Icons Field from Noun Project]

The provider forwards to paying servers

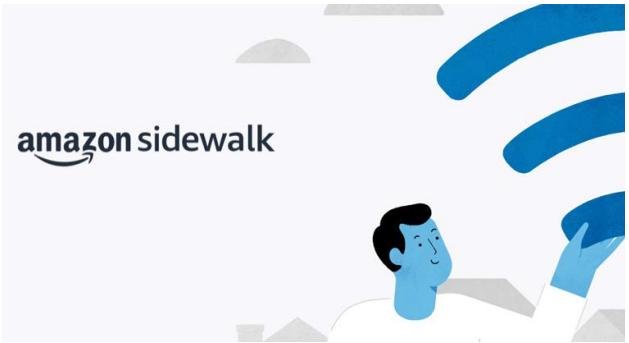


[icons by Icons Field from Noun Project]

The provider forwards to paying servers

Sensor

Backhaul systems are *already* being deployed

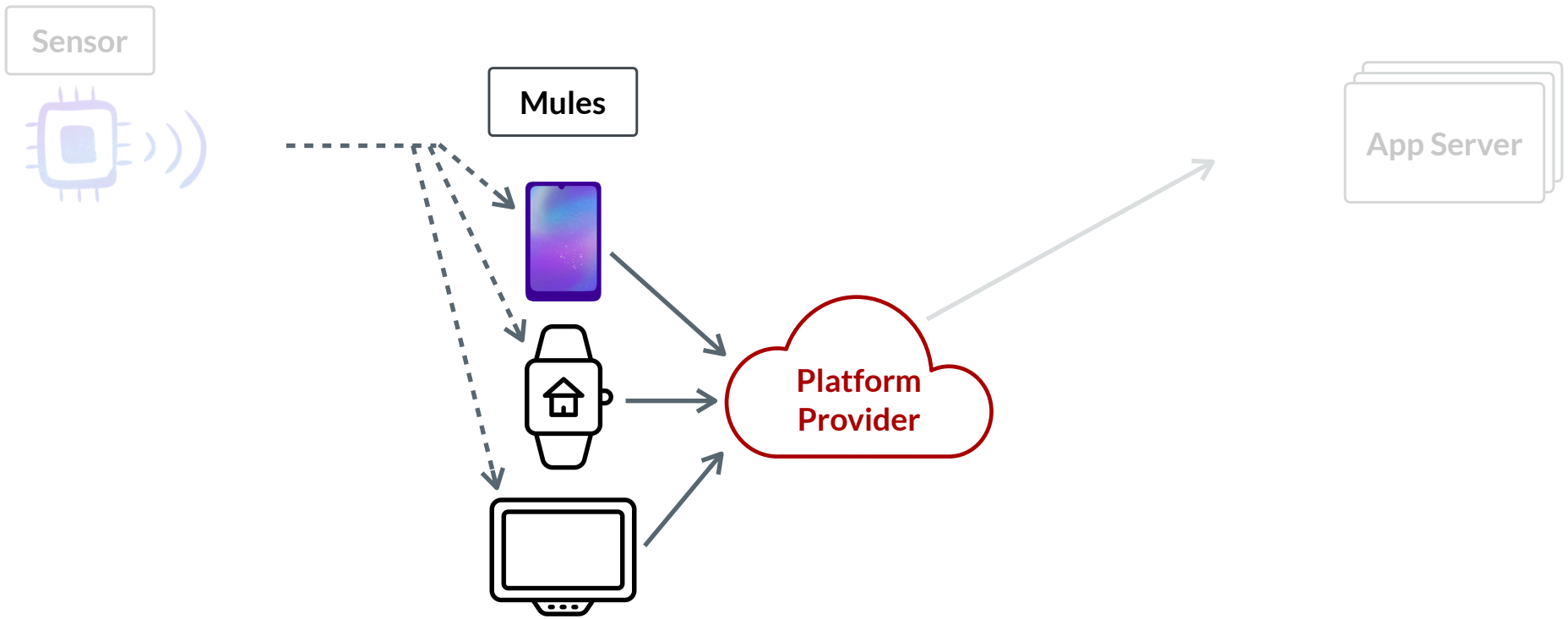


Find My

Exposure Notification

[icons by Icons Field from Noun Project]

Centralized backhaul threatens privacy



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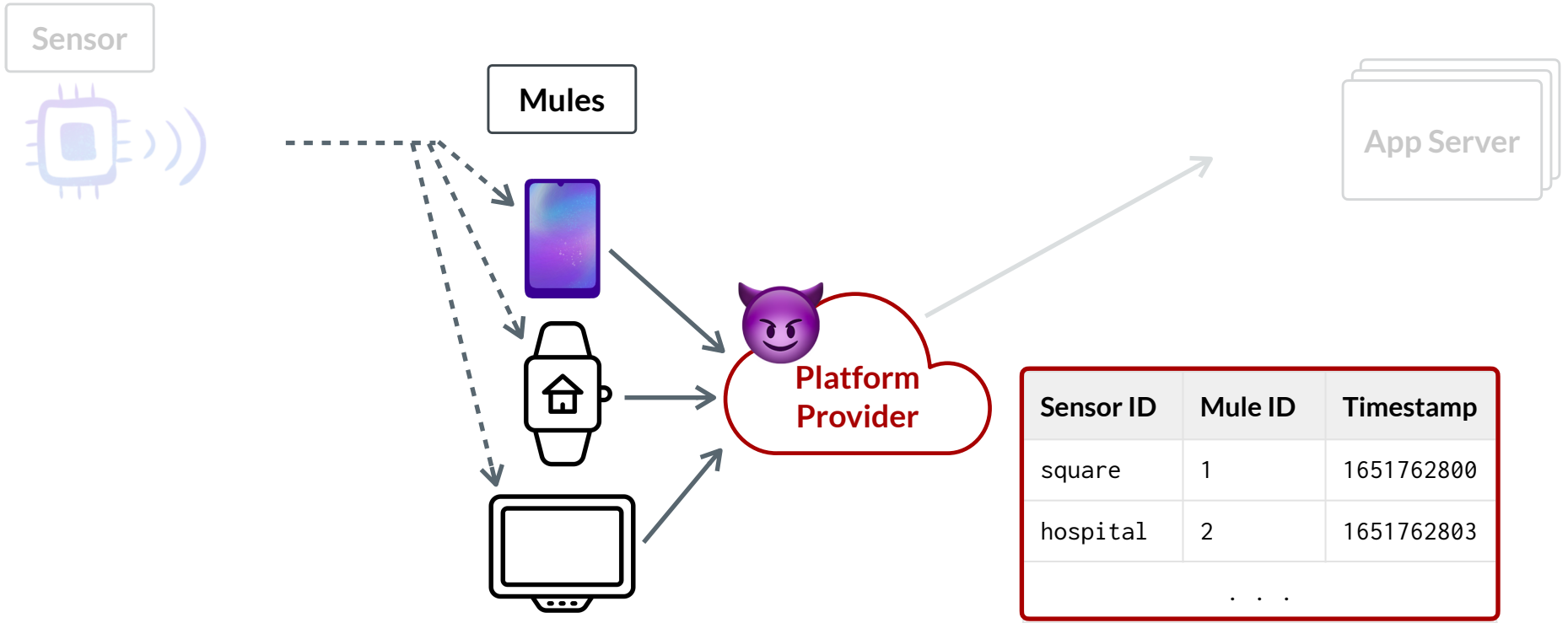
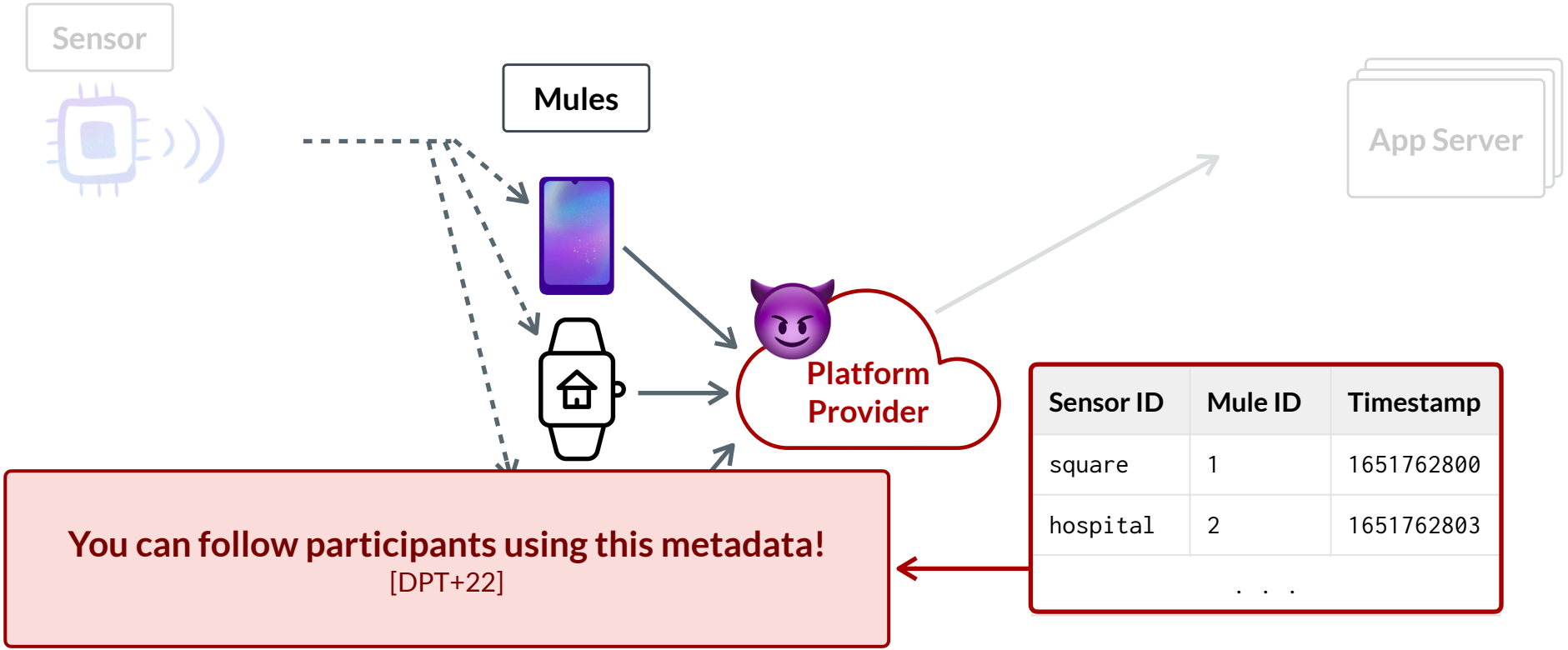


Sensor ID	Mule ID	Timestamp
square	1	1651762800
hospital	2	1651762803
. . .		

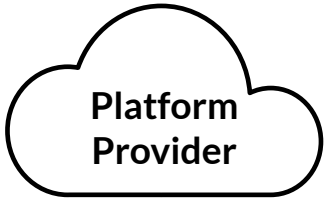
[icons by Icons Field from Noun Project]

Centralized backhaul threatens privacy



[icons by Icons Field from Noun Project]

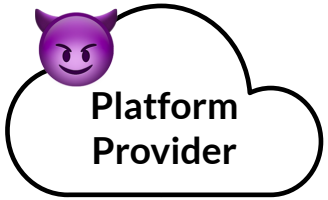
Challenge: maintaining usability



General-purpose
Scalability
Preventing misuse
Payment
Privacy

Challenge: maintaining usability

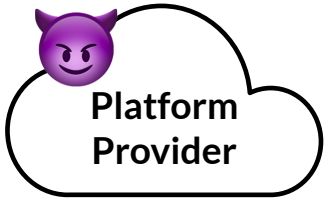
Provider can run a **general-purpose** service that is not private



	Sidewalk
General-purpose	✅
Scalability	✅
Preventing misuse	✅
Payment	✅
Privacy	❌

Challenge: maintaining usability

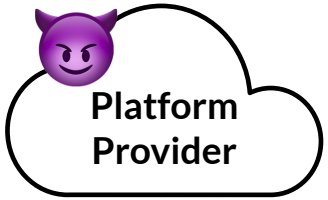
Provider can run a **private** service if it limits application scope



	Sidewalk	FindMy
General-purpose	✅	❌
Scalability	✅	✅
Preventing misuse	✅	❌
Payment	✅	❌
Privacy	❌	✅*

Challenge: maintaining usability

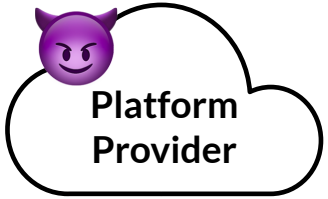
Provider can run a **private and general-purpose** service but not at scale



	Sidewalk	FindMy	Private communication [Chaum88, HLZ+15, ECG+21] Anonymous sensors [CKD+08, KTC+08]
General-purpose	✅	❌	✅
Scalability	✅	✅	❌
Preventing misuse	✅	❌	✅
Payment	✅	❌	❌
Privacy	❌	✅*	✅

Challenge: maintaining usability

Nebula accomplishes each of these at the same time



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NEBULA

A backhaul system that *preserves mule privacy* while:

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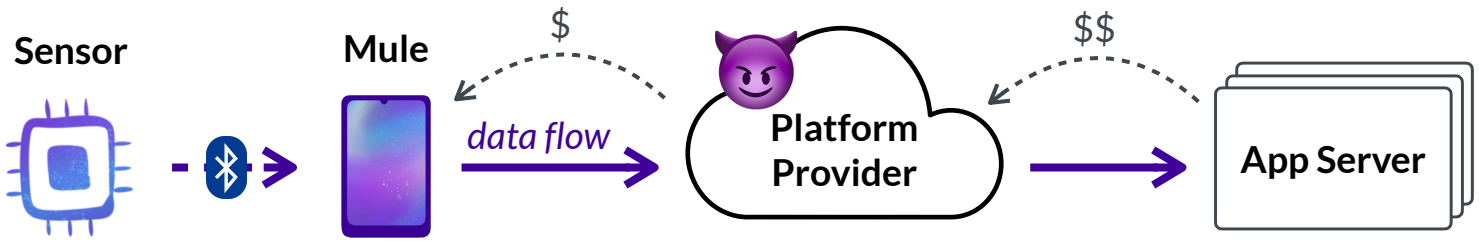
Nebula’s approach: decentralize protocol onto mules



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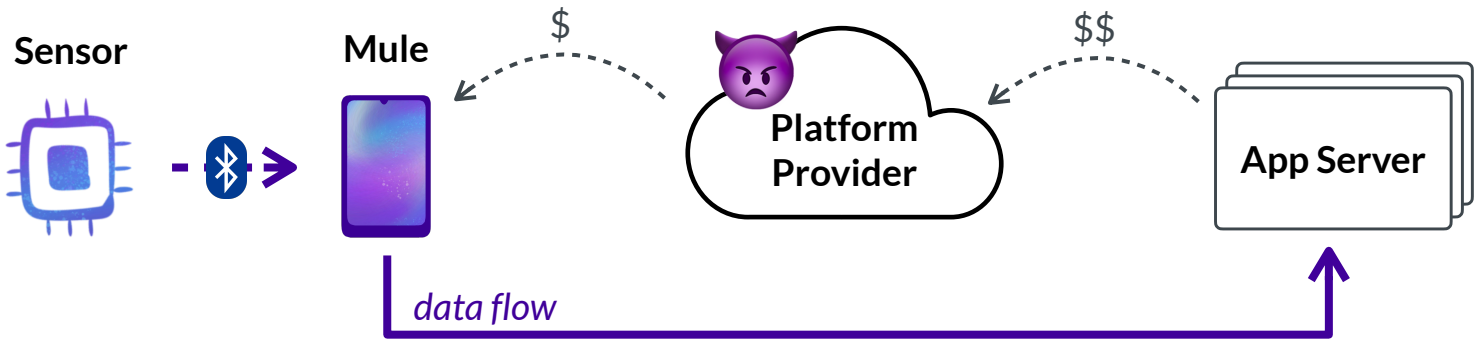

Core Design: Tokens

- System usage is tracked with PrivacyPass [DGS+18] **tokens** 
  - *Unlinkable*: when tokens are redeemed to a malicious server, cannot be linked to the client(s) that generated them

[icons by Chunk Icons from Noun Project]

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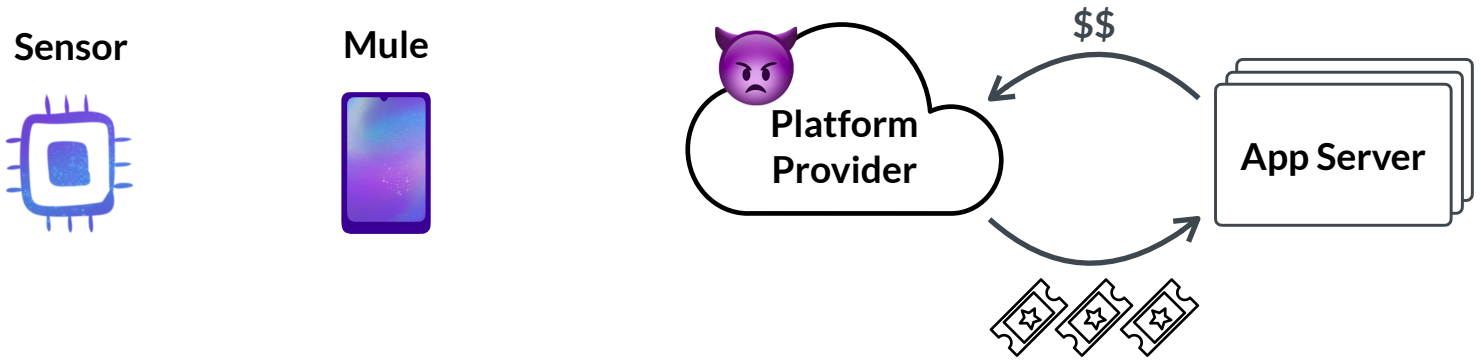
    Only way to acquire more tokens is to participate in backhaul

[icons by Chunk Icons from Noun Project]

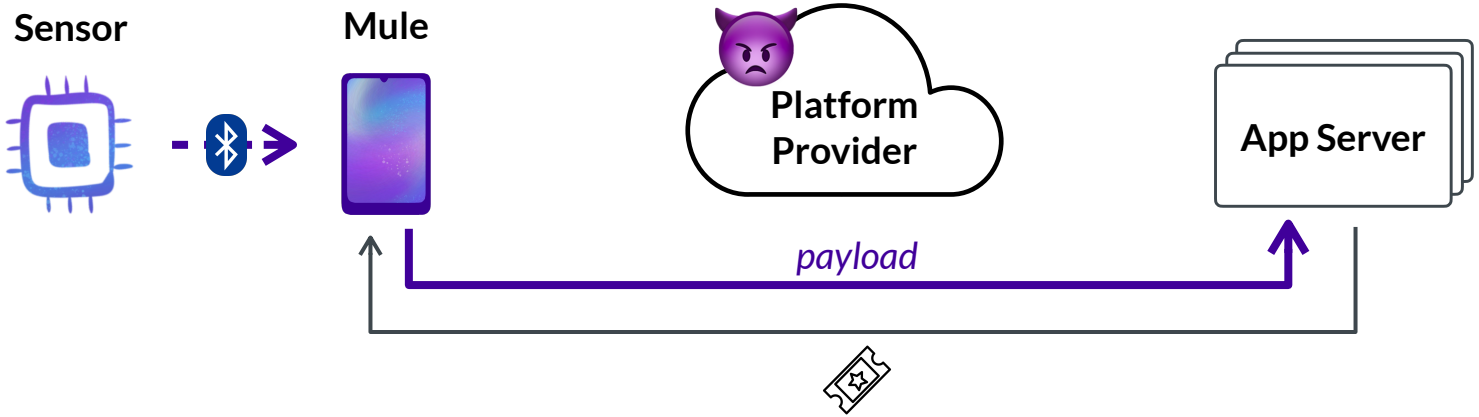
(1) Token Pre-purchase

- At the beginning of an epoch, app servers *pre-purchase* tokens from the provider



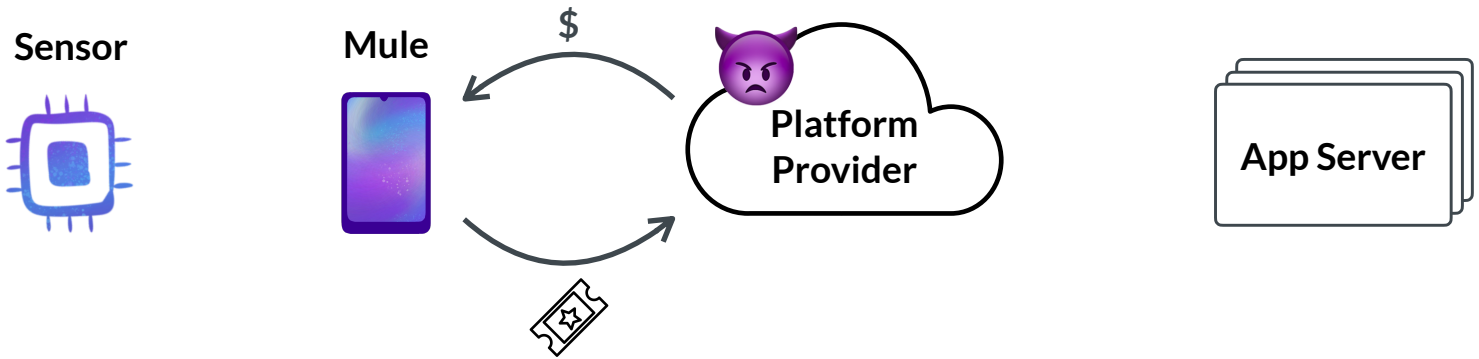
(2) Payload Delivery

- Mules send data directly to application servers over anonymous connections and receive tokens in exchange



(3) Token Redemption

- At the end of an epoch, mules redeem tokens with the platform provider in exchange for compensation



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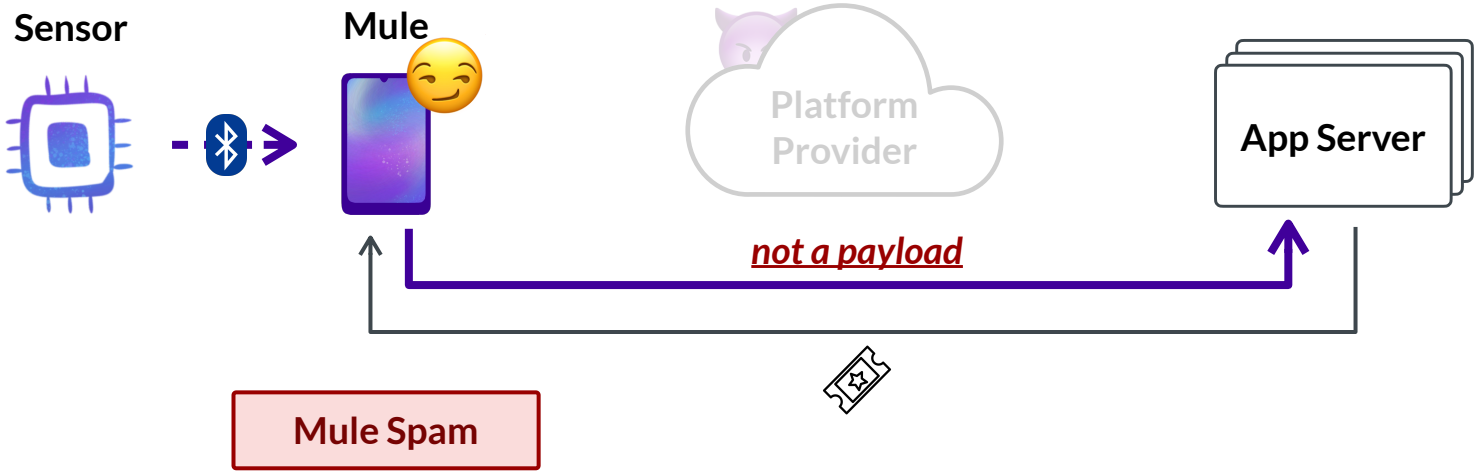
Big problem: **delivery misbehavior**



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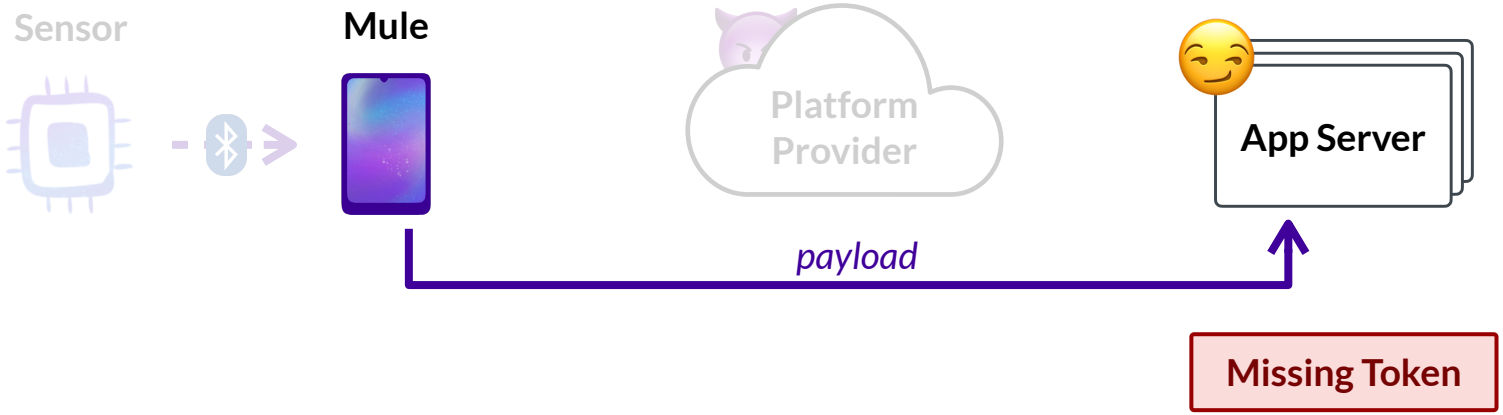

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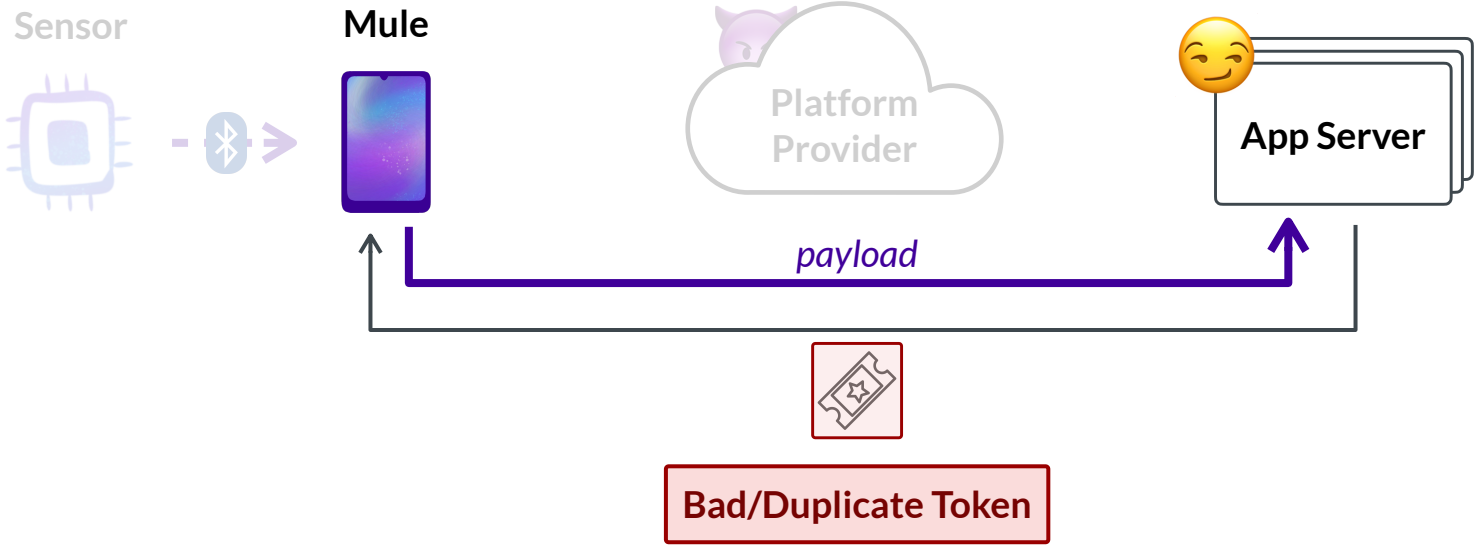
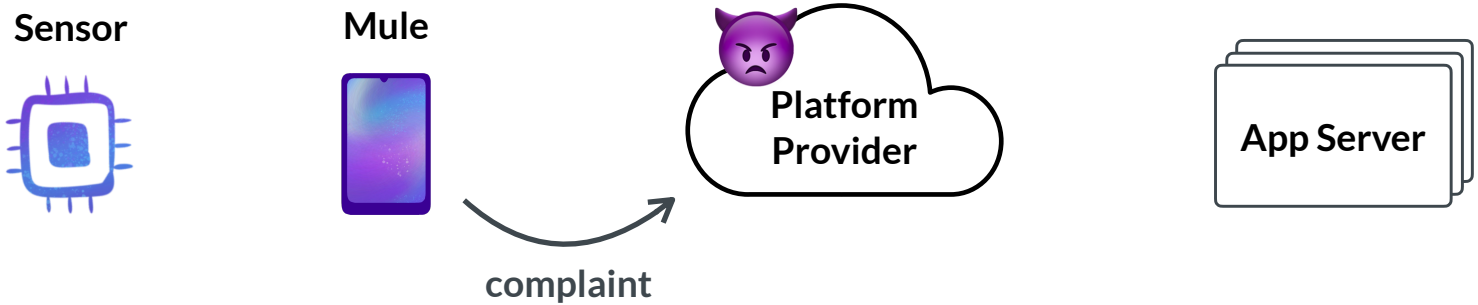


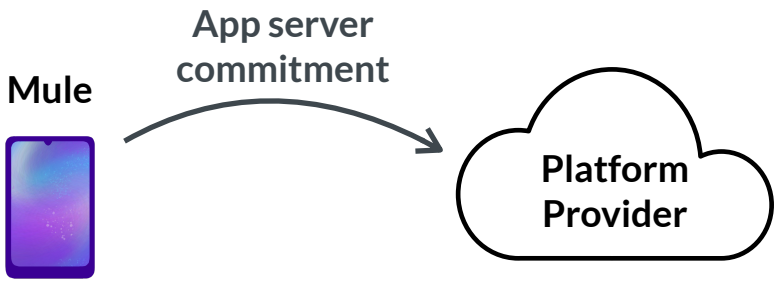
(4) Complaint

- After an epoch, if a mule notices misbehavior (e.g. invalid token), it can *complain* to the provider for a new one



Complaints are based on app server commitments

Before receiving data, app servers commit to token they will use if payload is uploaded



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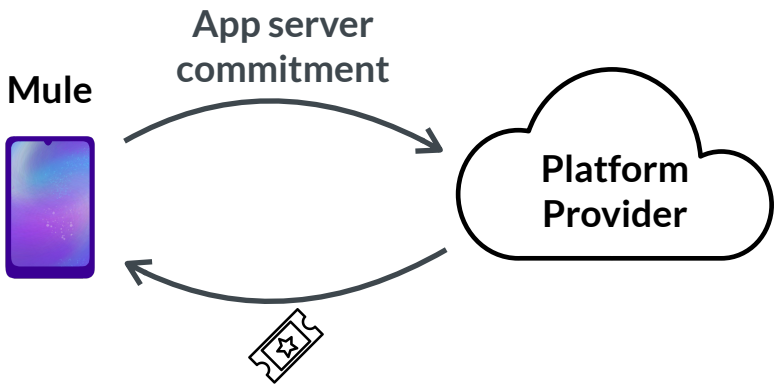
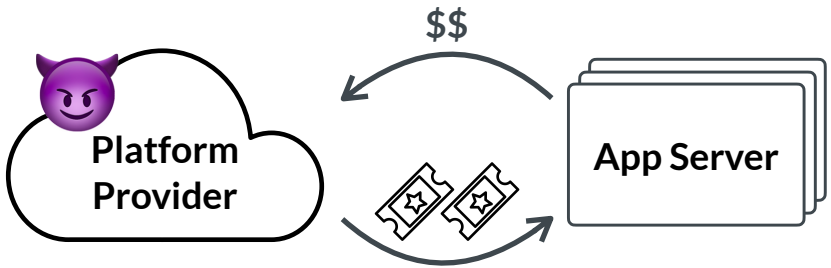
A *new* token is granted for *proof of misbehavior*



Privacy guarantees



Overall, the provider learns:

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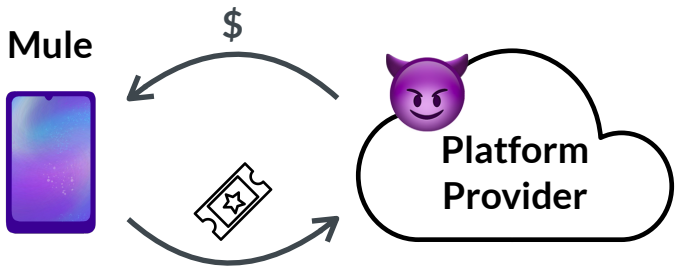
Privacy guarantees



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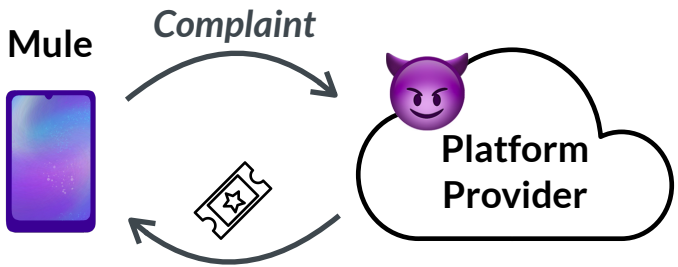

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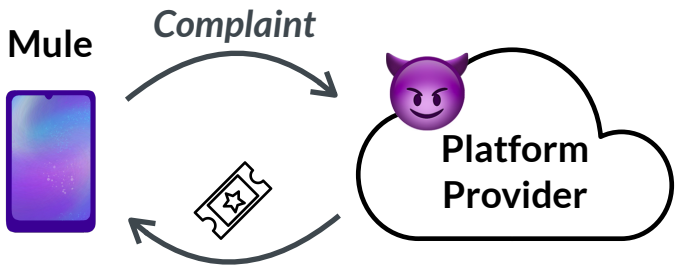

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Formal Proof Sketch in Paper

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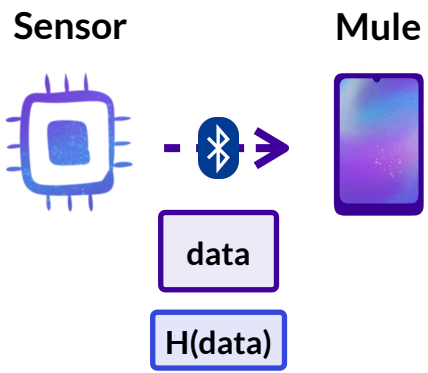
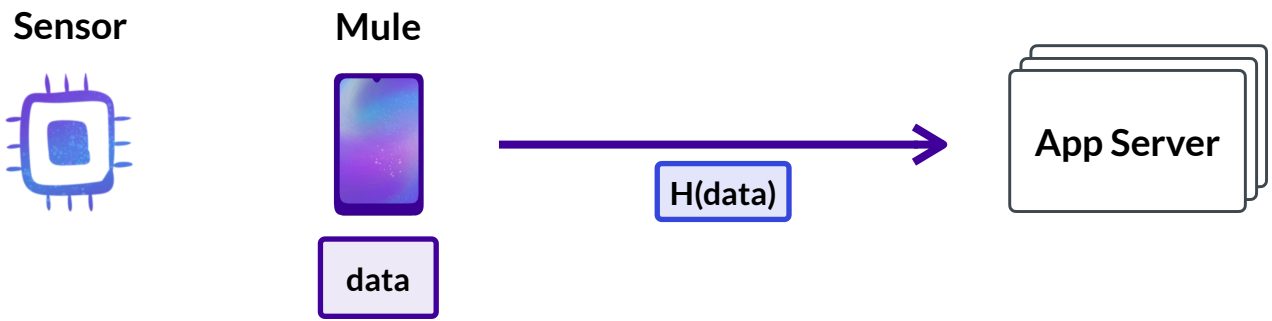
Delivery in Detail

(1) Mule encounters and authenticates a sensor, receiving a E2E-encrypted payload and a *sensor-signed payload hash*



Delivery in Detail

(2) Mule sends signed hash to desired application server. Server checks hash and decides whether they want the payload.



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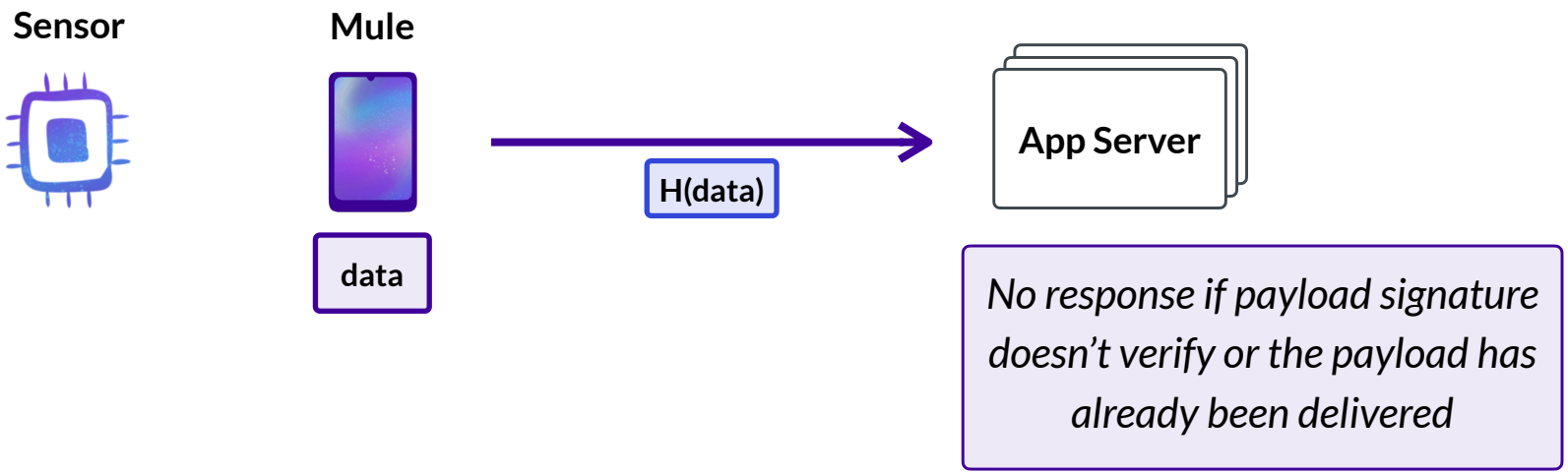
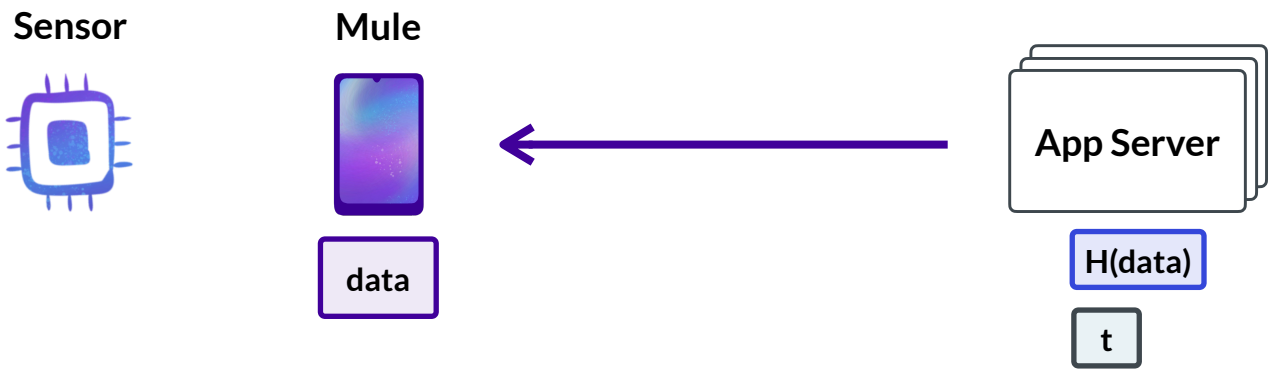


Delivery in Detail

(3) If the server would like the payload, they sign a **commitment** to the hash and an encrypted token they are willing to spend in exchange



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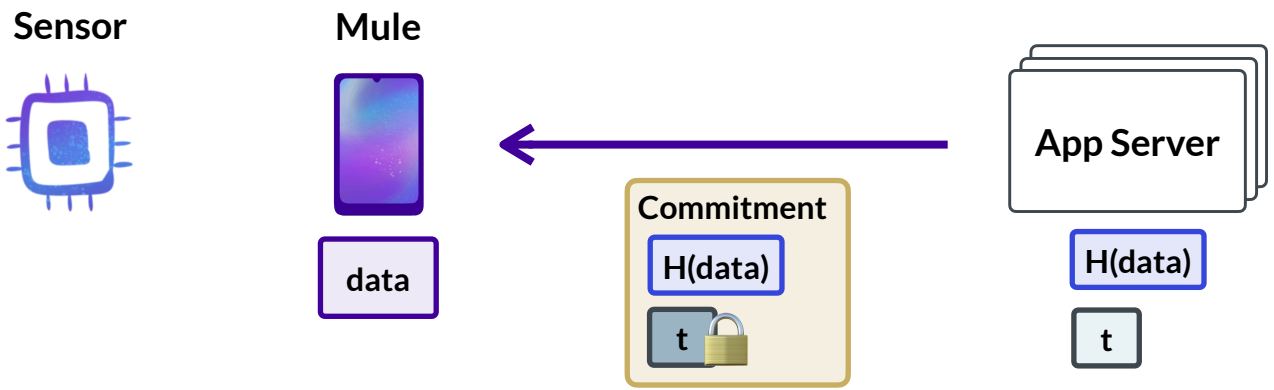
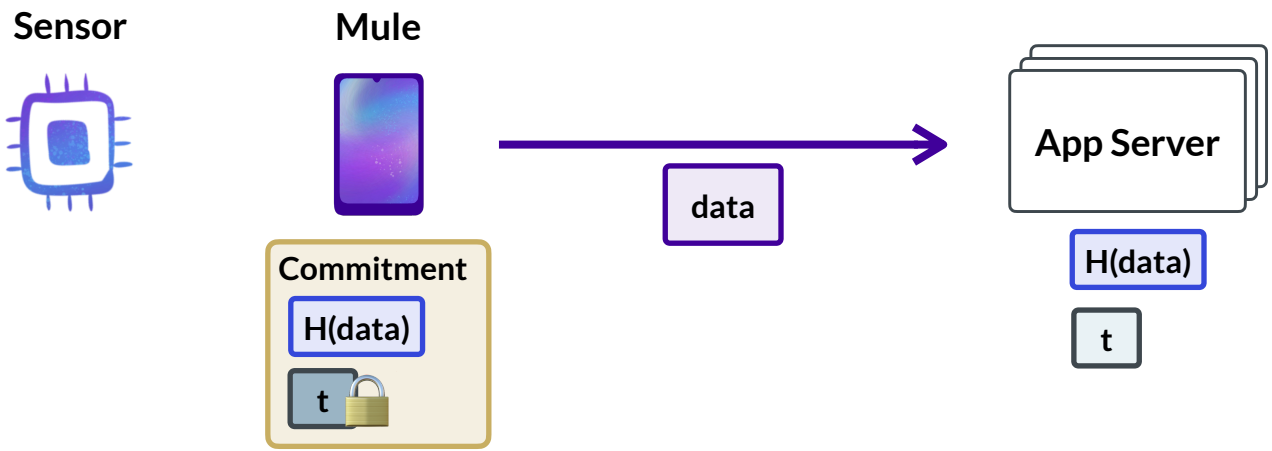


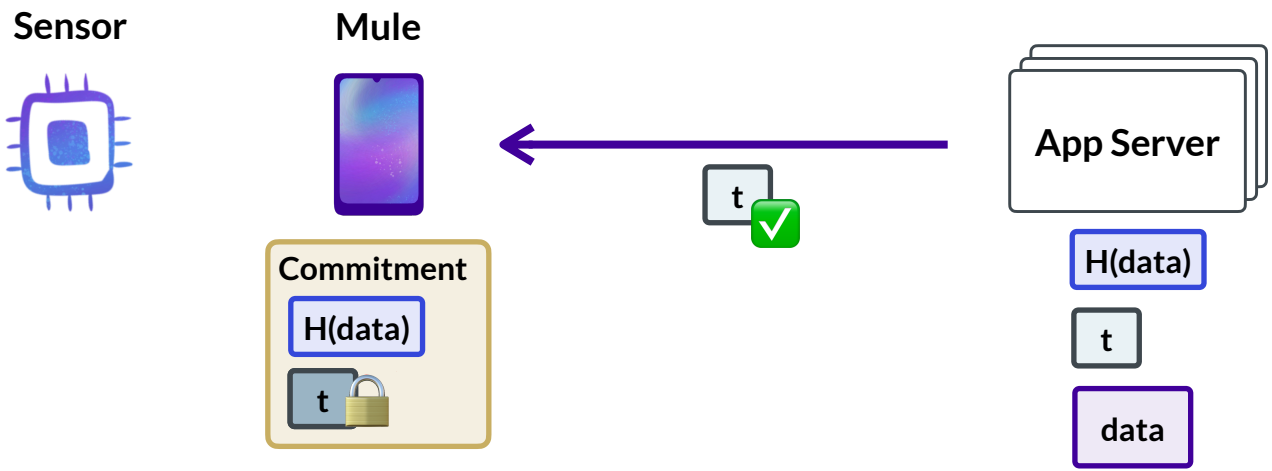
Delivery in Detail

(4) Commitment in hand, the mule sends the actual payload to the app server.



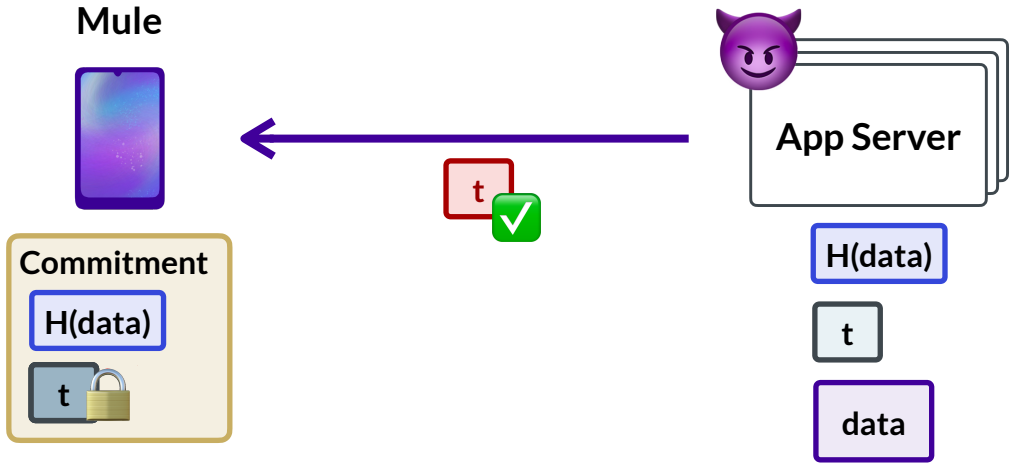
Delivery in Detail

(5) The server checks the data against the hash it previously got; if successful, it signs a response containing the unencrypted token



Complaints in Detail

What happens if the mule gets a bad token, or no token at all?



Complaints in Detail

Provider will notify mule of duplicate/invalid tokens it redeems at end of epoch

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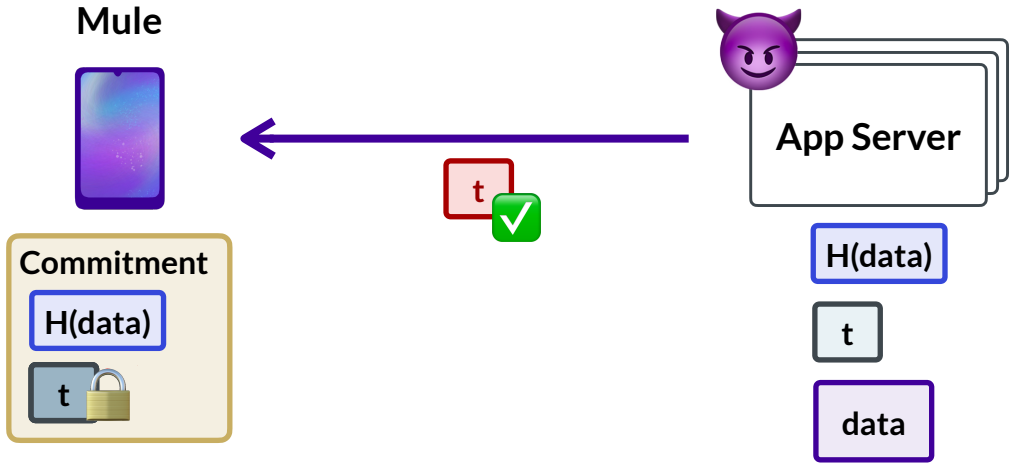
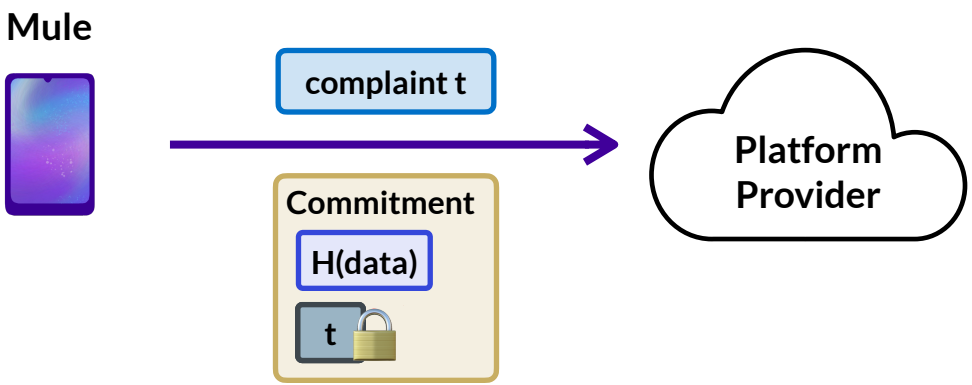


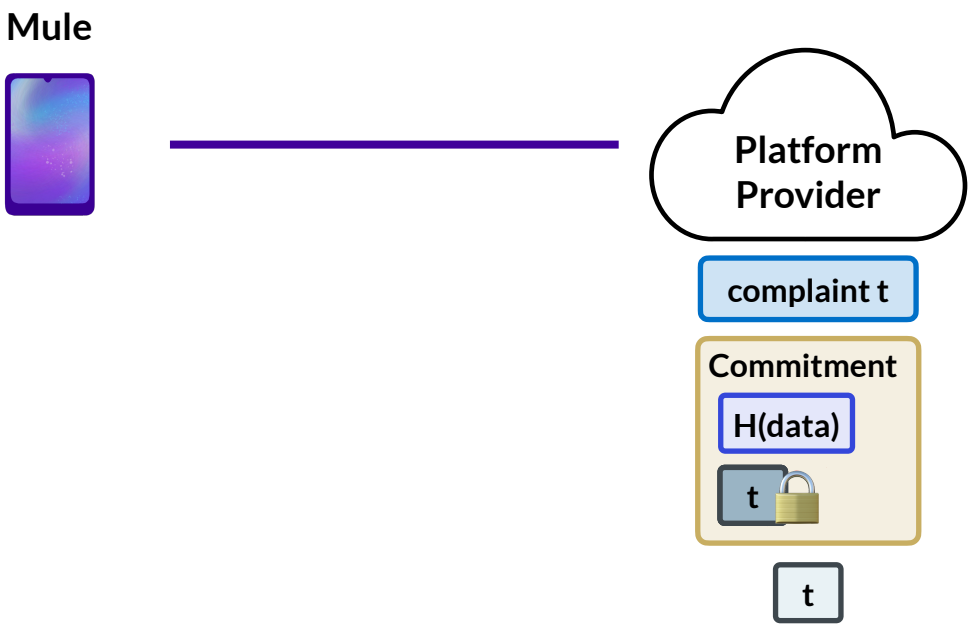
Complaints in Detail

(1) At end of epoch, mule will send a complaint token and commitment to provider



Complaints in Detail

(2) Provider will check complaint token, then decrypt and verify the delivery token, invalidating it



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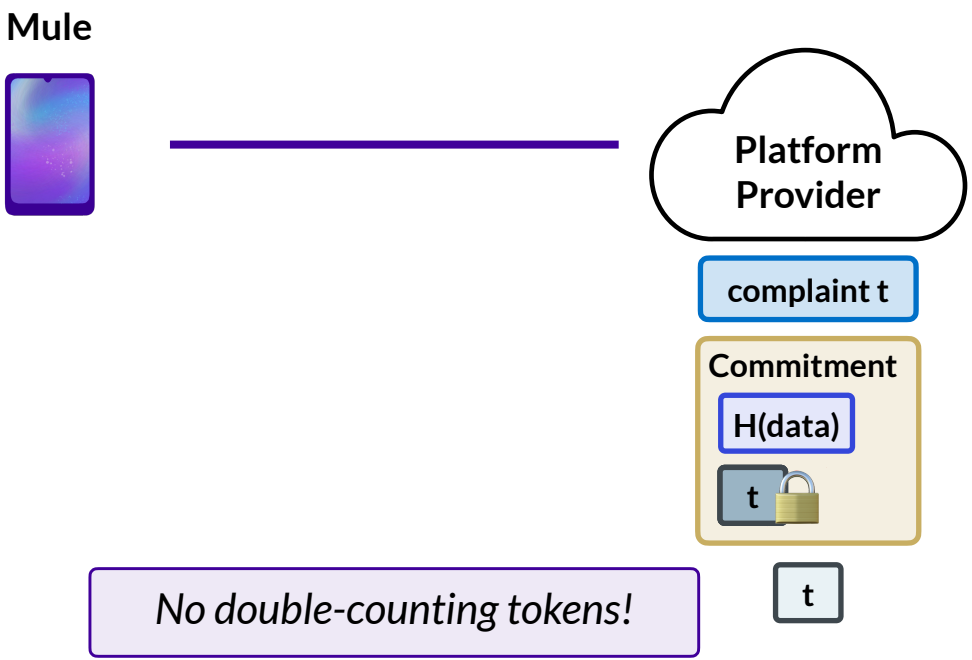
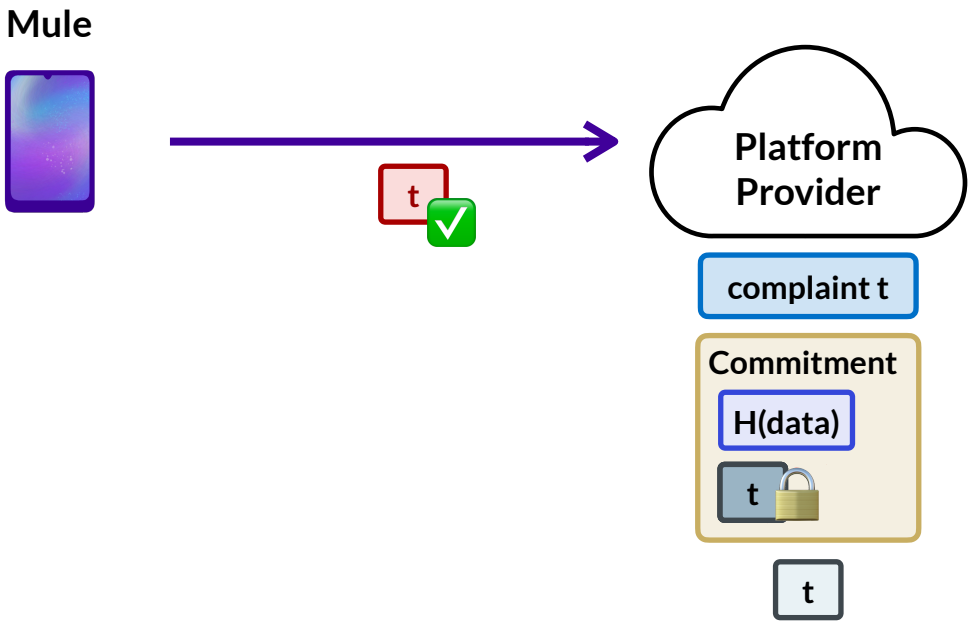


Complaints in Detail

(3) If the token was rejected by the platform provider (wrong or a duplicate), the mule sends over the signed token it got from the app server



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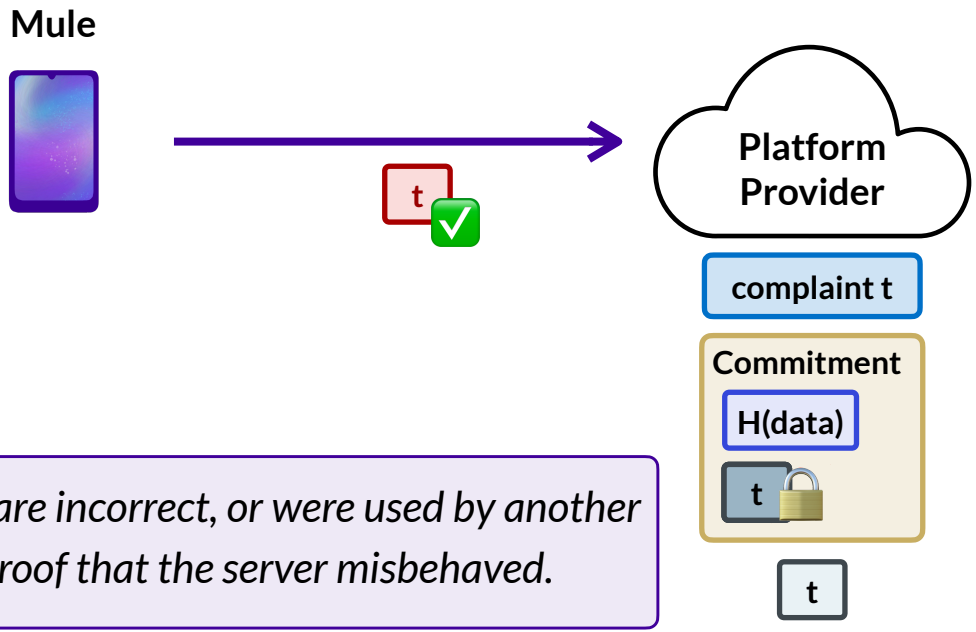
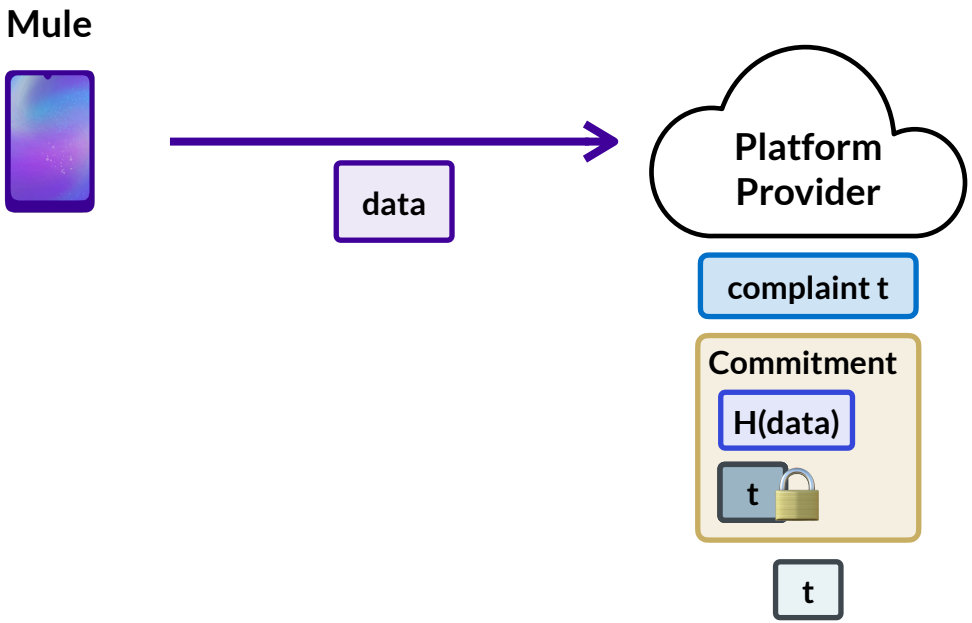


If the tokens mismatch, are incorrect, or were used by another payload, we have proof that the server misbehaved.

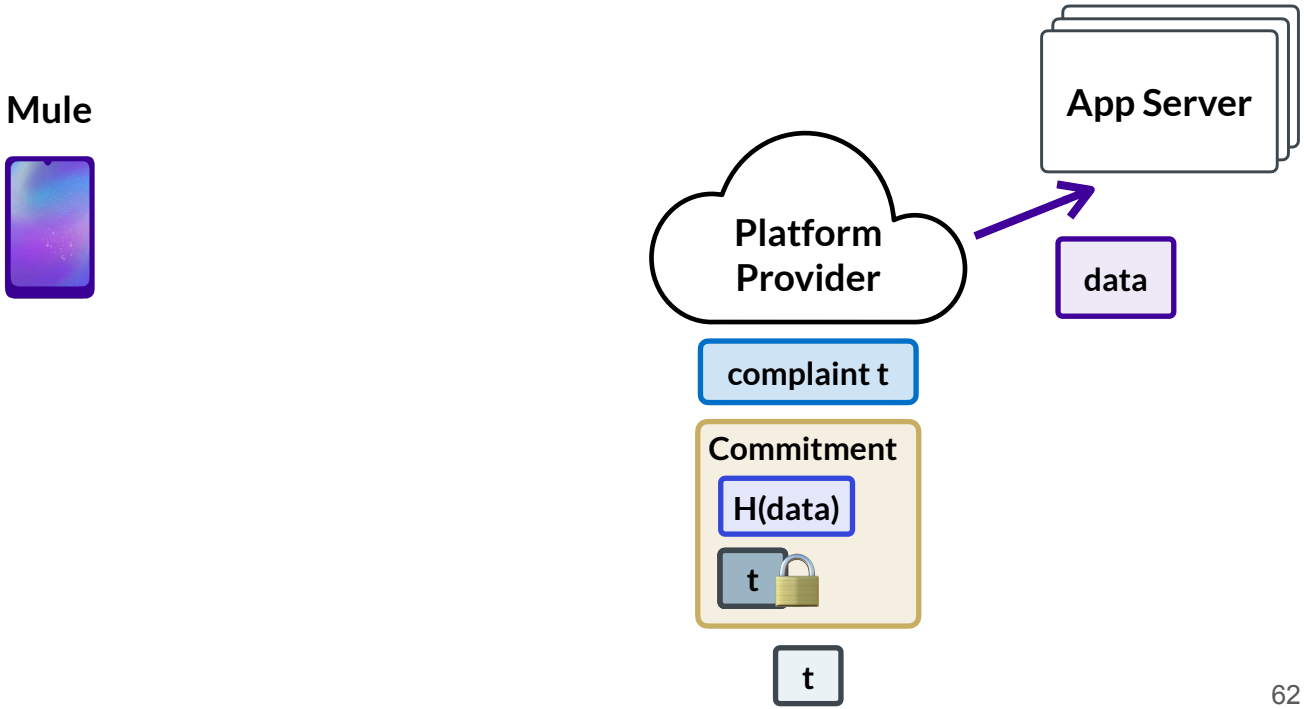
Complaints in Detail

(3b) If no token was received by the mule, it has the option of sending the original data payload matching the committed hash



Complaints in Detail

(3b) If the data matches the committed hash, it's forwarded to the app server



Complaints in Detail

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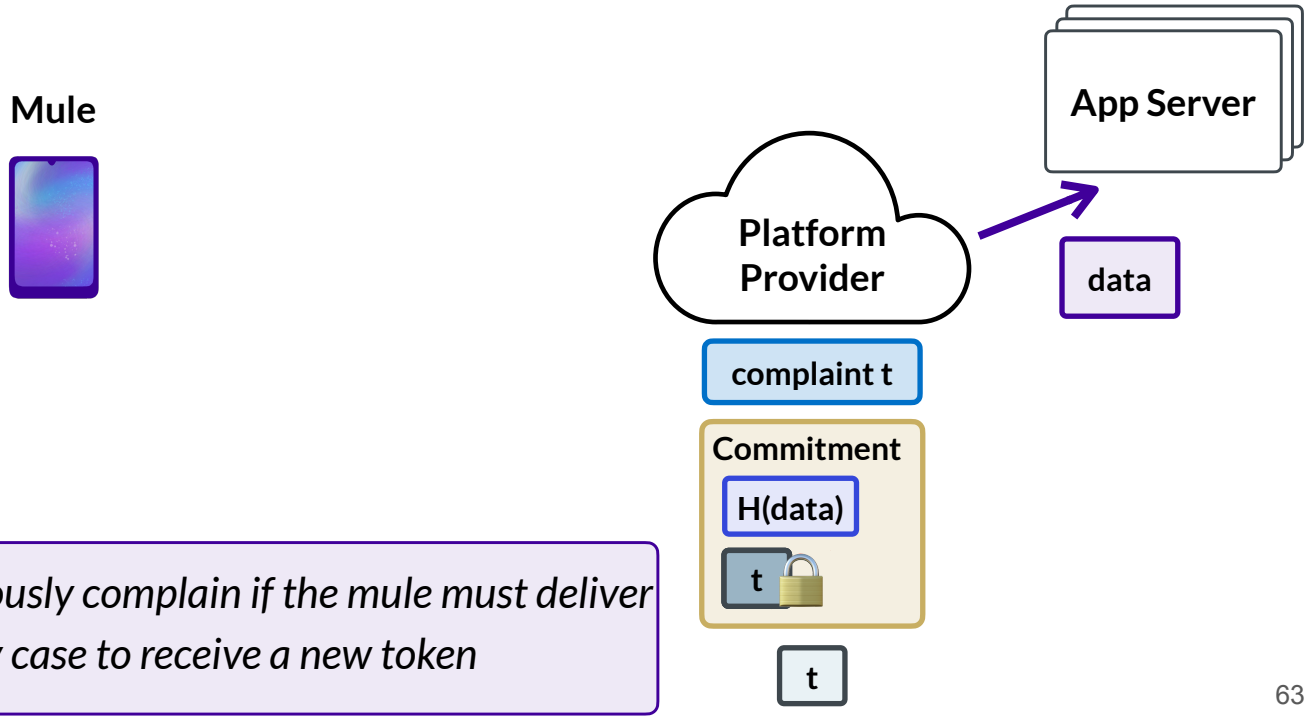
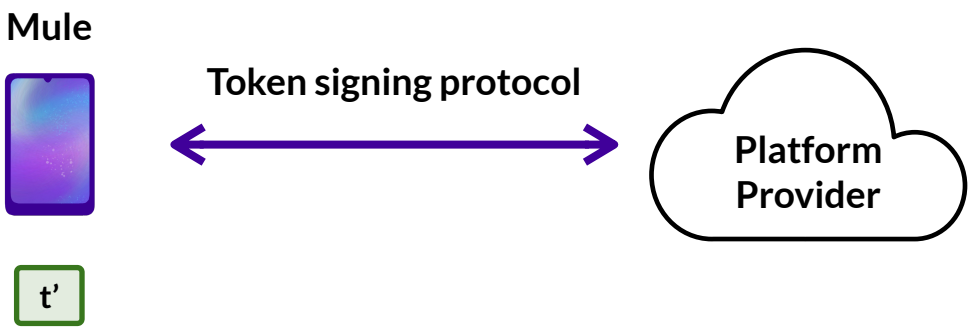


Little incentive to maliciously complain if the mule must deliver the data in any case to receive a new token

Complaints in Detail

(4) Platform provider and mule work together to blindly sign a new token!



Complaints in Detail

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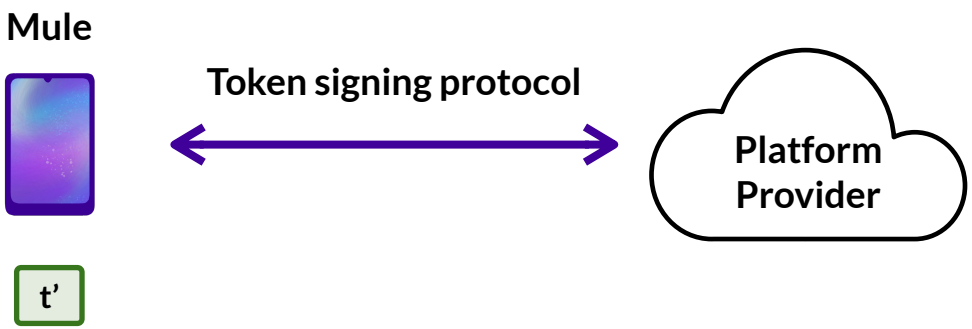


For duplicate tokens: first-come first-served to avoid generating more tokens than were used during delivery while incentivizing complaints

NEBULA

A backhaul system that *preserves mule privacy* while:

1. Charging for backhaul use and incentivizing mule participation

   Out-of-band accounting: app servers buy untraceable *tokens* from provider and exchange them for data.

2. Detecting mule and application server misbehavior

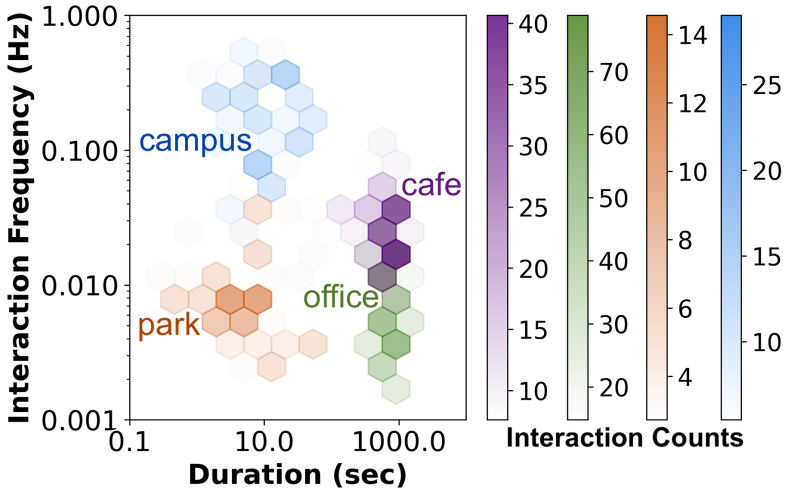
   Allow mules to submit anonymous complaints with *proof* of misbehavior to the provider.

3. Supporting millions of mules

   Nebula can process ~445k tokens/second, or **250M tokens/dollar**

Supporting upload in varied environments

We measured likely *frequency* of sensor-mule interaction



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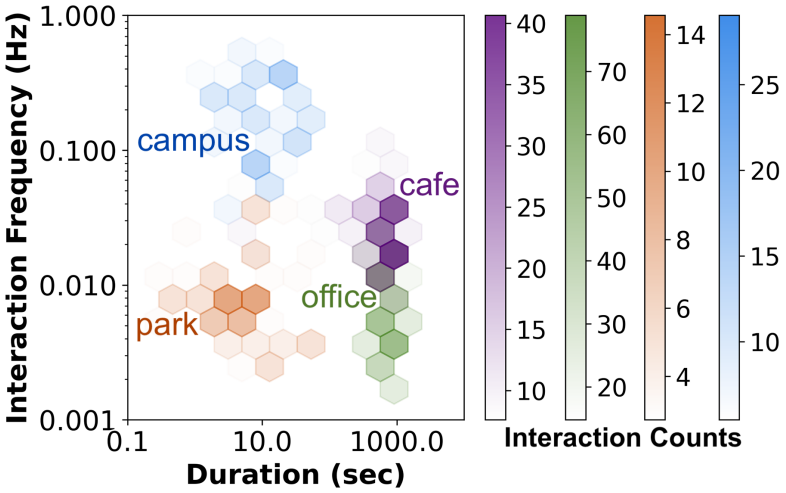
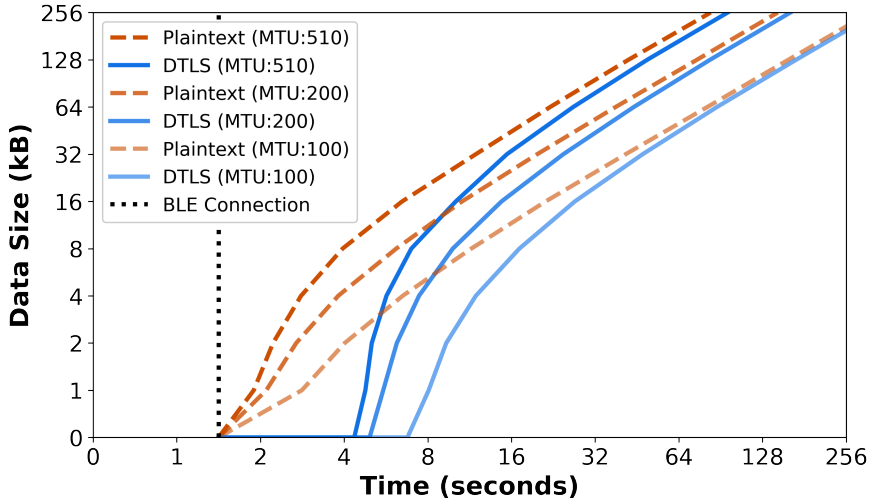
We measured likely *frequency* of sensor-mule interaction, and *duration* of data transfer





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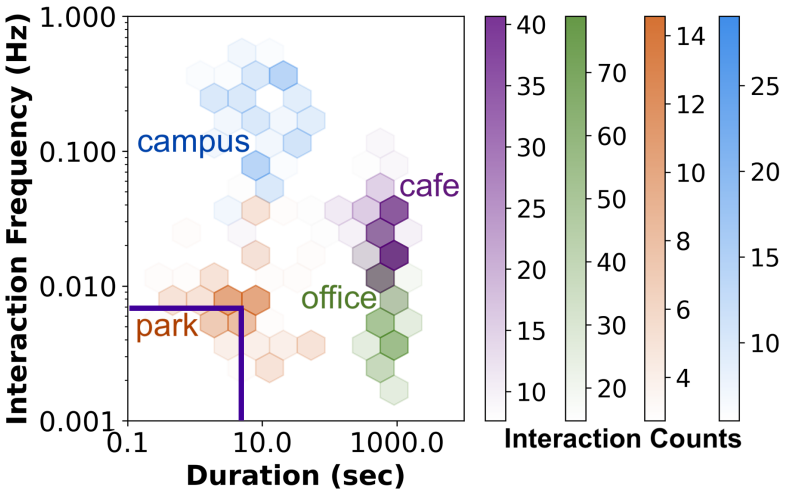

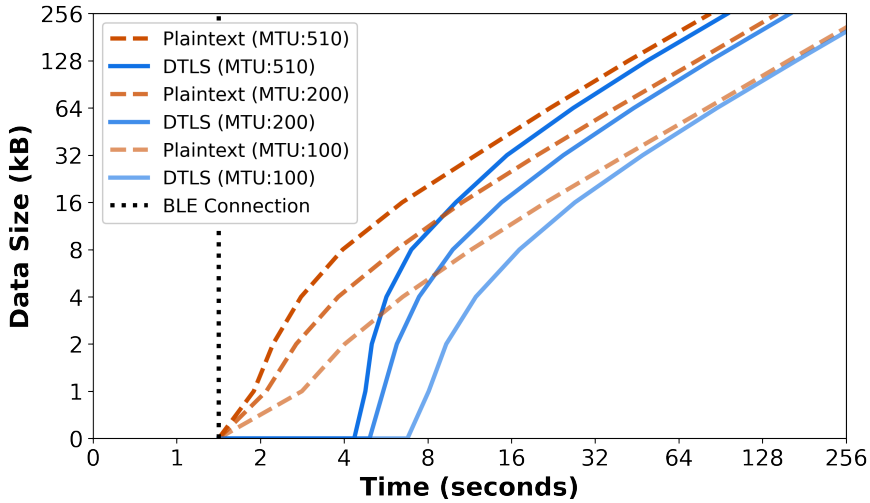

Example: in a park, we can expect a mule every few minutes

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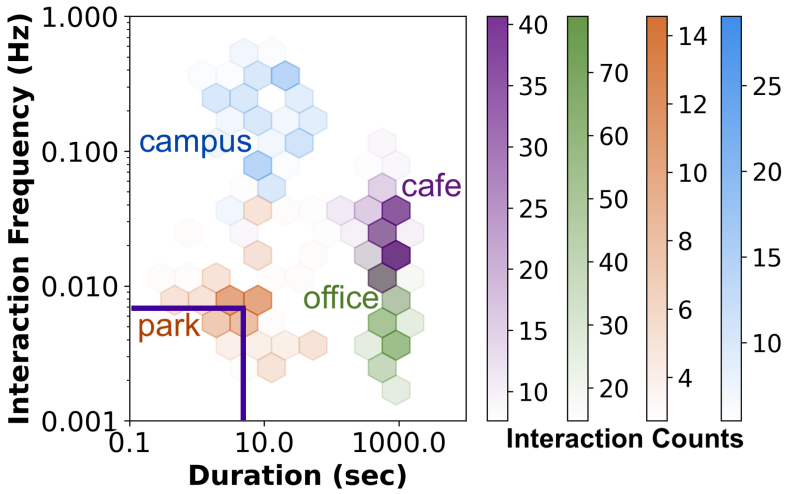

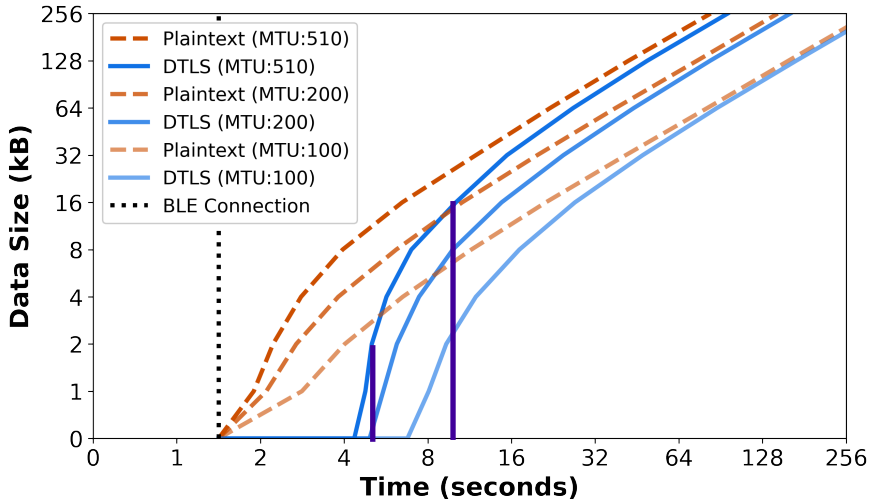

Example: in a park, we can expect a mule every few minutes,
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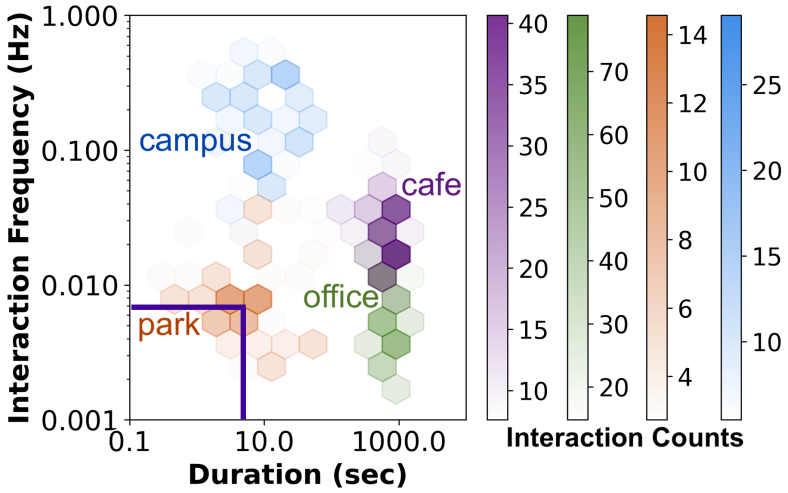

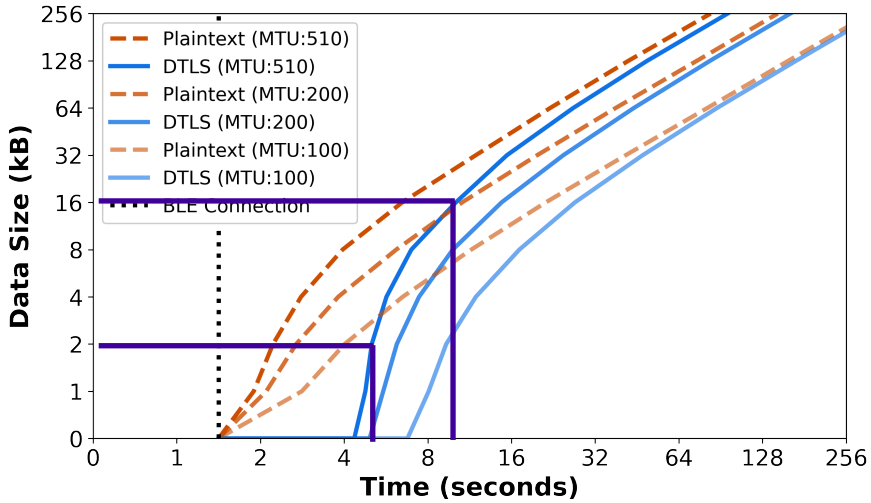

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Supporting upload in varied environments

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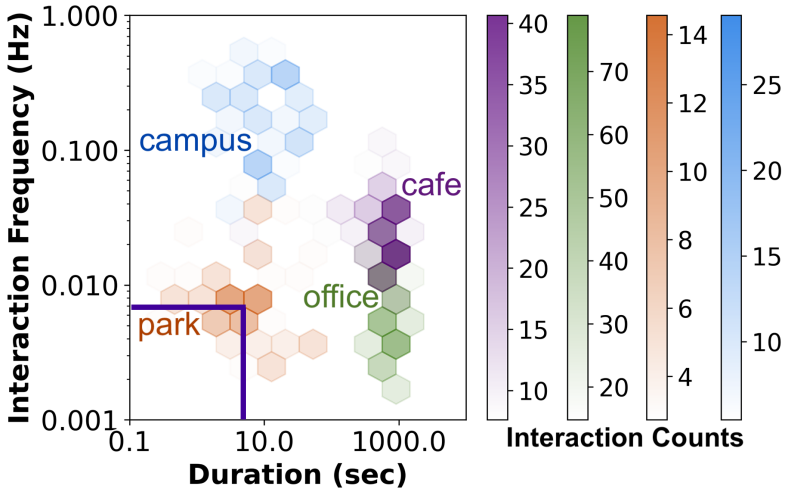

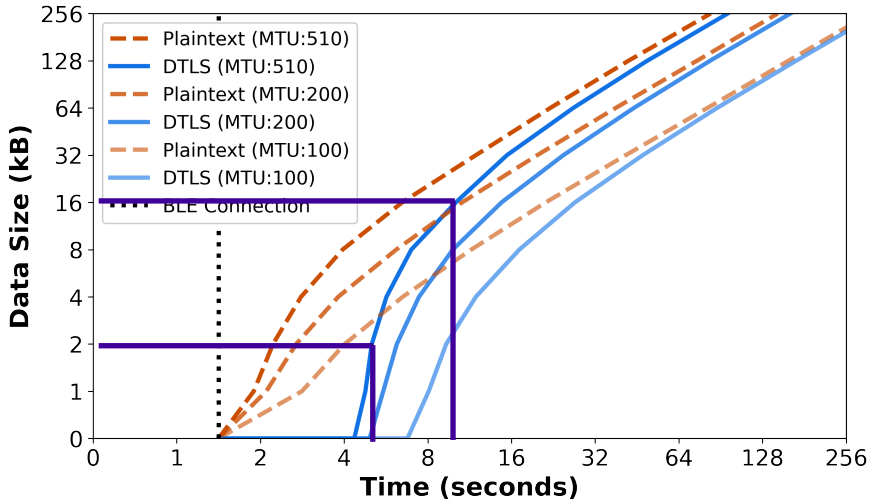

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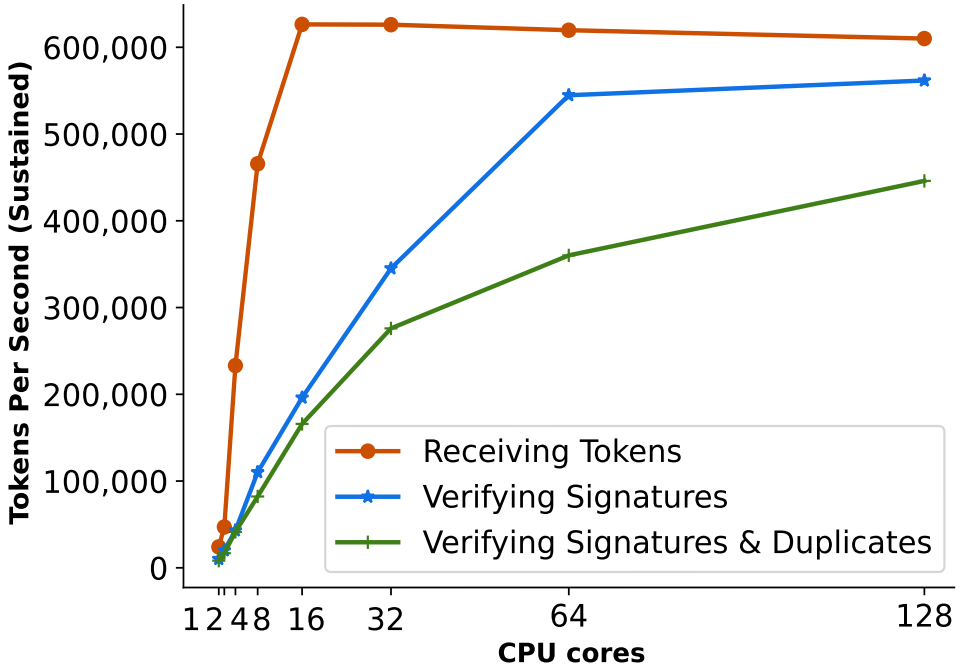
Analytical Energy/Memory models in paper

Provider performance

High-throughput database to check token validity and detect duplicates.



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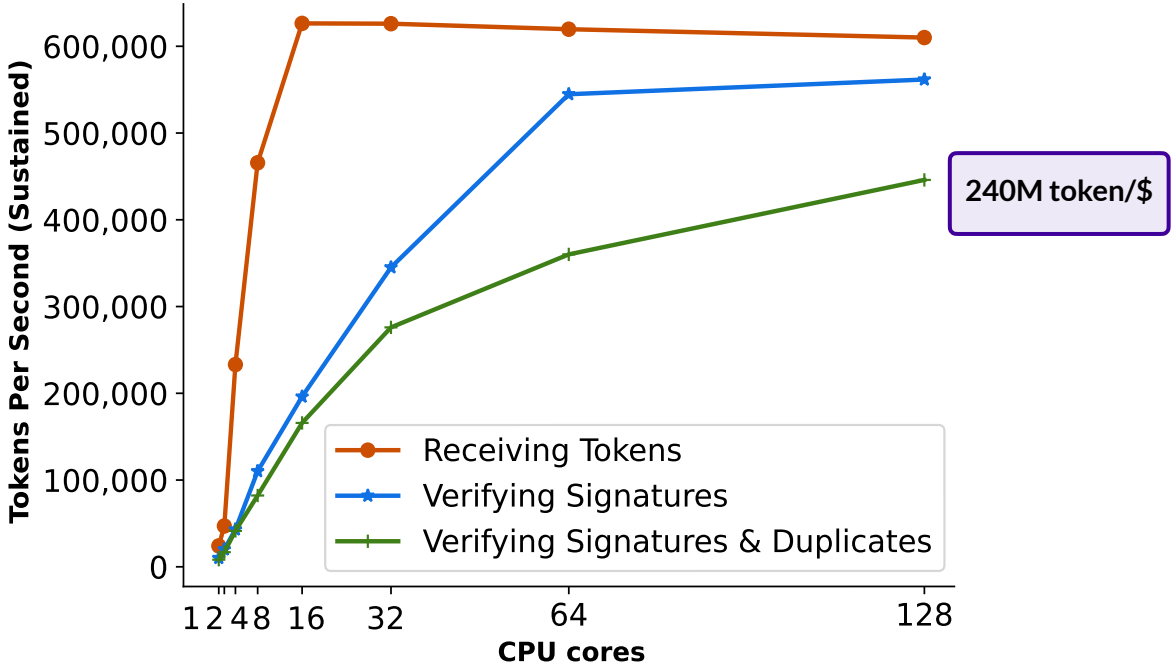
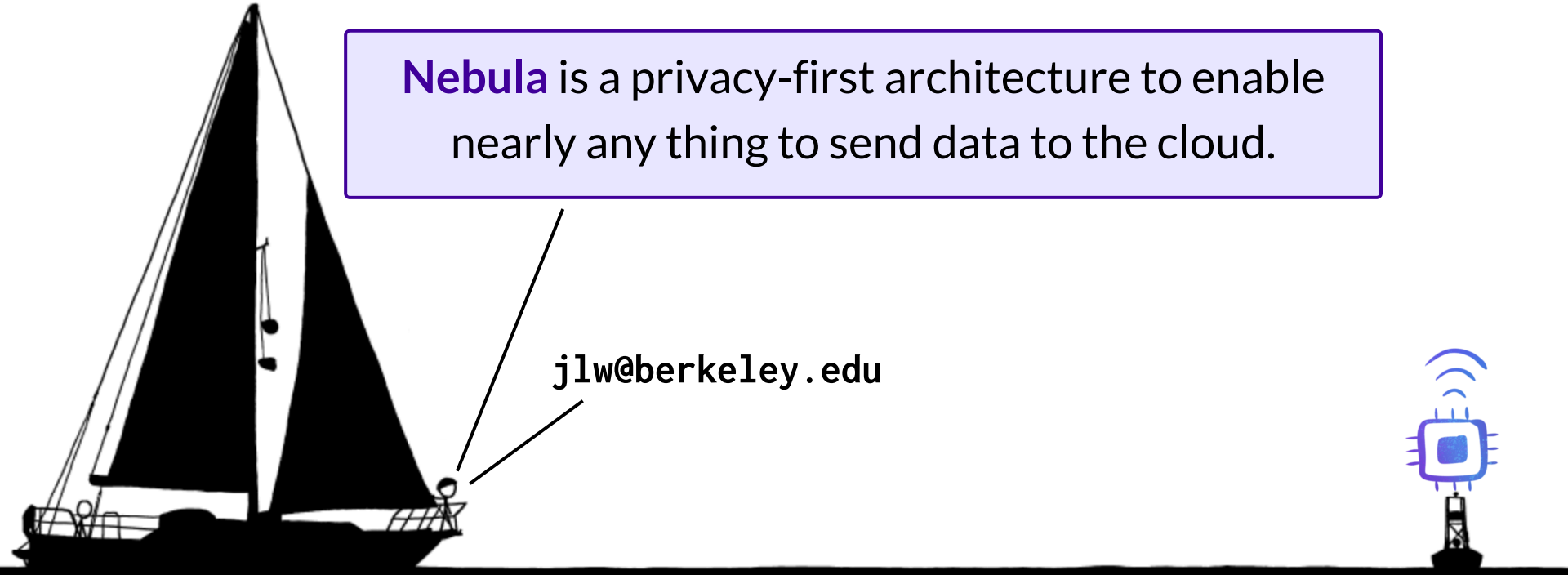


Fast enough for every person in the US to redeem each month

Find us at our poster!

Nebula is a privacy-first architecture to enable nearly any thing to send data to the cloud.



`jlw@berkeley.edu`

[xkcd 1100]