Democratizing Direct-to-Cell Low Earth Orbit Satellite Networks

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Direct-to-Cell Satellites

STARLINK DIRECT TO CELL
Seamless access to text, voice, and data for LTE phones across the globe. Starlink has successfully sent and received texts to cell phones via our first six Direct to Cell satellites.

LEARN MORE

SpaceX's Cellular Starlink Hits 17Mbps Download Speed to Android Phone
Why Direct-to-Cell Satellites?

Affordable ubiquitous connectivity for our regular phones

Special-purpose Satphone

Ground Station

Terrestrial Mobile Network

Geostationary Orbit (GEO)

35,786km
Why Direct-to-Cell Satellites?

Affordable ubiquitous connectivity for our regular phones

Lower energy cost

More affordable hardware

Low Earth Orbit (LEO)

340-2,000km

Regular Phone

Ground Station

Terrestrial Mobile Network

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Terrestrial Mobile Network
From Monopoly to Multi-Tenancy

- SpaceX launches first satellites for T-Mobile’s direct-to-cell service
- AT&T, Google join Vodafone in backing AST SpaceMobile

Satellite Network Operators (SNOs):
- AST SpaceMobile
- STARLINK
- LYNK
- iridium connected
- Globalstar

Mobile Network Operators (MNOs):
- T-Mobile
- AT&T
- Vodafone
- Salt
- KDDI
- Rogers
Why LEO Satellite Multi-Tenancy?

Mobile Network Operators (MNOs)

Scarce satellite resources
Why LEO Satellite Multi-Tenancy?

Mobile Network Operators (MNOs)

- Scarce satellite resources
- Prohibitive capital expenses

![Satellite launch cost graph]

- Satellite launch cost (million)
- Number of satellites

- Satellite launch cost:
  - 0 million
  - 1000 million
  - 2000 million
  - 3000 million
  - 4000 million
  - 5000 million
  - 6000 million

- Number of satellites:
  - 0
  - 400
  - 800
  - 1200
  - 1600
  - 2000
Why LEO Satellite Multi-Tenancy?

Mobile Network Operators (MNOs)
- Scarce satellite resources
- Prohibitive capital expenses

Satellite Network Operators (SNOs)
- Lack of licensed spectrums

Satellite launch cost (million)

Number of satellites

Occupied by MNOs
- LTE band covered by SpaceX filings
- Non-LTE band
- LTE band partly covered by SpaceX filings
- LTE band not covered by SpaceX filings
Why LEO Satellite Multi-Tenancy?

Mobile Network Operators (MNOs)
- Scarce satellite resources
- Prohibitive capital expenses

Satellite Network Operators (SNOs)
- Lack of licensed spectrums
- Increased Revenues and ROI

Starlink’s GLOBAL CUSTOMERS
- T-MOBILE (USA)
- OPTUS (AUSTRALIA)
- ROGERS (CANADA)
- ONE NZ (NEW ZEALAND)
- KDDI (JAPAN)
- SALT (SWITZERLAND)
- ENTEL (CHILE, PERU)
- . . .
Why LEO Satellite Multi-Tenancy?

FCC Proposes Framework to Facilitate Supplemental Coverage From Space

FCC FACT SHEET
Single Network Future: Supplemental Coverage from Space
Report and Order and Further Notice of Proposed Rulemaking
GN Docket No. 23-65 and IB Docket No. 22-271

Background: This Report and Order would establish a domestic regulatory framework—the first of its kind in the world—to enable collaborations between satellite operators and terrestrial service providers to offer ubiquitous connectivity, directly to consumer handsets using spectrum previously allocated only to terrestrial service. Supplemental Coverage from Space, or SCS, would enable expanded coverage to a terrestrial licensee’s subscribers, especially in remote, unserved, and underserved areas, and would increase the availability of emergency communications.

FCC enables collaborations between SNOs and MNOs

A win-win solution for everyone
How Should Multi-Tenancy Work?

Monopoly

Ideal multi-tenancy

Satellite Network Operators (SNOs) Mobile Network Operators (MNOs)

UEs
How to Enable LEO Satellite Multi-Tenancy?

Option 1: Infrastructure-as-a-Service Model
How to Enable LEO Satellite Multi-Tenancy?

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How to Enable LEO Satellite Multi-Tenancy?

Option 1: Infrastructure-as-a-Service Model

- Inter-Satellite Link
- RF
- IQ samples

Incomplete serviceable areas 😞
Missed 4G/5G radio processing deadline 😞
How to Enable LEO Satellite Multi-Tenancy?

Option 1: Infrastructure-as-a-Service Model

Missed 4G/5G radio processing deadline

Incomplete serviceable areas

Inter-Satellite Link

RF

≥ 2.6ms

IQ samples

Demodulation

Decoding

< 100µs
How to Enable LEO Satellite Multi-Tenancy?

Option 2: Function-as-a-Service Model

Can this model enable multi-tenancy?
Function-as-a-Service Model in Space?

MNO’s cellular functions are offloaded to SNOs’ satellites

Fast-moving
Intermittently accessible
Potentially untrusted
Function-as-a-Service Model in Space?

Hop-by-hop stateful session

Tight functional coupling
Function-as-a-Service Model in Space?

- Inflexible use of SNOs 😞

Unlikely to cooperate due to competition

Tight functional coupling
Function-as-a-Service Model in Space?

Each satellite can cover multiple MNOs (each having 1,000s of UEs)

Inflexible use of SNOs 😞
Signaling storms due to huge coverage 😞

Tight functional coupling
Function-as-a-Service Model in Space?

Dynamic SNO-MNO-UE service relationship

- Trust establishment
- Coupled with MNOs
- Hop-by-hop stateful session
Function-as-a-Service Model in Space?
Dynamic SNO-MNO-UE service relationship

Trust establishment
Reconfiguration

UEs  SNOs  MNOs  Cells
Function-as-a-Service Model in Space?

Dynamic SNO-MNO-UE service relationship

- Exhaustive MNO reconfigurations
- Dynamic trust establishment
Function-as-a-Service Model in Space?

In-Orbit Function Multi-Tenancy is Impeded by **Hop-by-Hop Stateful Session**
How do we share mobile infrastructure in life?

- Pay for the travel and don’t care which car

Pay-as-you-go self-service

Self-service car
How to Enable LEO Satellite Multi-Tenancy?

Pay-as-you-go satellite self-service

Pay for the service and don’t care which SNO

Self-service SNO
Our Solution: MOSAIC

Online/Offline token provisioning

Token issuer
Token database

MNO

Satellite APP
Token database

Pay-as-you-go local access

UE

SNO

MNO certificates
Token bucket
UE blacklist

UPF
State proxy

Radio
Self-serve orbital functions

Online/Offline token clearing
How to Realize MOSAIC?

How can SNOs enable self-service?

How can MNOs enable pay-as-you-go tokens?

How can UEs access satellite with tokens?
How can SNOs Enable Multi-Tenant Self-Service?

Self-service

Full-fledged cellular functions

State proxy

Control

Data

Data

Radio

Radio
How can SNOs Enable Multi-Tenant Self-Service?

Self-service  Full-fledged cellular functions

State proxy  Data  Radio  Control  Data  Radio
How can SNOs Enable Multi-Tenant Self-Service?

- Self-service
- Multi-tenancy

Full-fledged cellular functions
Decouple function in a stateless design

State proxy
Control Data
Data Radio
Radio
How can MNOs Enable Pay-As-You-Go Token?

Policy-embedded tokens

UE Online/Offline token provisioning

MNO
How can MNOs Enable Pay-As-You-Go Token?

Concern: Token misuse

Cannot timely detect token multi-spending 😞

Multi-spending one token to gain free satellite access
How can MNOs Enable Pay-As-You-Go Token?

Key idea: SIM-enforced one-time token consumption

MNO-issued tamper-resistant SIM card
How can MNOs Enable Pay-As-You-Go Token?

Token Generation

MNO

UE

SNO

random numbers, policy

SIM-involved
token generation

signed token

Metadata

ID QoS
Billing
Security
Location

How can MNOs Enable Pay-As-You-Go Token?
How can MNOs Enable Pay-As-You-Go Token?

Token Consumption

Token Generation

- MNO
- UE
- SNO

ID | QoS | Billing | Security | Location
---|-----|---------|----------|----------
random numbers, policy

SIM-involved token generation

send token (service request)

challenge
response

Service available

Verification

Metadata

ID | QoS | Billing | Security | Location
---|-----|---------|----------|----------

Token Generation
How can MNOs Enable Pay-As-You-Go Token?

**Token Generation**
- MNO: ID, QoS, Billing, Security, Location
- UE: SIM-involved token generation

**Token Consumption**
- MNO: SIM-enforced one-time spending
- UE: Service available

**Token Clearing**
- MNO: Multi-spending detection
- UE: Token has been cleared

- ID, QoS, Billing, Security, Location
- Verification

Random numbers, policy

Signed token

Send token (service request)

Challenge

Response

Send token, response sent by UE, date/time

Send UE blacklist
How can MNOs Enable Pay-As-You-Go Token?

Token Generation

- MNO
  - ID, QoS
  - Billing
  - Security
  - Location
  - random numbers, policy
  - token
  - signed token

- UE
  - SIM-involved token generation

- SNO
  - ID, QoS
  - Billing
  - Security
  - Location

Token Consumption

- send token (service request)
- challenge
- response
- Service available

- Verification

- send token, response sent by UE, date/time
- Multi-spending detection

Token Clearing

- Token has been cleared
How can UEs Access Satellite with Tokens?

Alleviate the dependency on MNOs
Minimize the amount of signaling

RRC system information broadcast (satellite ID)
RRC connection setup
ULInformationTransfer (token)
DLInformationTransfer (challenge)
ULInformationTransfer (response)
verify response
Service available

Piggyback via in-band signaling

ID, QoS, Billing, Security, Location
Experimental Setup

Commodity off-the-shelf 3GPP Non-Terrestrial Network (NTN) protocol stack (Amarisoft Callbox NR-4-U Ultimate)

Driven by operational satellite datasets
Evaluation: Overall Benefits

SNOs: Signaling storm freedom

- Number of signalings (s)

- 1 MNO
- 2 MNOs
- 3 MNOs

MNOs & UEs: 100% serviceable area

- 100% serviceable area

- Service ratio $\eta$ (%)
Evaluation: Overhead

Low token consumption latency

- Starlink
- Globalstar
- Iridium

Token misuse time is still bounded in the worst case

Existing SIM cards can host sufficient tokens

Num of tokens

<table>
<thead>
<tr>
<th>Plan</th>
<th>Num of Tokens</th>
</tr>
</thead>
<tbody>
<tr>
<td>sysmolSIM</td>
<td>20k</td>
</tr>
<tr>
<td>T-mobile</td>
<td>15k</td>
</tr>
<tr>
<td>Basic</td>
<td>10k</td>
</tr>
<tr>
<td>Medium</td>
<td>5k</td>
</tr>
<tr>
<td>Hologram IoT</td>
<td>5k</td>
</tr>
</tbody>
</table>

- Existing SIM cards can host sufficient tokens.
Conclusion

- Direct-to-cell satellite multi-tenancy: A win-win solution.

- **MOSAIC**: Pay-as-you-go satellite self-service
  - As easily shareable as ridesharing.

- A long voyage toward full multi-tenancy for 6G and beyond.
Thank you!

Q&A

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Welcome to read our paper!