Gearing up for the 21st century

**SPACE RACE**

Most slides are from Debopam Bhattacherjee
SpaceX Starlink becomes first US mega-constellation to gain FCC approval

SpaceX has successfully launched its first broadband satellites

OneWeb gets FCC approval for 720 low-Earth orbit satellites to offer global internet services

by Mike Dano | Jun 22, 2017 11:58am

OneWeb weighing 2,000 more satellites

by Tereza Pultarova and Caleb Henry — February 24, 2017
OPPORTUNITY: GLOBAL COVERAGE
Internet users as % of population

[Jeff Ogden and Jim Scarborough via Wikimedia, CC BY-SA 3.0]
OPPORTUNITY: LOW LATENCY
OPPORTUNITY: LOW LATENCY

- 35,768 km
- 1,100 km
OPPORTUNITY: LOW LATENCY

35,768 Km
(~240 ms RTT)

1,160 Km
(~7.8 ms RTT)
OPPORTUNITY: LOW LATENCY

35,768 Km
(~240 ms RTT)

1,160 Km
(~7.8 ms RTT)
WASHINGTON D.C. TO FRANKFURT WITH POLAR SATELLITES
WASHINGTON D.C. TO FRANKFURT WITH POLAR SATELLITES

CDF

DC-Frankfurt latency (ms)

HotNets 2018 : Gearing up for the 21st Century Space Race

Debopam Bhattacherjee, Waqar Aqeel, Ilker Nadi Bozkurt, Anthony Aguirre, Balakrishnan Chandrasekaran, P. Brighten Godfrey, Gregory Laughlin, Bruce Maggs, Ankit Singla
WASHINGTON D.C. TO FRANKFURT WITH POLAR SATELLITES

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WASHINGTON D.C. TO FRANKFURT, TODAY’S HFT
WASHINGTON D.C. TO FRANKFURT, TODAY’S HFT

T1

4ms

T2

T2 - T1
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Sidenote: Airplanes ??

35,768 Km (~240 ms RTT)

1,160 Km (~7.8 ms RTT)
SIDENOTE: AIRPLANES ??

- 21 hops, Avg stretch: 1.06
- 19 hops, Avg stretch: 1.01
- Partially available, 23 hops, Avg stretch: 1.16
UNDERSTANDING SATELLITE TOPOLOGIES
**Orbital Elements**

- Longitude of ascending node
- Argument of periapsis
- True anomaly
- Inclination
- Ascending node
- Reference direction
- Plane of reference
- Orbit

[Lasunncty via Wikimedia, CC BY-SA 3.0]
UNIFORM POLAR CONSTELLATION
LOWER INCLINATIONS
LOWER INCLINATIONS
CHALLENGES
Objectives

- Global coverage
- Bandwidth where needed
- Low latency

Challenges

- Satellites have different orbital elements (inclination, speed, etc.)
- ISLs to achieve the objectives
- Population distribution is not uniform
A high dimensional optimization problem
CHALLENGE FOR BGP?

AS_{Sat}
CHALLENGE FOR BGP?
CHALLENGE FOR BGP?

AS path lengths are poor proxies for performance

AS path lengths are even poorer proxies for performance
Figure 2: Snapshot of the coverage areas of SpaceX's "Starlink" constellation at 10% of its stage-one deployment. Coverage at a location varies over time as satellites move in and out of view. The red horizontal line highlights the 40° parallel north. (Visualization: Savi tool [5])

We optimize coverage. Other parameters to the simulations are taken from SpaceX's FCC application [30]. We abstract from the low-level details of connection initialization and handover protocols between satellites, and simply assume that GSTs within the footprint of a satellite are connected.

Results. Our results for the 10% partial deployment of the SpaceX constellation are shown in Figures 2–4. Figure 2 shows a snapshot of the global footprint of the constellation, given by the (partially overlapping) footprints of each satellite.

Figure 3 draws the connectivity profile of the earth's surface by latitude. The left y-axis shows the portion of time during the day that regions (identified by latitude) are in the footprint of at least one satellite. The right y-axis shows the number of connect-disconnect events that a single GST would observe in a day (by latitude). Note that this includes only events in which a GST's connectivity to the SN as a whole changes—the much more frequent handovers between satellites are not considered here. We highlight two observations: First, some of the most highly populated latitudes have connectivity most of the time (> 90%), while the other areas have an up-time of at least 50% (excluding latitudes entirely beyond reach of the SN). Second, as expected, there are no connect-disconnect events for fully covered areas. However, there can be hundreds of such events for areas that are partially covered, even where there is more than 90% connectivity. Figure 4 shows the connectivity profile for a latitude of 40° (solid line). While the uptime is on average more than 90%, there are many connect-disconnect events.

3.2.2 Effect on BGP announcements. We next study the effect of the connectivity profile on the number of announcements that a BGP speaker must make. We assume that a terrestrial AS has only one GST and therefore interdomain connectivity with the SN depends only on the up-time of one satellite link. Whenever the connectivity between the GST and the SN is lost, there is a cascade of BGP messages: the SN withdraws all prefixes of the terrestrial AS customer; the terrestrial AS withdraws all prefixes that were advertised through the SN and then announces new paths to its own customers. The number of BGP messages depends on the location of the failed link in the AS graph and on specific implementation details of the BGP speakers (e.g., batching withdrawal messages for multiple prefixes).

We present results for a GST that is positioned at 40° latitude. We chose this setting, as the 40° northern parallel traverses some of the most populated areas in the world (see Figure 2). As Figure 3 shows, such a GST has more than 150 connect-disconnect events per day. Even if each event triggered only a single BGP message, the fact that they occur in bursts (cf. Figure 4) will trigger route-flap dampening, preventing the propagation of BGP announcements.

To reduce the number of BGP messages, we apply a simple filtering mechanism. The connectivity profile of a GST is predictable based on the satellite orbits and can therefore be computed in advance. Connect events that are shortly followed (e.g., within minutes) by disconnect events are thus ignored, and the satellite path, while available, is not announced.
Connectivity changes imply BGP announcements
Announce every time satellite link dis/connects?
  Large churn in BGP announcements
  Typically triggers “route-flap dampening”
Use predictability of changes to limit announcements?
  Can announce availability longer than X minutes
  Skip (i.e. waste) smaller periods of availability
Tobias Klenze, Giacomo Giuliani, Christos Pappas, Adrian Perrig, and David Basin

**Worse in Partial Deployments!**

The figure also indicates that for the 40\degree latitude, most connect-disconnect events could be buffered with a small impact on latency and latency interruptions would introduce a significant overhead for BGP announcements. In contrast, disconnect events that occur during satellite handovers. For such durations, traffic could be buffered with a small impact on latency and latency variations. This filtering approach can drastically reduce the number of effective events, which can predict outages in the order of milliseconds, which can impede communication. Exceptions to this include that filtering greatly reduces the number of effective events, whereas connectivity waste increases. Overall, our results demonstrate that while the connectivity variation. This filtering approach can drastically reduce the number of effective events, and the percentage of connectivity waste as a function of the filtering threshold.

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**Effective events**

<table>
<thead>
<tr>
<th>Filtering threshold (min)</th>
<th>Events per day</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0</td>
<td>0</td>
</tr>
<tr>
<td>2.5</td>
<td>20</td>
</tr>
<tr>
<td>5.0</td>
<td>40</td>
</tr>
<tr>
<td>7.5</td>
<td>60</td>
</tr>
<tr>
<td>10.0</td>
<td>80</td>
</tr>
<tr>
<td>12.5</td>
<td>100</td>
</tr>
<tr>
<td>15.0</td>
<td>120</td>
</tr>
</tbody>
</table>

**HotNets 2018 : Networking in Heaven as on Earth**
Worse in partial deployments!

The figure also indicates that for the 40° latitude, connectivity waste increases. This way, the number of effective events and thus BGP activity bursts have an interval of less than 5 minutes. However, filtering greatly reduces the number of effective events, fewer BGP messages, and thus better convergence, but at the cost of a higher threshold implies fewer effective events, fewer BGP announcements, but at the same time introduces connectivity waste; and vice versa.

Results.

Figure 5 shows filtering being applied (dashed line) and the percentage of connectivity waste as a function of the filtering threshold. We fix the filtering threshold to 6 minutes (above the情况来看, more than 10% of uptime, close to 20 connect-disconnect events could take time due to legal, financial, or technical difficulties, the commoditization of space-based hardware. While reducing interruptions would introduce a significant overhead for BGP into the backbone infrastructure. Even if one sacrifices 15 years or more). Similarly, failures can also occur unexpectedly and can range from a failed networking system to unexpected satellite failures, expected contributions to the dynamic environment are failures, expected and unexpected. Satellites in LEO have a significantly shorter life span than satellites in GEO, and they are usually replaced after 5 years due to technical reasons. However, given that satellite replacement is a non-trivial task that may take time due to legal, financial, or technical difficulties, the mass production of satellites with redundant systems to provide high reliability, but at a significant cost. The mass production of satellites with redundant systems to provide high reliability, but at a significant cost. The mass production of

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The figure also indicates that for the 40° latitude, most connectivity bursts have an interval of less than 5 minutes. However, higher connectivity waste; and vice versa.

Results.

Overall, our results demonstrate that while the connectivity waste ranging from 15% to 45%.

Dynamic Topologies.

Many problems remain open or require better approaches to speakers and negatively impact BGP convergence times. An ocurrence per day for a single GST. This rate of connectivity in-...}

**Figure 5:** The effect of the filtering threshold on the number of connect-disconnect events and the resulting connectivity waste as a function of the filtering threshold.

<table>
<thead>
<tr>
<th>Filtering threshold (min)</th>
<th># Effective events / day</th>
<th>Connectivity waste (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.5</td>
<td>160</td>
<td>10.0</td>
</tr>
<tr>
<td>5.0</td>
<td>140</td>
<td>12.5</td>
</tr>
<tr>
<td>7.5</td>
<td>120</td>
<td>15.0</td>
</tr>
<tr>
<td>10.0</td>
<td>100</td>
<td>17.5</td>
</tr>
<tr>
<td>12.5</td>
<td>80</td>
<td>20.0</td>
</tr>
<tr>
<td>15.0</td>
<td>60</td>
<td>22.5</td>
</tr>
</tbody>
</table>

**Figure 4** shows filtering being applied (dashed line) and the percentage of connectivity waste as a function of the filtering threshold.

**Figure 3** shows the number of BGP announcements used, but remains unused due to filtering.

Given that satellite replacement is a non-trivial task that may take time due to legal, financial, or technical difficulties, the frequency of unexpected failures will increase. With the commoditization of space-based hardware, while reduced maintenance costs, the frequency of unexpected failures will increase. Satellites in LEO have a significantly shorter deployment and its effect on connectivity. Another aspect that is highly dynamic topologies, as opposed to 15 years or more). Similarly, failures can also occur per day for a single GST. This rate of connectivity in-...
WEATHER DISRUPTIONS

Higher loss rates

Lower loss rates but higher latency
CHALLENGE FOR CONGESTION CONTROL?
Challenge for congestion control?

Delay-based congestion control?
DELAY-BASED CC (COPA) PERFORMANCE

RTT = L ± δ

[every 100 ms]
Delay-based CC (COPA) Performance

- Throughput (Mbps)
- Latency $L$ (ms)
- Variation $\delta$ (ms)

Color Legend:
- 0
- 2
- 4
- 6
- 8
- 10
- 12

To be filled with specific performance data.
**DELAY-BASED CC (COPA) PERFORMANCE**

Throughput (Mbps)

Latency $L$ (ms)

Variation $\delta$ (ms)

Throughput (Mbps)

No variation $\Rightarrow$ High performance

Variation $\delta$ (ms)
**DELAY-BASED CC (COPA) PERFORMANCE**

Throughput (Mbps) vs. Latency $L$ (ms) vs. Variation $\delta$ (ms)

- **Throughput (Mbps)**: Vertical axis
- **Latency $L$ (ms)**: Horizontal axis
- **Variation $\delta$ (ms)**: Color-coded

**Legend**:
- Throughput (Mbps)
  - 12
  - 10
  - 8
  - 6
  - 4
  - 2
  - 0

**Graph**:
- Graph shows a trend where modest variation leads to breakdown.
- Throughput decreases as latency and variation increase.

**Observation**:
- Modest variation results in a breakdown in the performance of delay-based CC (COPA) systems.
QUESTIONS?