Mobile Wireless Networking
The University of Kansas EECS 882
Satellite Links and Networks – Fall 2007

James P.G. Sterbenz

Department of Electrical Engineering & Computer Science
Information Technology & Telecommunications Research Center
The University of Kansas

jbios@eecs.ku.edu

http://www.ittc.ku.edu/~jbios/courses/mwnets

Mobile Wireless Networking
Satellite Links and Networks

SL.1 Satellite applications and overview
SL.2 Satellite links and MAC
SL.3 Satellite networks
SL.4 End-to-end communication over satellite networks

05 December 2007
Satellite Links and Networks

Satellite Applications and Overview

SL.1 Satellite applications and overview
SL.2 Satellite links and MAC
SL.3 Satellite networks
SL.4 End-to-end communication over satellite networks

Satellite Communication

Applications

- Imaging and situational awareness
  - weather and environmental monitoring
  - mapping and espionage
- Entertainment broadcast
  - television (e.g. EchoStar DISH, DirecTV) BS
  - radio (e.g. XM, Sirius)
- Communication links
  - Internet access and telephony
    - remote locations
    - ships and airplanes
    - other wireless links impractical
Communication Satellites

Orbital Types

<table>
<thead>
<tr>
<th>Type</th>
<th>Name</th>
<th>Altitude</th>
<th>Coverage [# sats]</th>
<th>Orbital Period</th>
<th>Velocity</th>
<th>Visibility</th>
<th>Path Delay</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aircraft</td>
<td></td>
<td>1 – 25 km</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>LEO</td>
<td>Low Earth Orbit</td>
<td>400 – 1500 km</td>
<td>40 – 300</td>
<td>1.5 – 2 hr</td>
<td>8 – 12 km/s</td>
<td>10 – 20 min</td>
<td>5 – 10 ms</td>
</tr>
<tr>
<td></td>
<td>Inner Van Allen Belt</td>
<td>700 – 10 000 km</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>MEO</td>
<td>Medium Earth Orbit</td>
<td>8000 – 18000 km</td>
<td>10 – 12</td>
<td>5 – 10 hr</td>
<td>2 – 8 hr</td>
<td>30 – 100 ms</td>
<td></td>
</tr>
<tr>
<td>GEO</td>
<td>Geostationary</td>
<td>35 786 km</td>
<td>3 ±76°</td>
<td>24 hr</td>
<td>3.07 km/s</td>
<td>permanent</td>
<td>240 ms</td>
</tr>
<tr>
<td></td>
<td>Outer Van Allen Belt</td>
<td>31 000 – 65 000 km</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
</tbody>
</table>

Orbital Mechanics

[Stallings 2005, Fig 9.2]
Communication Satellites

Doppler Effect

- High relative velocity of LEO satellites to ground
  - significant Doppler shift in frequency
  - challenges receiver tuning

Geostationary Satellites

Characteristics

- Geostationary satellites
  - proposed by Arthur C. Clarke [1945]
  - ~ 36,000 km / 22,000 mi altitude
  - geosynchronous equatorial circular orbit
  - stationary above spot on equator
    -~ .1 ° – 3° wander due to imperfect orbit

Advantages and disadvantages?
Geostationary Satellites

Advantages

- GEO advantages
  - earth-station transceiver fixed
    - no need for tracking
    - no Doppler shift
  - only 3 satellites provide nearly global coverage
    - Lawrence KS ≈ 40°
    - Lancaster UK ≈ 54°
Geostationary Satellites

Advantages

- GEO satellite advantages
  - earth-station transceiver fixed
    - no need for tracking
    - no Doppler shift
  - only 3 satellites provide nearly global coverage
    - Lawrence KS ≈ 40°
    - Lancaster UK ≈ 54°
  - large footprint
    - good for broadcast

Geostationary Satellites

Disadvantages

- GEO satellite disadvantages
  - poor coverage beyond 76° latitude
    - transceiver dish aimed at horizon
    - extreme N. Canada, Russia, Scandinavia
    - Antarctica
Geostationary Satellites

Disadvantages

- GEO satellite disadvantages
  - poor coverage beyond 76° latitude
    - transceiver dish aimed at horizon
    - extreme N. Canada, Russia, Scandinavia
    - Antarctica
  - additional non-GEO satellites needed
    - e.g. Russian Molniya satellites

- long delay: ~240 ms each way
  - 480 ms up+down link significant delay for telephony
    - significantly impacts conversation
  - 960 ms RTT challenge for TCP
Geostationary Satellites
Disadvantages

• GEO satellite disadvantages
  – poor coverage beyond 76° latitude
  • additional non-GEO satellites needed
  – long delay: ~240 ms each way
  – significant attenuation due to distance
    • challenge for battery powered handsets uplinks
Geostationary Satellites

Disadvantages

- GEO satellite disadvantages
  - poor coverage beyond 76° latitude
  - additional non-GEO satellites needed
  - long delay
  - significant attenuation due to distance
  - large footprint
    - no spatial reuse among receivers
    - alternative: multiple *spot beams*
      - frequency reuse within total footprint

Low Earth Orbiting Satellites

Characteristics

- Low earth orbiting satellites
  - ~ 400 –1500 km altitude
    - generally below inner Van Allen belt (700 –10 000 km)

*Advantages and disadvantages?*
Low Earth Orbiting Satellites

Advantages

• LEO satellite advantages
  – negligible delay: 5 – 10 ms each way
  • comparable to MAN or regional network
  • does not affect conversation in telephony
  • does not affect TCP

Low Earth Orbiting Satellites

Disadvantages

• LEO satellite disadvantages
  – small footprint
Low Earth Orbiting Satellites
Disadvantages

- LEO satellite disadvantages
  - small footprint
    - many satellites needed in a constellation
    - ~ 50 to 1000
    - more expensive to deploy
  - non-stationary
    - mobile w.r.t. ground
    - Doppler effects
    - hand-offs between satellites
    - antenna tracking or beam width
Communication Satellites
Orbital Classification

<table>
<thead>
<tr>
<th>Type</th>
<th>Name</th>
<th>Altitude</th>
<th>Coverage [ # sats]</th>
<th>Orbital Period</th>
<th>Velocity</th>
<th>Visibility</th>
<th>Path Delay</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aircraft</td>
<td></td>
<td>1 – 25 km</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>LEO</td>
<td>Low Earth Orbit</td>
<td>400 – 1500 km</td>
<td>40 – 300</td>
<td>1.5 – 2 hr</td>
<td>8 – 12 km/s</td>
<td>10 – 20 min</td>
<td>5 – 10 ms</td>
</tr>
<tr>
<td></td>
<td>Inner Van Allen Belt</td>
<td>700 – 10 000 km</td>
<td>–</td>
<td>–</td>
<td></td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>MEO</td>
<td>Medium Earth Orbit</td>
<td>8000 – 18000 km</td>
<td>10 – 12</td>
<td>5 – 10 hr</td>
<td></td>
<td>2 – 8 hr</td>
<td>30 – 100 ms</td>
</tr>
<tr>
<td>GEO</td>
<td>Geostationary</td>
<td>35 786 km</td>
<td>3 ±76°</td>
<td>24 hr</td>
<td>3.07 km/s</td>
<td>permanent</td>
<td>240 ms</td>
</tr>
<tr>
<td></td>
<td>Outer Van Allen Belt</td>
<td>31 000 – 65 000 km</td>
<td>–</td>
<td>–</td>
<td></td>
<td>–</td>
<td>–</td>
</tr>
</tbody>
</table>

Satellite Links and Networks
SL.2 Satellite Links

SL.1 Satellite applications and overview
SL.2 Satellite links and MAC
SL.3 Satellite networks
SL.4 End-to-end communication over satellite networks
Satellite Links

Link Terminology

- Satellite link
  - downlink: satellite to earth station
  - uplink: earth station to satellite
  - inter-satellite link (ISL)

Service Types

- FSS: fixed satellite service
  - to fixed earth stations
- MSS: mobile satellite service
  - vehicles
    - aircraft
    - ships
    - trains
    - automobiles, busses, trucks, etc.
  - mobile terminals (MTs)
    - satellite phones
- BSS: broadcast satellite service
  - large number of receivers
### Satellite Links
#### Communication Bands

<table>
<thead>
<tr>
<th>Band</th>
<th>Name</th>
<th>Partition</th>
<th>Frequencies</th>
<th>Bandwidth</th>
<th>Satellite Usage</th>
</tr>
</thead>
<tbody>
<tr>
<td>VHF</td>
<td>VHF</td>
<td>30–300MHz</td>
<td>television, FM radio</td>
<td></td>
<td></td>
</tr>
<tr>
<td>UHF</td>
<td>UHF</td>
<td>300MHz–1GHz</td>
<td>television, p2p radio</td>
<td></td>
<td></td>
</tr>
<tr>
<td>L</td>
<td>UHF</td>
<td>1–2GHz</td>
<td>1 GHz</td>
<td>MSS, cordless and mobile phones</td>
<td></td>
</tr>
<tr>
<td>S</td>
<td>SHF</td>
<td>2–4GHz</td>
<td>2 GHz</td>
<td>MSS, NASA, LAN, WPAN, WMAN</td>
<td></td>
</tr>
<tr>
<td>C</td>
<td>EHF</td>
<td>4–8GHz</td>
<td>4 GHz</td>
<td>FSS, PSTN relay, WLAN</td>
<td></td>
</tr>
<tr>
<td>X</td>
<td>SHF</td>
<td>8–12GHz</td>
<td>4.5 GHz</td>
<td>FSS, military, earth exploration meteorology</td>
<td></td>
</tr>
<tr>
<td>Ka</td>
<td>SHF</td>
<td>12–18GHz</td>
<td>5.5 GHz</td>
<td>FSS &amp; BSS</td>
<td></td>
</tr>
<tr>
<td>K</td>
<td>EHF</td>
<td>18–27GHz</td>
<td>8.5 GHz</td>
<td>FSS &amp; BSS, µwave links</td>
<td></td>
</tr>
<tr>
<td>Ku</td>
<td>EHF</td>
<td>27–40GHz</td>
<td>13.5 GHz</td>
<td>FSS, WMAN</td>
<td></td>
</tr>
<tr>
<td>V</td>
<td>EHF</td>
<td>40–75GHz</td>
<td>emerging WMAN</td>
<td></td>
<td></td>
</tr>
<tr>
<td>W</td>
<td>EHF</td>
<td>75–110GHz</td>
<td>future</td>
<td></td>
<td></td>
</tr>
<tr>
<td>mm</td>
<td>EHF</td>
<td>110–300GHz</td>
<td>future</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Based in part on Stallings 2005, Table 9.2

### Satellite Links
#### Link Characteristics

- Satellite link characteristics
  
  what is different from traditional networks?
Satellite Links
Link Characteristics

- Satellite link characteristics
  - high delay for MEO and GEO
  - high bandwidth x delay product
    - high-rate MEO and GEO links
  - very high error rate

Satellite Links
Link Characteristics: High Delay

- Satellite link characteristics: high delay
  - high delay for MEO
  - very high delay for GEO
- High delay links contribute to end-to-end delays

more later
Satellite Links
Link Characteristics: High Bandwidth-Delay

- Satellite link characteristics: bandwidth×delay
  - high delay for MEO and GEO... coupled with high-rate links in higher frequency bands
  - high bandwidth×delay product ⇒ large buffers
    - problem for limited resources on satellite transceivers
    - affects end-to-end transport protocols such as TCP

Satellite Links
Link Characteristics: High Bit Error Rate

- Satellite link characteristics: very high error rate
  - BER of $10^{-1}$ to $10^{-2}$ common

*Error control alternatives?*
Satellite Links

Link Characteristics: High Bit Error Rate

- Satellite link characteristics: very high error rate
  - raw BER can be worse than $10^{-2}$
- Error control alternatives
  - forward error correction
    - heavy FEC needed to reach reasonable link-layer BER
  - link-layer ARQ
    - can be used for reliable transmission on top of FEC

- Requires buffering of frame until acknowledged
- May not be practical for high bandwidth-delay MEO and GEO links
- Limited resources available on satellite
Satellite Links

Bent Pipe Link

- Bent pipe link
  - satellite is repeater between two earth stations
  - long distance link where wired network too expensive

Satellite Links

Bent Pipe Link Concatenation

- Bent pipe links
  - concatenated for longer link
  - disadvantage: multiple uplink + downlink delays
Satellite Links
Medium Access Control

- FDM and FDD
  - multiple channels
- FDMA: frequency division multiple access
- TDMA: time division multiple access
- CDMA: code division multiple access
- SDMA: space division multiple access
  - distinct satellite orbits
  - but orbits do intersect, e.g. polar orbits at north and south pole
  - multiple spot beams per satellite

Satellite Links and Networks
SL.3 Satellite Networks

SL.1 Satellite applications and overview
SL.2 Satellite links and MAC
SL.3 Satellite networks
SL.4 End-to-end communication over satellite networks
Satellite networks using bent pipe links
- switches (or IP routers) in earth stations
- Example: Globalstar

- Globalstar  www.globalstar.com
  - 48 satellite LEO constellation
  - inclined (non-polar) orbits
    - coverage: Americas, Europe, N. Africa, N. Asia, Australia
    - 16 spot beams
    - FDM/CDMA
  - bent-pipe links with earth-station switching
    - 2400 calls/satellite
Satellite Networks
Example: Globalstar History

- **History**
  - 1991 joint venture between Loral and Qualcomm
  - 1998 – 2000 satellite launches: $52 = 48 + 4$ spares
    - significant launch failures
  - 2005 – 2007: technical problems
    - satellites ending life
      - dead satellites moved to graveyard orbit above LEO
    - S-band amplifiers failing more quickly
    - 8 additional satellites launched in 2007
  - 2009: 2nd generation 48-constellation planned

Satellite Networks
Example: Globalstar Services

- **Global service types**: use SIM card or IS-41
  - telephony services: voice
    - E.164 allocations +8818 and +8819
  - data services up to 9.6 kb/s (uncompressed)
- **Qualcomm GSP 1700 handset**: ~ $1000
  - similar form factor to cordless phone
    - significantly bigger than typical mobile clamshell
- **Globalstar services**:
  - $50/month unlimited service from North America
  - $30/month + $1.50/minute voice
Satellite Network
On-Board Switching

• Satellite network: on board switching
  – satellites contains switches (or IP routers)

• Example: Iridium

Satellite Networks
Example: Iridium Overview

• Iridium [www.iridium.com]
  – 66 satellite LEO constellation
    • atomic number of Ir = 77 satellites originally planned
    • atomic number 66 is Dysprosium; not as marketable
  – polar LEO constellation
    • 48 spot beams in 3 sectors
    • FDM/TDMA
    • 2.4 kb/s effective link rate
  – on-board switches in satellites
    • 10 Mb/s inter-satellite links
    • 1100 call/satellite capacity
Satellite Networks

Example: Iridium History

- History
  - launched 1998; Motorola provided financial backing
    - first public call made by Al Gore
  - possibly the most spectacular telecom business failure
    - went bankrupt in 1999 with deorbiting planned
    - didn’t anticipate importance of mobile cellular telephony
    - didn’t adequately engineer for data services
  - saved by US government
    - used by DOD
  - still a commercial service
    - telephone numbers +8816 and +8817
    - approximately 200,000 subscribers (June 2007)

Satellite Networks

Example: Iridium Services

- Iridium service types: use SIM card
  - telephony services: voice, SMS, paging
    - E.164 allocations +8816 and +8817
  - data services
    - dial-up data at 2.4 kb/s
    - compressed data services ≈ 10 kb/s
- Iridium 9505A handset: ~ $1700
  - similar form factor to cordless phone
    - slightly larger than Globalstar Qualcomm GSP 1700
- Iridium services: sold by third-party reseller
  - monthly and prepaid plans at $3 to $15 / min
Satellite Networks
Example: Teledesic

- **Teledesic** (formerly [www.teledesic.com](http://www.teledesic.com))
  - 840-satellite LEO constellation at 700 km altitude
  - scaled back to 288-satellite constellation at 1400 km altitude
  - high-speed Internet: 720 Mb/s downlinks / 100 Mb/s uplinks
  - on-board switched network
- **Teledesic history**
  - 1994 backed by Microsoft and ...
    - Bill Gates, Paul Allen, Craig McCaw, Alwaleed bin Talal
  - 1997 LEO constellation plans scaled back
  - 2002 plans shifted to 30-satellite LEO constellation
  - 2002 – 2003 bankruptcy and dissolution
End-to-End Satellite Communication
Challenges

Challenges?

- high delay for MEO and GEO
- high bandwidth-delay product for high data-rate
- high link error rate if not corrected by link-ARQ
TCP over Satellite

TCP Issues

- IETF tcpsat working group (no longer active)
  - transport layer issues affecting TCP over satellite links
  - existing TCP options
  - compliant implementations with improved performance
  - recommendation of well understood protocol changes
  - protocol changes that are potentially promising

- IETF pilc working group:
  Performance Implications of Link Characteristics
  - “End-to-End Performance Implications of Links with Errors”
    [RFC 3155] / [BCP 0050]

TCP over Satellite

TCP Standard Mechanisms

- Enhancing TCP over Satellite Channels using Standard Mechanisms
  - [RFC 2488] / [BCP0028] (best current practice)

- Recommendations for use of standard-compliant TCP
  - path MTU discovery
  - error control on satellite links
  - TCP congestion control options
  - TCP options for high bandwidth-x-delay (large windows)
TCP over Satellite
TCP Standard Mechanisms

<table>
<thead>
<tr>
<th>Mechanism</th>
<th>Use</th>
<th>Location</th>
<th>Ref</th>
</tr>
</thead>
<tbody>
<tr>
<td>Path MTU discovery</td>
<td>recommended</td>
<td>sender</td>
<td>RFC 1191</td>
</tr>
<tr>
<td>FEC</td>
<td>recommended</td>
<td>link</td>
<td></td>
</tr>
<tr>
<td>TCP congestion control</td>
<td>RFC 2581</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Slow start</td>
<td>Required</td>
<td>sender</td>
<td></td>
</tr>
<tr>
<td>Congestion avoidance</td>
<td>required</td>
<td>sender</td>
<td></td>
</tr>
<tr>
<td>Fast retransmit</td>
<td>recommended</td>
<td>sender</td>
<td></td>
</tr>
<tr>
<td>Fast recovery</td>
<td>recommended</td>
<td>sender</td>
<td></td>
</tr>
<tr>
<td>TCP for Large Windows</td>
<td>RFC 1323</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Window scaling</td>
<td>recommended</td>
<td>sender + receiver</td>
<td></td>
</tr>
<tr>
<td>PAWS</td>
<td>recommended</td>
<td>sender + receiver</td>
<td></td>
</tr>
<tr>
<td>RTTM</td>
<td>recommended</td>
<td>sender + receiver</td>
<td></td>
</tr>
<tr>
<td>TCP SACK</td>
<td>recommended</td>
<td>sender + receiver</td>
<td></td>
</tr>
</tbody>
</table>

Ongoing TCP Research Related to Satellites

- T/TCP: TCP for transactions [RFC 1379, 1644]
  - reuse of 3-way handshake across flows
  - modifications to slow start, e.g. larger initial windows
  - corruption detection and modifications to loss recovery
  - parallel TPC connections
  - TCP pacing to smooth segment bursts
  - header compression
  - state sharing
  - ACK congestion control and filtering

RefLocation UseMechanism

© James P.G. Sterbenz
ITTC
SCPS-TP

SCPS Overview

- SCPS: space communications protocol standards
  - JPL protocol suite for satellite & deep-space communication
  - www.scps.org
- SCPS-TP: SCPS transport protocol
  - based on TCP
  - SCPS-TP options now registered with IANA as TCP options
    - SCPS-TP–TCP inter-operation possible
- SCPS proposed for IPN: interplanetary internet
  - rejected in favor of bundling between planetary Internets

SCPS-TP

SCPS Features

- SCPS-TP features
  - congestion control based on TCP Vegas
    - bandwidth-\times\text{-delay} product input parameter
  - corruption awareness
    - default error assumption can be set to corruption
    - contain corruption-experienced bit in ACK
    - corruption-experienced ICMP signalling message
  - end-to-end header compression
  - episodic connectivity
    - 1ink-outage ICMP message
  - SNAK: selective negative acknowledgements
    - allows negative ACK of segment ranges
Satellite Links and Networks

Further Reading


Satellite Links and Networks

Acknowledgements

Some material in these foils is based on the textbook
- Murthy and Manoj, *Ad Hoc Wireless Networks: Architectures and Protocols*

Some material in these foils enhanced from EECS 780 foils