TCOM 607/ECE 699 005
SATELLITE COMMUNICATIONS

Fall 2011
IN 131 Thursdays 4:30 – 7:10 p.m.
Dr. Jeremy Allnutt jallnutt@gmu.edu
General Information - 1

- Contact Information
  - Room: Engineering Building, Room 3104
  - Telephone (703) 993-3969
  - Email: jallnutt@gmu.edu
  - Office Manager: Toshiko Uchiyama
  - Office Hours
    - Tuesdays, 3:00 – 6:00 p.m.
      Please, by appointment only
General Information - 2

- Course Outline
  - Go to [http://ece.gmu.edu/](http://ece.gmu.edu/) and select Courses, then Course web pages, and scroll to TCOM 607 or ECE 699 005
  - Bad weather days: call (703) 993-1000
- You **MUST** Have The Following
  - Pratt, Bostian, & Allnutt Textbook
  - A Mathematical Calculator – please, simple ones only
General Information - 3

- Homework Assignments
  - Feel free to work together on these, \textit{BUT}
  - All submitted work must be your own work

- Web and other sources of information
  - You may use any and all resources, \textit{BUT}
  - You must acknowledge all sources
  - You must enclose in quotation marks all parts copied directly – and you must give the full source information
General Information - 4

- **Research Paper:**
  - Students must prepare and present a research paper on a satellite communications topic (see web doc.)
  - If you select a topic not directly connected to satellite communications, it MUST be pre-approved
  - The research paper will be presented in class
  - Only the slides need to be delivered (hard and soft)
  - All students must attend each others’ presentations
General Information - 5

- **Course grades**
  - Homework assignments – 15%
  - Test number 1 – 35%
  - Test number 2 – 35%
  - Research paper presentation – 15%

- **Deliverables**
  - Soft copy of presentation (Email attachment is fine)
  - Hard copy of presentation
General Information – 6A

- **Exam and Homework Answers**
  - For problems set, most marks will be given for the solution procedure used, not the answer
  - So: please give as much information as you can when answering questions: partial credit cannot be given if there is nothing to go on
  - If something appears to be missing from the question set, make – and spell out clearly – assumptions used to find the solution

Fall 2011

TCOM 607/ECE 699 005  Lecture number 1
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General Information – 6B

- **Exam and Homework Answers**
  - For problems set, most marks will be given for the solution procedure used, not the answer.
  - So: please give as much information as you can when answering questions: partial credit cannot be given if there is nothing to go on.
  - If something appears to be missing from the question set, make – and spell out clearly – assumptions used to find the solution.
General Information – 7

- In-Class Tests scheduled for
  - Test number 1  October 6\textsuperscript{th}, 2011
  - Test number 2  November 17\textsuperscript{th}, 2011

- In-Class Research Project presentations scheduled for
  - December 8\textsuperscript{th} and December 15\textsuperscript{th}, 2011, depending on how many students are in the class
## General Information – 8

### First Half of the Semester

<table>
<thead>
<tr>
<th>Date</th>
<th>Lecture Topic</th>
<th>Chapter</th>
</tr>
</thead>
<tbody>
<tr>
<td>September 1&lt;sup&gt;st&lt;/sup&gt;</td>
<td>Lecture 1 – Introduction</td>
<td>1</td>
</tr>
<tr>
<td>September 8&lt;sup&gt;th&lt;/sup&gt;</td>
<td>Lecture 2 – Orbital Mechanics</td>
<td>2</td>
</tr>
<tr>
<td>September 15&lt;sup&gt;th&lt;/sup&gt;</td>
<td>Lecture 3 – Link Budgets, part 1</td>
<td>4</td>
</tr>
<tr>
<td>September 22&lt;sup&gt;nd&lt;/sup&gt;</td>
<td>Lecture 4 – Link Budgets, part 2</td>
<td>4</td>
</tr>
<tr>
<td>September 29&lt;sup&gt;th&lt;/sup&gt;</td>
<td>Lecture 5 – Satellites</td>
<td>3</td>
</tr>
<tr>
<td>October 6&lt;sup&gt;th&lt;/sup&gt;</td>
<td>Test Number 1</td>
<td></td>
</tr>
<tr>
<td>October 13&lt;sup&gt;th&lt;/sup&gt;</td>
<td>Lectures 6&amp;7 – Error Control</td>
<td>7</td>
</tr>
<tr>
<td>October 20&lt;sup&gt;th&lt;/sup&gt;</td>
<td>Lecture 8 – Propagation Effects</td>
<td>8</td>
</tr>
</tbody>
</table>

Based on lectures 1 through 5 and homeworks 1, 2, and 3
## General Information – 9

### Last Half of the Semester

<table>
<thead>
<tr>
<th>Date</th>
<th>Event</th>
<th>Chapter(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>October 27th</td>
<td>Lecture 9 – VSAT</td>
<td>(Chapter 9)</td>
</tr>
<tr>
<td>November 3rd</td>
<td>Lecture 10 – NGSO</td>
<td>(Chapter 10)</td>
</tr>
<tr>
<td>November 10th</td>
<td>Lecture 11 – Multiple Access</td>
<td>(Chapter 6)</td>
</tr>
<tr>
<td>November 17th</td>
<td>Test Number 2</td>
<td></td>
</tr>
<tr>
<td>November 24th</td>
<td>Thanksgiving Day – no class</td>
<td></td>
</tr>
<tr>
<td>December 1st</td>
<td>Lecture 12 &amp; 13 – GPS</td>
<td>(Chapter 11)</td>
</tr>
<tr>
<td>December 8th</td>
<td>DBS Systems - <em>OR</em> Research Paper presentations, part 1</td>
<td></td>
</tr>
<tr>
<td>December 15th</td>
<td>Research Paper presentations, part 2</td>
<td></td>
</tr>
</tbody>
</table>

Based on lectures 6 through 11 and homeworks 4, 5, and 6
General Information – 10 Grading Guidelines

- Papers will be judged in three categories
  - Technical Content: 35 points
  - Presentation Material Quality: 35 points
  - Delivery: 30 points
- Papers delivered in the first session (papers 1 through 7) will be given an additional 5 points for ‘going early’
- Volunteers are requested for papers 1 through 7 (first come first served) – or you will be ‘volunteered’
# Presentation Schedule for 14 papers

<table>
<thead>
<tr>
<th>December 8^{th}, 2011</th>
<th>December 15^{th}, 2011</th>
</tr>
</thead>
<tbody>
<tr>
<td>4:30 – 4:50 paper 1</td>
<td>4:30 – 4:50 paper 8</td>
</tr>
<tr>
<td>4:52 – 5:12 paper 2</td>
<td>4:52 – 5:12 paper 9</td>
</tr>
<tr>
<td>5:26 – 5:56 paper 4</td>
<td>5:26 – 5:56 paper 11</td>
</tr>
<tr>
<td>6:42 – 7:02 paper 7</td>
<td>6:42 – 7:02 paper 14</td>
</tr>
</tbody>
</table>

### Please note:

(a) Allocated time includes any questions posed and answered  
(b) If your presentations is too long, please prepare two presentations – one that will meet the 20 minute limit and the second to be delivered as a soft copy  
(c) The above schedule will be confirmed after the add/drop date
Acknowledgement

A significant amount of material in the TCOM 607 lectures came from material and ideas generated by Dr. Tim Pratt and Dr. Seema Sud.

I would like to offer my thanks to them for permission to use their material.
Lecture 1 Outline

• Background
  • Transmission of information over long distances

• History of satellite communications
  • LEO and MEO efforts
  • GEO orbit
  • Interplanetary communications

• Recent advances in satellite communications
  • DBS, MSS, IP services
  • Big satellite? Or lots of networked satellites?
Lecture 1 Outline – A

- Background
  - Transmission of information over long distances
- History of satellite communications
  - LEO and MEO efforts
  - GEO orbit
  - Interplanetary communications
- Recent advances in satellite communications
  - DBS, MSS, IP services
  - Big satellite? Or lots of networked satellites?
Long Distance Communications

- Person-to-person long distance communications not possible centuries ago: you either traveled or sent a letter

- Long-distance communications evolved through chains of hill-top fires (that could be lit to signal the approach of the enemy) to copper wire telegraphy

- **By the way:**
  do you know what was the first form of long distance, digital communications?
Why Satellites?

This is a hypothetical single-hop link between New York and London. To reach London from New York, the towers each need to be 750 km tall.
Why Satellites?

750 km high tower

Trans-Atlantic Link

New York

750 km high tower

London

Clearly, a single-hop trans-Atlantic link is not feasible— but how far can you reach in a one-way link via a satellite, with orbital height and elevation angles as parameter?
How Far Can You Reach?
Long Distance Communications

- Person-to-person long distance communications not possible centuries ago: you either traveled to meet the person you wanted to speak to or you sent a letter.

- Long-distance communications evolved through chains of hill-top fires (that could be lit to signal the approach of the enemy) to copper wire telegraphy.
Evolution of Telecommunications

- Copper wires
  - Telegraph 1840
  - Telephone 1880
- Radio
  - Broadcasting 1920
  - Line of Sight microwave links 1950
  - Satellite Communications 1965
- Optical fiber
  - High capacity, long distances 1985
## Milestones in Telecommunications – 1

<table>
<thead>
<tr>
<th>Date</th>
<th>Achievement</th>
</tr>
</thead>
<tbody>
<tr>
<td>1837</td>
<td>Telegraph demonstrated (Wheatstone, Morse)</td>
</tr>
<tr>
<td>1865</td>
<td>News of Lincoln’s assassination took <em>12 days</em> to reach Europe</td>
</tr>
<tr>
<td>1905</td>
<td>Wireless telegraphy demonstrated (Marconi)</td>
</tr>
<tr>
<td>1922</td>
<td>Radio Broadcasting begins</td>
</tr>
<tr>
<td>1927</td>
<td>HF Trans-Atlantic Link initiated</td>
</tr>
</tbody>
</table>
Milestones in Telecommunications – 2

<table>
<thead>
<tr>
<th>Date</th>
<th>Achievement</th>
</tr>
</thead>
<tbody>
<tr>
<td>1937</td>
<td>PCM Proposed (Reeves)</td>
</tr>
<tr>
<td>1944</td>
<td>PCM implemented on transatlantic links (Bell Labs)</td>
</tr>
<tr>
<td>1945</td>
<td>Geostationary orbit proposed (Arthur C. Clarke)</td>
</tr>
<tr>
<td>1956</td>
<td>Trans-Atlantic cable opened (36 channels)</td>
</tr>
<tr>
<td>1957</td>
<td>Sputnik 1 LEO satellite orbited</td>
</tr>
</tbody>
</table>
## Milestones in Telecommunications – 3

<table>
<thead>
<tr>
<th>Date</th>
<th>Achievement</th>
</tr>
</thead>
<tbody>
<tr>
<td>1958</td>
<td>Project Score&lt;br&gt;The first voice message from space&lt;br&gt;(Pre-recorded message from Eisenhower)</td>
</tr>
<tr>
<td>1960</td>
<td>Echo 1 (passive repeater)</td>
</tr>
<tr>
<td>1961</td>
<td>The USA has 550 overseas telephone circuits – total!</td>
</tr>
<tr>
<td>1962/3</td>
<td>First satellite links across Atlantic&lt;br&gt;(Telstar 1 and 2)</td>
</tr>
</tbody>
</table>
### Milestones in Telecommunications – 4

<table>
<thead>
<tr>
<th>Date</th>
<th>Achievement</th>
</tr>
</thead>
<tbody>
<tr>
<td>1963</td>
<td>Syncom 1 (first GEO.; comms. failed)</td>
</tr>
<tr>
<td>1963</td>
<td>Syncom 2 (first link between three continents simultaneously (Africa; N&amp;S Am.))</td>
</tr>
<tr>
<td>1964</td>
<td>Intelsat formed</td>
</tr>
<tr>
<td>1965</td>
<td>First commercial GEO comsat (Intelsat 1 – Early Bird – 240 tel. circuits)</td>
</tr>
<tr>
<td>1966</td>
<td>Optical fiber communications (Kao and Hockman)</td>
</tr>
</tbody>
</table>
## Milestones in Telecommunications – 5

<table>
<thead>
<tr>
<th>Date</th>
<th>Achievement</th>
</tr>
</thead>
<tbody>
<tr>
<td>1968</td>
<td>Intelsat III satellites form global communications network (just in time for the Apollo program)</td>
</tr>
<tr>
<td>1974</td>
<td>Domestic satellite communications begins (Canada, USA, USSR)</td>
</tr>
<tr>
<td>1974</td>
<td>First 30/20 GHz experimental satellite launched (ATS-6)</td>
</tr>
<tr>
<td>1980</td>
<td>INTELSAT V F-1 launched (December)</td>
</tr>
</tbody>
</table>
### Milestones in Telecommunications

<table>
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</table>

**INTELSAT V** was the first hybrid Ku/C-band satellite. When the fourth INTELSAT V satellite was launched about 18 months later, there were more Ku-Band commercial Earth-space antennas in orbit than there were on the ground! Nobody wanted to move to Ku-Band as “everybody knew” the propagation conditions made the use of this new band “impossible”.
## Milestones in Telecommunications – 6

<table>
<thead>
<tr>
<th>Date</th>
<th>Achievement</th>
</tr>
</thead>
<tbody>
<tr>
<td>1985</td>
<td>VSAT systems started</td>
</tr>
<tr>
<td>1989</td>
<td>Olympus 30/20 GHz satellite launched</td>
</tr>
<tr>
<td>1989</td>
<td>ACTS 30/20 GHz satellite launched</td>
</tr>
<tr>
<td>1991</td>
<td>ITALSAT 50/40/19 GHz satellite launched</td>
</tr>
<tr>
<td>1993</td>
<td>First Directv satellite launched</td>
</tr>
<tr>
<td>2001</td>
<td>Several Ku/Ka-band satellites operational</td>
</tr>
<tr>
<td>2005</td>
<td>First two INMARSAT 4 satellites launched</td>
</tr>
</tbody>
</table>
When Intelsat was developing the RFP for INTELSAT VI, I suggested 30 GHz global Ka-band beacons be put on the satellites so that propagation experiments could begin in the late-1980s, thus providing the necessary information to design the Ka-band satellites that would be needed by the year 2000. There was little enthusiasm for this proposal as “everybody knew” the Ka-band propagation conditions made the use of Ka-band “impossible”.

- 1985
- 1989
- 1989
- 1991
- 1993
- 2001
- 2005

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- 1985
- 1989
- 1989
- 1991
- 1993
- 2001
- 2005
### Milestones in Telecommunications – 6

<table>
<thead>
<tr>
<th>Date</th>
<th>Achievement</th>
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<tbody>
<tr>
<td>1985</td>
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</tr>
<tr>
<td>2005</td>
<td>First two INMARSAT 4 satellites launched – they are the largest comsats to date</td>
</tr>
</tbody>
</table>
INMARSAT 4 satellite

~40 foot deployable, unfurlable main reflector

~100 foot solar panels

250 Tx and 250 Rx beams

5959 kg mass
13 year lifetime
Left image: Harold Rosen, right, at an Eiffel Tower presentation in 1961 with a mock-up of the Syncom satellite. Right image: A Boeing-built Galaxy IIIC communication satellite that is scheduled for a late-May launch.

From: New York Times web site, April 2\textsuperscript{nd}, 2009

http://www.nytimes.com/2009/04/02/science/space/02export.html?_r=1&hp

How Things Have Changed – 2
Growth of World Transmission Capacity

Capacity in billions of equiv. voice ccts

- Satellite
- Terrestrial fiber
- Under-sea fiber
- Copper wire
- Microwave


10^11
10^10
10^9
10^8
10^7

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## Capacity of Telecommunications Links

<table>
<thead>
<tr>
<th>Transmission Medium</th>
<th>Capacity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Telegraph line</td>
<td>50 – 300 bit/s</td>
</tr>
<tr>
<td>Telephone line</td>
<td>33 kbit/s</td>
</tr>
<tr>
<td>T1 conditioned line</td>
<td>1.544 Mbit/s</td>
</tr>
<tr>
<td>GEO Satellite</td>
<td>2.5 Gbit/s – 5 Gbit/s</td>
</tr>
<tr>
<td>Microwave LOS link</td>
<td>5 Gbit/s</td>
</tr>
<tr>
<td>Optical fiber</td>
<td>10 Gbit/s</td>
</tr>
<tr>
<td>Optical fiber using WDM</td>
<td>100 Gbit/s – 1 Tbit/s</td>
</tr>
</tbody>
</table>
Growth in Telecommunications – 1

Worldwide capacity in bits/sec

Relative cost per 100km

Capacity

10^11
10^9
10^7
10^5
10^3
1840 1880 1920 1960 2000 Year

Relative Cost

1000 100 10

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Growth in Telecommunications – 2

- In 1961, US had 550 overseas telephone lines
- Typical overseas call cost $1.00 per minute
- In 1960, average industrial wage was $1.50/hr
- 40 minutes of work per call minute
- In 2004, typical cost was $0.09 per minute
- In 2004, minimum wage was $5.20/hr
- 1 minute of work per call minute
- What other service costs 1/40th of 1960 price?
Growth in Telecommunications – 3

There are basically four types of commercial communications satellite systems:

- **Necessary systems**
  - Market-driven to a perceived need (e.g. Intelsat, PanAmSat)

- **National/Industrial systems**
  - Market-driven, but requiring significant subsidies (e.g. Anik)

- **National Prestige Systems**
  - Driven politically rather than by the market initially

- **Paper Satellite Systems**
  - First to register a slot; first-come-first-served FRB system
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- **Paper Satellite Systems**
  - First to register a slot; first-come-first-served FRB system

We will only be dealing with these two cases, primarily, through this course.
Lecture 1 Outline – B

- Background
  - Transmission of information over long distances
- History of satellite communications
  - LEO and MEO efforts
  - GEO orbit
  - Interplanetary communications
- Recent advances in satellite communications
  - DBS, MSS, IP services
  - Big satellite? Or lots of networked satellites?
Early orbital attempts barely had enough energy to attain orbit, all of the fuel was used just to reach orbital velocity. With no fuel to change the plane of the orbit, any satellite that reached orbit had the plane of the orbit equal to the latitude of the launch site.

- Sputnik 1 was launched from 65°N, and so had an orbital inclination of 65° to the equator.
- Explorer 1 was launched from 28.5° N and so had an orbital inclination of 28.5° to the equator.
Launch Sites

- Following the first launches by the USA (from the Canaveral site) and the USSR (from the Khazakstan site), many other launch sites were developed.
World-wide Launch Locations

Space Rocket Launch Sites Around the World

1 - Vandenberg
2 - Edwards
3 - Wallops Island
4 - Cape Canaveral
5 - Kourou
6 - Alcantara
7 - Hammaguir
8 - Torrejon
9 - Andoya
10 - Plesetsk
11 - Kapustin Yar
12 - Palmachim
13 - San Marco
14 - Baikonur
15 - Sriharikota
16 - Jiuquan
17 - Xichang
18 - Taiyuan
19 - Svobodny
20 - Kagoshima
21 - Tanegashima
22 - Woomera

Michael Medlock
TCOM 607
Spring 2009
LEO and MEO Efforts – 2

- All early satellite launches were, and most of those today are, to the east to take advantage of the rotational energy of the Earth.
- The rotational velocity of the Earth at the equator is about 1,000 mph.
- The closer a launch site is to the equator, the more energy the spin of the earth imparts to the launch vehicle.
- Sea Launch® is the only operational launch system directly on the equator.
Sea Launch® Odyssey Platform
Airborne Launchers

- In addition to Sea Launch©, there have been many airborne launches by the Orbital Sciences Pegasus rocket, dropped from a modified Lockheed 1011 aircraft.
- Airborne launchers can drop the rocket at almost any location, and so can take advantage of the spin of the Earth as launch rockets do from equatorial launch sites.
Orbital Sciences Pegasus Launcher

http://en.wikipedia.org/wiki/Pegasus_rocket
By 1960, scientific satellites started to be launched with mission-specific orbital requirements: the first of these was TIROS 1 on April 1st, 1960.

TIROS 1 was a satellite designed to photograph cloud cover under a general classification of weather satellite.

To be able to photograph all of the Earth, a weather satellite needs to be in close to a polar orbit.

To give TIROS good lighting conditions from the sun, the orbit is a sun synchronous orbit.
Sun Synchronous Orbit

Launched in a retrograde sense, the ground track repeats about every 12 hours. The precession of the orbit ensures the sun is directly behind the satellite when the satellite is on the sunlit side of the Earth.
The first communication satellite was a passive repeater, Echo 1, launched August 12th, 1960.

Echo 1 was a 100 foot balloon with a metallic skin that reflected signals transmitted to it in its 1519 x 1687 km orbit.

Echo 2 was launched about four years later.
Echo 2 Satellite
To be able to carry a significant amount of traffic, a communications satellite needs to be “active”

An active satellite receives a signal transmitted to it from an earth station, changes the frequency, and then transmits the signal back down to the ground.

The process of receiving and (re-)transmitting a signal without detecting the signal is called “transponding”.
The first active communications satellite was Telstar I, launched into a MEO orbit in July 1962.
Telstar 1 and 2 allowed short communications sessions between the USA and Europe.
Telstar 1 and 2 failed early due to radiation damage from the Van Allen radiation belts.
There are two main Van Allen radiation belts, although in extreme solar activity, a third ‘belt’ seems to form between the two main belts.
Van Allen Radiation Belts – 1
Van Allen Radiation Belts – 2

The third belt forms in here

Van Allen Radiation Belts – 3

**LEO** is under the lower belt but above the atmosphere.

**GEO** is well above the upper belt at a unique altitude.

**MEO** is above the lower belt but below the upper belt.
The Sun’s atmosphere – 1

- The Earth moves through the sun’s atmosphere
- Although tenuous at the orbit of the Earth, there is nevertheless a strong ‘solar wind’ of particles flowing from the sun past the Earth
- The sun’s atmosphere, known more accurately as the *heliosphere* in the region of the Earth, consists of particles that have escaped the sun’s gravitational pull
The Sun’s atmosphere – 2

- The majority of the heliosphere particles are energetic protons and electrons, many with energies exceeding 1 keV.
- The particles travel at velocities up to values that are in excess of one million miles an hour until they meet the magnetic field of the Earth, and are deflected in what is known as the “bow shock”.
Bow Shock
In August 1962, the US Congress passed the “Communications Satellite Act”

This critical step led to the formation of what was to become Intelsat – the International Telecommunications Satellite Organization – on July 19th, 1964

Even before Intelsat was formed, there was considerable debate as to what would be the architecture of the first communications satellite system

The two contenders were MEO (supported by BT and AT&T) and GEO (supported by COMSAT)
In mid-1963, 99% of all satellites being launched were into LEO or MEO orbits.

No satellite had successfully achieved GEO orbit.

BT and AT&T favored a MEO system of 10 satellites.

COMSAT favored a GEO system with three central locations over the major equatorial oceans.

The argument was basically settled by launch vehicle success rates.
The launch success rate in the early 1960’s was 25%
To achieve 24/7 global communications with a 10 satellite MEO system, 40 launches would be required
To achieve 24/7 communications over one ocean region with a GEO satellite, 4 launches would be required; to achieve 24/7 communications globally over all three ocean regions with GEO satellites, 12 launches would be required
There were also earth station considerations
A MEO system requires accurate earth station tracking, power balancing because of the variable path loss as the earth stations track.
Path A is a lot longer than path B and, since path loss increases as the square of the distance, power balancing will be needed to ensure that the power level at the satellite remains within acceptable limits.
A MEO system requires accurate earth station tracking, power balancing because of the variable path loss as the earth stations track, and – more importantly – two earth stations at each location to achieve hand-off between satellites following in sequence.
Hand-Off Between Satellites

To ensure no drop in communications, two earth stations are needed for a constellation of satellites that are not in geostationary orbit. Earth station 1 picks up a satellite in the constellation as it rises above the local horizon (link A) while earth station 2 is tracking a satellite that is just about to drop below the local horizon (link B).
LEO and MEO Efforts – 12

- A MEO system requires accurate earth station tracking, power balancing because of the variable path loss as the earth stations track, and – more importantly – two earth stations at each location to achieve hand-off between satellites following in sequence.

- But the real clincher was: a GEO system needed only a maximum of 12 launches while the MEO system required up to 40 launches to complete the system.

- The GEO architecture won the day.
Lecture 1 Outline – C

• Background
  • Transmission of information over long distances

• History of satellite communications
  • LEO and MEO efforts
  • GEO orbit
  • Interplanetary communications

• Recent advances in satellite communications
  • DBS, MSS, IP services
  • Big satellite? Or lots of networked satellites?
GEO orbit – 1

- Geostationary Earth Orbit (GEO) is a special case where the angular rotation of the satellite over the equator exactly matches the rotation of the Earth.
- The GEO orbital height is 35,786.03 km.
- This is the height above the Earth:
  - The radius of the Earth is 6,378.137; and
  - this gives the radius of GEO as 42,164.167 km.
- But the GEO satellites cannot reach the poles of the Earth. You need to have an inclined orbit to do this.

Molniya
Molniya orbit – 1

- The first commercial Highly Elliptical Orbit (HEO) satellite designed specifically to reach high latitude locations was Molniya
- Molniya means “Flash of lightning”
- The Molniya series were the second domestic satellite system
- Anik was the first

http://www.stk.com/corporate/partners/edu/AstroPrimer/primer96.htm
The key to the Molniya orbit is not just that it reaches well north or (if launched in the opposite sense) south, easily reaching either pole, but that the period of the orbit is exactly half a sidereal day.

Because the orbit is a half sidereal day, the orbital track repeats every other orbit: i.e., if the orbit went over Moscow on orbit 1, it will do so in orbit 3, 5, 7, etc.

By sequencing a series of Molniya satellites, any particular part of the orbit can be covered 24/7.
Molniya orbit – 3

This is the ground track of a Molniya satellite
View of the Earth from the apogee of a Molniya orbit designed to reach apogee at 0° longitude

Molniya orbit – 4

Molniya Orbit is
~500 to ~39,152 km
Back to the GEO orbit
GEO orbit – 2

- The Earth is rotating about its axis; it is also orbiting around the sun; the sun is orbiting around the center of the home galaxy (the “Milky way”); and the Milky Way is moving around the core of our part of the universe; etc., etc.

- It is therefore important to understand two concepts when dealing with Earth satellites
  - (a) The difference between a Solar day and a Sidereal day
  - (b) The difference between Inertial Space and Local Space
A solar day is about 24 hours and 1 minute. We use 24 hours for a day, and the minute “lost” every day is added every four years as one day in a “leap year”.

When the Earth rotates on its axis, it is also moving in its orbit around the sun. Each day, the Earth needs to rotate more than 360° to reach the same look angle towards the sun.

You can find an interesting animation of sidereal day at [http://physics.gac.edu/physlets/Chaisson/Prologue/ChaissonP_1.html](http://physics.gac.edu/physlets/Chaisson/Prologue/ChaissonP_1.html)
GEO orbit – 4

The orbit of the Earth around the sun from the first position shown on the left to the second position in the middle, necessitates an additional rotation of the Earth that corresponds to an additional 3 minutes and 56 seconds.

A Sidereal Day = 23 h 56 min 4.091 s
A Solar Day = 24 hours
Once launched, any satellite or interplanetary probe will have its pointing direction referenced to *Inertial Space*.

In the diagram, the reference point is given as a “distant star”, which will be essentially fixed in one direction as far as the relative motion of the satellite, i.e. in inertial space.
Three geostationary satellites, spaced 120° apart, can provide global coverage..

.. except at high latitudes
GEO satellites cannot “see” the poles. The elevation angle becomes 0° at longitudes 80.3°.

Earth radius = 6,378.14 km

GEO Orbital radius = 42,164.57 km

Ratio of GEO orbital radius to earth radius = 6.6
GEO orbit – 8

- GEO fact summary:
  - Orbital **height** = 35,786.03 km
  - Orbital **radius** = orbital height + Earth radius
    = 35,786.03 km + 6,378.137 km (average)
    = 42,164.17 km
  - Orbital **circumference** = 2 π 42,164.17 = 264,925.2935 km
  - Orbital velocity = 3.0747 km/s
  - Orbital period = 264,925.2935/3.0747
    = 23 h 56 minutes 4.091 seconds
    = one **sidereal day**
Communications Principles

- Satellites need to communicate with earth stations and, in some cases, with satellites, aircraft, UAVs, etc.
- Communications is established using agreed parts of the radio spectrum
- The ITU (International Telecommunications Union), an intergovernmental agency established through the United Nations has, as one of its departments, the IFRB – the International Frequency registration Board
- The IFRB allocates spectrum to users within the specified bands approved by the ITU
Radio Frequency Spectrum: Commonly Used Bands*

* See http://www.ntia.doc.gov/osmhome/allochrt.pdf for complete spectrum allocation
Satellites vs. Optical Fibers

- Telephone links via GEO satellites
  - A long way to travel (~80,000 km one way)
  - Round trip delay is ~500 ms – very noticeable

- Optical fibers provide competition for satellites
  - Much cheaper to operate than satellites
  - Have 30-year lifetime - do not have to be re-launched
  - Have huge capacity - 2.7 Gigabits/s per fiber is common
  - Guarantee lower Bit Error Rate (BER)

- Optical Fiber cannot be used to moving platforms
Satellites vs. *Terrestrial*

- Satellite systems can be deployed in 4-5 years, whereas terrestrial systems take longer.
- One satellite can cover the same region that it would take multiple base stations of a terrestrial system to cover.
  - Better for covering sparsely populated areas.
- Of course, satellite systems cost a lot.
  - Careful studies must be done to assure success – IRIDIUM.
- A satellite failure can have catastrophic results, but:
  - Launch reliability is currently >95%.
  - Most satellites proven to be reliable beyond predicted lifetime.
Satellite System Elements: Overview
Satellite System Elements: Space Segment – 1

- Satellite launch phase
- Transfer orbit phase
- Deployment
- Operation
  - TT&C - tracking telemetry and command station:
  - SCC – satellite control center, a.k.a.:
    - OCC – operations control center
    - SCF – satellite control facility
- Retirement phase
Satellite System Elements: Space Segment – 2

- Satellite launch phase
- Transfer orbit phase
- Deployment
- Operation
  - TT&C - tracking telemetry and command station:
    - SCC – satellite control center, a.k.a.:
      - OCC – operations control center
      - SCF – satellite control facility
- Retirement phase

Too much space debris!
Space Debris

93% of orbiting objects are NOT operational.

Only 43% of GEO satellites appear to have been de-orbited correctly (raised 300 km in their orbit)

There is an increasingly significant risk of collisions.

Jodi Kressin
Spring 2009
Satellite System Elements: Ground Segment

Collection of facilities, users, and applications

Earth Station = Satellite Communication Station (air, ground or sea, fixed or mobile).

FSS – Fixed Satellite Service
MSS – Mobile Satellite Service
Basic Principles: Signals (1)

- **Signals**
  - Carried by wires as voltage or current
    - Increasingly relying on fiber optic cables
  - Transmitted through space as electromagnetic waves
  - Analog
    - Voltage or current proportional to signal
    - E.g. Telephone
  - Digital: Generated by computers
    - Binary = 0 and 1 corresponding to 1 Volt [V] and –1 V
    - Ternary = 0, 1, or 2
Basic Principles: Signals (2)

• Sine waves
  – Carry no information
  – Sine wave frequency is the carrier (center) frequency of the data
• Data (information) is impressed onto the sine wave (carrier) by modulation
  – Results in signal (carrier plus data) occupying finite frequency band (bandwidth)
• Modulation: Vary a parameter of the sine wave based on the information content
  – ASK, FSK, or PSK
Basic Principles: Separating Signals (1)

- **Uplink and Downlink**
  - **FDD**: Frequency Division Duplexing
    - $f_1 = \text{Uplink}$
    - $f_2 = \text{Downlink}$
  - **TDD**: Time Division Duplexing
    - $t_1 = \text{Up}, t_2 = \text{Down}, t_3 = \text{Up}, t_4 = \text{Down}, \ldots$
- **Polarization**
  - V & H linear polarization
  - RH & LH circular polarizations
- **Spatial**
Basic Principles: Separating Signals (2)

- **Between users or “channels” (multiple access):**
  - **FDMA:** Frequency Division Multiple Access
    - $f_1 = \text{User 1}$
    - $f_2 = \text{User 2}$  (Refers to carrier frequencies)
    - $f_3 = \text{User 3}$
  - **TDMA:** Time Division Multiple Access.
    - $t_1 = \text{User 1}$,  $t_2 = \text{User 2}$,  $t_3 = \text{User 3}$,  $t_4 = \text{User 4}$, ...
  - **CDMA:** Code Division Multiple Access
    - Code 1 = User 1; Code 2 = User 2; Code 3 = User 3
Basic Principles: System Block Diagram

EARTH STATION TRANSMITTER
- Source Data from User
- Source Coding
- Channel Coding
- Modulator
- HPA
- Antenna
- To Satellite (Uplink)
- (Carrier)

EARTH STATION RECEIVER
- Source Data To User
- Source Decoder
- Channel Decoder
- Demodulator
- LNA
- Antenna
- From Satellite (Downlink)
- (Carrier)
Basic Principles: Satellites (Typical Transponder)

- Responsible for frequency translation
  - From uplink ($f_1$) to downlink ($f_2$) (FDD)
- Linear and non-linear transponders
- Movement is from passive to active satellites
  - Passive: No on-board processing ("transponds" signal)
  - Active: On-board processing (detects and manipulates)
Basic Principles: Satellites (Typical Transponder)

- **Responsibility for frequency translation**
  - From uplink \(f_1\) to downlink \(f_2\) (FDD)
- **Linear and non-linear transponders**
- **Movement is from passive to active satellites**
  - Passive: No on-board processing (“transponds” signal)
  - Active: On-board processing (detects and manipulates)
Passive, linear transponder

- LNA
- Image reject
- BPF
- Mixer
- 1 GHz BPF
- IF amplifier

Uplink:
- 14 GHz
- First LO: 13 GHz
- Mixer
- Second LO: 10 GHz
- 11 GHz BPF
- LPA
- HPA
- Downlink: 11 GHz

Ku-band Bent Pipe Transponder
Active, processing transponder

LNA

Image reject BPF Mixer 1 GHz BPF 1 GHz IF amplifier

First LO 13 GHz

Mixer 14 GHz Second LO 10 GHz

11 GHz BPF LPA HPA 11 GHz

Regenerative repeater – On-board processing

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Lecture 1 Outline – D

- Background
  - Transmission of information over long distances
- History of satellite communications
  - LEO and MEO efforts
  - GEO orbit
  - Interplanetary communications
- Recent advances in satellite communications
  - DBS, MSS, IP services
  - Big? Or lots of networked satellites?
The Solar System – 2

- Distances are vast by terrestrial standards
- The Earth orbits 93,000,000 million miles from the sun (~1.4967 \times 10^{11} \text{ meters})
- Light, traveling at $3 \times 10^{8} \text{ m/s}$, takes almost 500 seconds to reach the Earth from the sun
- To help deal with the huge distances, the radius of the Earth’s orbit is called 1 Astronomical Unit (AU)
- The other planets in the solar system are:
The Solar System – 3

<table>
<thead>
<tr>
<th>Planet</th>
<th>AU distance from sun</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mercury</td>
<td>0.31 to 0.46</td>
</tr>
<tr>
<td>Venus</td>
<td>0.72</td>
</tr>
<tr>
<td>Earth</td>
<td>1.00</td>
</tr>
<tr>
<td>Mars</td>
<td>1.52</td>
</tr>
<tr>
<td>(Asteroid Belt)</td>
<td>~ 2.5 to 3.5</td>
</tr>
<tr>
<td>Jupiter</td>
<td>5.20</td>
</tr>
<tr>
<td>Saturn</td>
<td>9.53</td>
</tr>
<tr>
<td>Uranus</td>
<td>19.18</td>
</tr>
<tr>
<td>Neptune</td>
<td>30.05</td>
</tr>
<tr>
<td>(Pluto)</td>
<td>39.46</td>
</tr>
</tbody>
</table>
The Solar System – 3A

- Planet
  - Mercury: 0.31 to 0.46 AU
  - Venus: 0.72 AU
  - Earth: 1.00 AU
  - Mars: 1.52 AU
  - (Asteroid Belt): ~2.5 to 3.5 AU
  - Jupiter: 5.20 AU
  - Saturn: 9.53 AU
  - Uranus: 19.18 AU
  - Neptune: 30.05 AU
  - (Pluto): 39.46 AU
The Solar System – 4

- To send a signal from Earth to Mars requires crossing a distance that varies from 0.52 AU to 2.52 AU.
- The time of travel for a signal will therefore vary between 260 and 1,260 seconds.
- Mars has an orbital velocity of 86,871 km/h and Earth has an orbital velocity of 107,229 km/h.
- Will the orbital velocities create communications problems?
- Let’s look at the nearest approach (0.52 AU).
The Solar System – 5

107,229 km/h
Earth

86,871 km/h
Mars

0.52 AU = 7.7828 × 10^{10} meters

We will assume a 2 meter antenna operating at 10 GHz:
What will the physical width of the beam be at 0.52 AU?
Will the planet move out of the beamwidth in the transit time?
We will look at a signal from Mars to Earth
The Solar System – 6

- Frequency of 10 GHz gives a wavelength of 0.03 m
- Beamwidth = $1.2\lambda/D$ radians = $1.2 \times \frac{0.03}{2}$ = 0.018 radians = 1.0313°
- Width of beam at 0.52 AU = $r \times \theta$ = $7.7828 \times 10^{10} \times 0.018$ = 1,400,911,200 meters
- A velocity of 107,229 km/h will cross this distance in about 13 hours, which is about 47,000 seconds
- The transit time from Mars to Earth is 259 seconds
- The transmit and receive beams can accommodate this
The Solar System – 7

- But what if optical communications is used?
- Assuming the same antenna diameter but at a frequency of 200 THz we have
  - A beamwidth of $9 \times 10^{-7}$ radians
  - A physical beam width of 70,045.2 meters
  - A velocity of 107,229 km/h will cross this distance in 2.35 s
- The transit time from Mars to Earth is 259 seconds
  - The receive end of the link will not be in the beam when the signal arrives unless the transmit antenna points ahead
The Solar System – 8

- NASA is investigating optical communications systems for future planetary missions.
- Optical communications will most likely use Pulse Position Modulation rather than on-off switching to convey the information.
- Accurate timing, acquisition, and tracking are key elements yet to be demonstrated operationally for optical communications systems.
- Nevertheless, using optical systems is the way to go.
Lecture 1 Outline – E

- **Background**
  - Transmission of information over long distances

- **History of satellite communications**
  - LEO and MEO efforts
  - GEO orbit
  - Interplanetary communications

- **Recent advances in satellite communications**
  - DBS, MSS, IP services
  - Big? Or lots of networked satellites?
DBS, MSS, IP Services – 1

- DBS (Direct Broadcast Satellites) systems have provided the greatest revenue growth over the last couple of decades

$14.75 Billion in 2006
$17.25 Billion in 2007

..

24.10 Billion in 2010
DBS, MSS, IP Services – 2

- DBS (Direct Broadcast Satellites) systems have provided the greatest revenue growth over the last couple of decades.

- MSS (Mobile Satellite Services) have been able to grow through maritime and other regions where a terrestrial alternative is not available. However, the next generation of really large MSS satellites will start to be competitive in economic growth areas.
DBS, MSS, IP Services – 3

TerreStar-1

Designed to provide integrated 4G hybrid mobile phone service over the continental USA, Hawaii, and Canada.

Hybrid in this context means via direct links to the hand sets and via terrestrial base stations

Antenna diameter is around 40 feet

DBS, MSS, IP Services – 4

- DBS (Direct Broadcast Satellites) systems have provided the greatest revenue growth over the last couple of decades.
- MSS (Mobile Satellite Services) have been able to grow through maritime and other regions where a terrestrial alternative is not available. However, the next generation of really large MSS satellites will start to be competitive in economic growth areas.
- But, whatever the service, the links are migrating to IP-based protocols.
The Challenges

- How do you provide high-speed, *two-way*, Internet access?
  - Earlier split-IP services did not catch on
  - Areas that can afford such services are usually well served by terrestrial systems
  - How do you obviate propagation problems?

- How do you migrate streaming video that is being introduced into terrestrial mobile to MSS systems?

- How do you handle hand-off between MSS GEO cells with a 460 ms round trip delay?
Current Trends

- Higher-powered satellites
- Deployable, unfurlable antennas
- Multi-service platforms
- Huge growth in IP-Based services fueled by Internet demand
- Expansion into Ka, Q, and V Bands (30.20, 50/40 GHz)
DBS, MSS, IP Services – 7

• Current Trends
  • Higher-powered satellites
  • Deployable, unfurlable antennas
  • Multi-service platforms
  • Huge growth in IP-Based services fueled by Internet demand
  • Expansion into Ka, Q, and V Bands (30.20, 50/40 GHz)
• LEO systems are being upgraded

Second generation Globalstar system was ordered in July 2009 for a cost of $738 million – including launches. Second generation Iridium is under design.
Current Trends
- Higher-powered satellites
- Deployable, unfurlable antennas
- Multi-service platforms
- Huge growth in IP-Based services fueled by Internet demand
- Expansion into Ka, Q, and V Bands (30.20, 50/40 GHz)
- LEO systems are being upgraded
- Some new satellite systems will dictate very large satellite buses that need a lot of power: so
Lecture 1 Outline

- Background
  - Transmission of information over long distances
- History of satellite communications
  - LEO and MEO efforts
  - GEO orbit
  - Interplanetary communications
- Recent advances in satellite communications
  - DBS, MSS, IP services
  - Big satellite? Or lots of networked satellites?
The first satellites were small, carrying few experiments. As launch vehicles became bigger, satellites increased in size and began to carry many experimental payloads. Large satellites, with many payloads, often had conflicting requirements for each of the experiments (e.g. ATS-6). Large military satellites also were required to meet many mission targets (e.g. MILSTAR\(^1\)).

\(^1\) http://milsatcom.tripod.com/advanced_ehf/00_07_26_milsta.html
Single Big Satellite, or Several Networked Satellites – 2

60 GHz cross-links

44 GHz up/20 GHz downlinks

UHF up/down-links
Designing, integrating, and launching large, complex satellites is very expensive in both time and money.

Such billion dollar plus assets are vulnerable to both launch failure and, for military satellites, to anti-satellite missiles.

Both NASA and the department of Defense are starting to look at small, dedicated satellites with mission-specific payloads.

First: some definitions
Satellites are often broken down into mass classes:

- "Dry" mass is when the satellite is empty of all fuel;
- "Wet" mass is the fully fueled satellite mass.

### Wet Mass

<table>
<thead>
<tr>
<th>Group Name</th>
<th>Wet Mass</th>
</tr>
</thead>
<tbody>
<tr>
<td>Large satellite</td>
<td>&gt; 1,000 kg</td>
</tr>
<tr>
<td>Medium satellite</td>
<td>500 – 1,000 kg</td>
</tr>
<tr>
<td>Mini satellite</td>
<td>100 – 500 kg</td>
</tr>
<tr>
<td>Micro satellite</td>
<td>10 – 100 kg</td>
</tr>
<tr>
<td>Nano satellite</td>
<td>1 – 10 kg</td>
</tr>
<tr>
<td>Pico satellite</td>
<td>0.1 – 1 kg</td>
</tr>
<tr>
<td>Femto satellite</td>
<td>&lt; 100 kg</td>
</tr>
</tbody>
</table>

For more details, visit: [http://centaur.sstl.co.uk/SSHP/sshp_classify.html](http://centaur.sstl.co.uk/SSHP/sshp_classify.html)
But there is a lot of competition for the small/micro/nano-satellite market
Single Big Satellite, or Several Networked Satellites – 6

- SpaceQuest, Fairfax, VA is launching a pair of microsatellites (AprizeSat 3 and -4; 12 kg. each) in late 2009 on a Russian Dnepr launcher from Baikonur.
- On the same rocket is a satellite from the leader in microsatellite development (Surrey Satellite Technology, Ltd.), called NanoSat-1.
- Slightly larger is a Satrec Satellite called DubaiSat-1 (200 kg.). The first Satrec satellite was orbited on SpaceX Falcon 1 rocket on July 14th, 2009.
Why would you need to have very small satellites?
- They can be single-payload satellites
- A group of small satellites can ‘share’ the payload of a large satellite
- More importantly, a group of small, relatively widely spaced satellites are less vulnerable to a single missile hit
- Networking satellites together is fast becoming a reality through IP technology\(^{(1)}\)

\(^{(1)}\) http://swik.net/Intelsat
Interorbital Systems (IOS), a U.S.-based rocket and spacecraft manufacturing company, is marketing the launch and orbit of personal-use satellites to the general public, the company announced August 4th, 2009.

“The spacecraft, named TubeSat Personal Satellite (PS), can be purchased for $8000, which includes the price of a launch into Low-Earth-Orbit about 310 kilometers (192 miles) above the Earth's surface on an IOS Neptune 30 launch vehicle.”

Most commercial satellite systems owe much of their technology to military developments.

Military requirements place a premium on network connectivity for all their assets, whether they are in space, on manned aircraft, UAV’s, or on the ground.

Commercial satellite systems have yet to follow this route, but it is likely that, around 2025, these satellite systems will have significant interconnectivity in much the same way as terrestrial mobile systems do today.
Single Big Satellite, or Several Networked Satellites – 10

However
“Intelsat 14 includes a ‘condosat’ arrangement for the Internet Router In Space (IRIS). The IRIS payload is part of a Department of Defense Joint Capabilities Technology Demonstration (JCTD) to assess the utility of a space-based computer processor that will enable U.S. military units and allied forces to communicate with one another using Internet protocol and existing ground equipment. The IRIS payload is expected to enhance satellite performance and reduce signal degradation from atmospheric conditions.” [1]
INTELSAT 14 – 1  (© SS-Loral, 2009)
INTELSAT 14 – 2

- INTELSAT 14 was successfully launched into geostationary transfer orbit by an Atlas V rocket on November 23rd, 2009.
- Satellite will be located at 315° E following in-orbit tests.
- Please see: http://www.satellitetoday.com/st/headlines/32929.html (extracted November 24th, 2009)
Intelsat announced in July 2009 that it will be launching a multi-mission satellite, Intelsat 22, in 2012. Intelsat 22 will carry the normal C-band and Ku-band commercial communication payload, but in addition it will carry a UHF military payload for use by the Australians (20% of the total payload). Multi-mission satellites have become possible with the modular design of spacecraft buses that allow “mix-and-match” payload designs.
INTELSAT 22 (© Boeing, 2009)