Satellite Systems

Outline

- Introduction
- Types of Satellites
- Characteristics of Satellite Systems
- Satellite System Infrastructures
- Call Setup and Handoff
- GPS
- Inter-Satellite Routing

Introduction

- Satellites are high above the earth and able to cover a larger area.
- Satellite relay: data transmitted from a mobile user is received by a satellite and forwarded to one of the earth stations (ESs).
- This makes the *Line of Sight* (LoS) communication to cover a much larger area and through a longer distance.

Application Areas of Satellite Systems

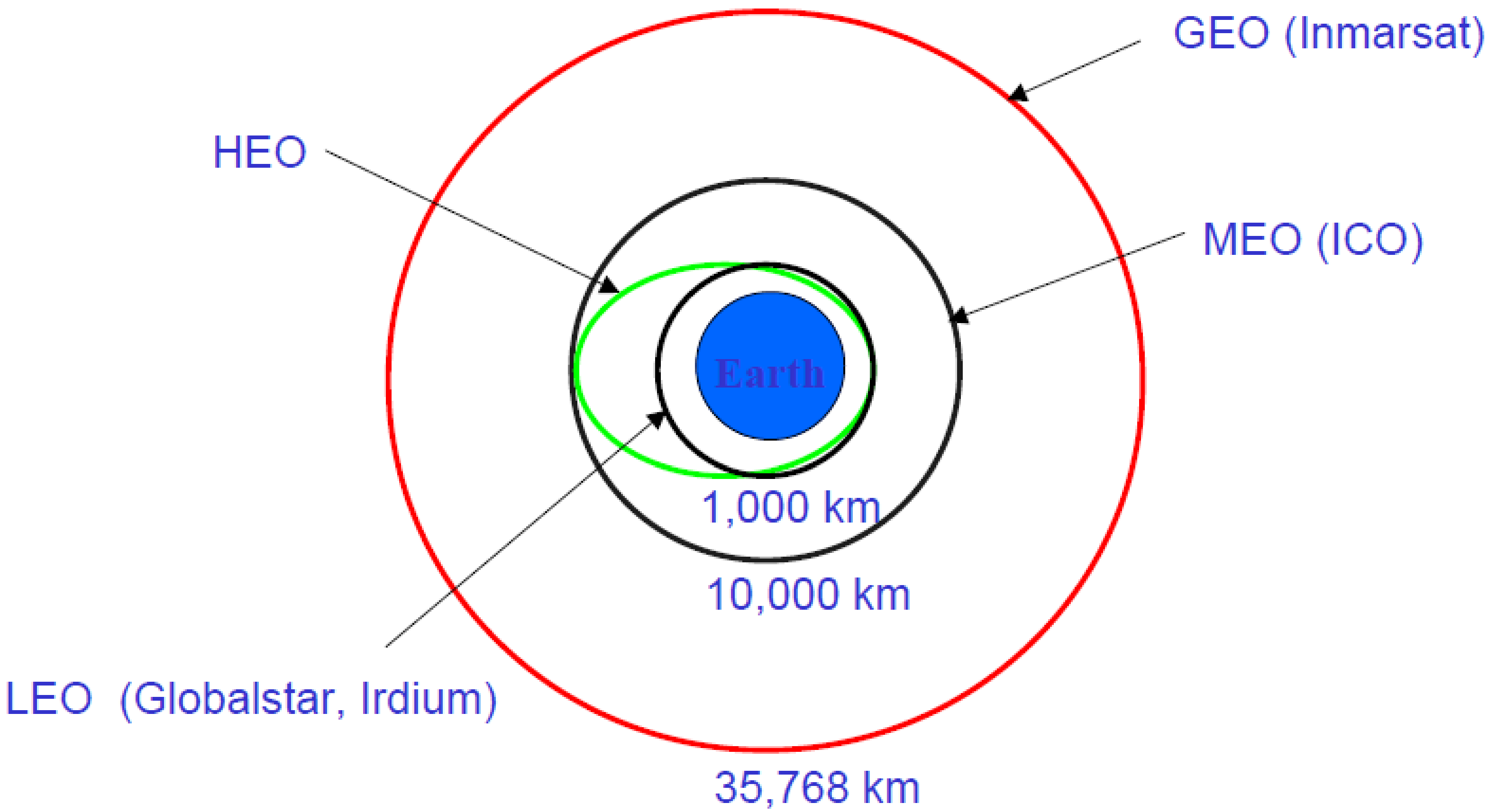
- Traditionally
  - Meteorological satellites
  - Radio and TV broadcast satellites
  - Military satellites
- Telecommunications
  - Satellites for navigation and localization (e.g GPS)
  - Global mobile communication (particularly in remote areas)
  - Backbone for global networks

Types of Satellite Systems

Four types of satellite orbits, classified according to the shapes and diameters of their orbits:

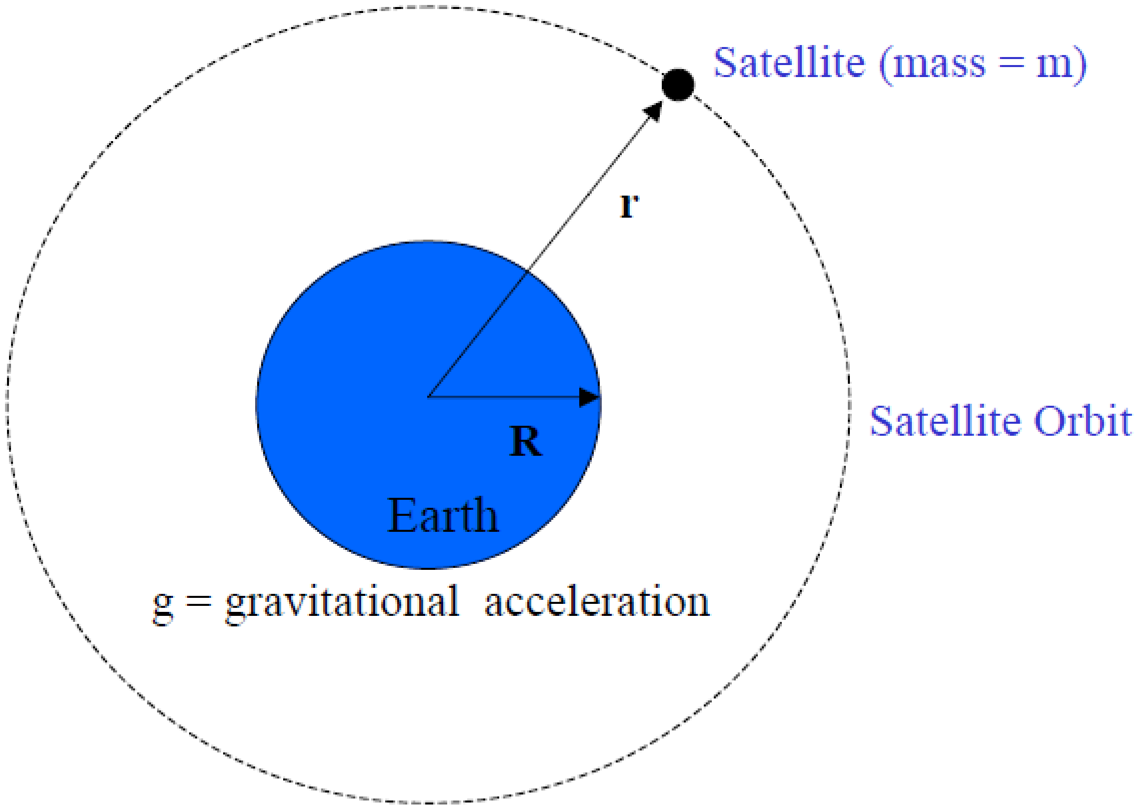
- LEO (Low Earth Orbit) at 500-1,500 kms above earth surface.
- MEO (Medium Earth Orbit) or ICO (Intermediate Circular Orbit) at 6,000-20,000 kms above earth surface.
- HEO (Highly Elliptical Orbit).
- GEO (Geostationary Earth Orbit) at 36,000 kms above earth surface.

Orbits of Different Satellites



Orbits of different satellites

Stable Orbiting Path of Satellites



Earth-Satellite Parameters

- Orbits could be elliptical or circular.
- Rotation time depends on the distance between the satellite and the earth.
- For satellites following circular orbits, applying Newton's gravitational law:

  F_g (attractive force) = $mg\,(R/r)^2$

  F_c (centrifugal force) = $mr\omega^2$

  $\omega = 2\pi f$

Where, m = *mass of the satellite*

g = *gravitational acceleration* ($9.81\ m/s^2$)

R = *radius of the earth (6,370 kms)*

r = *distance of the satellite to the center of earth*

ω = *angular velocity of satellite*

f = *rotational frequency*

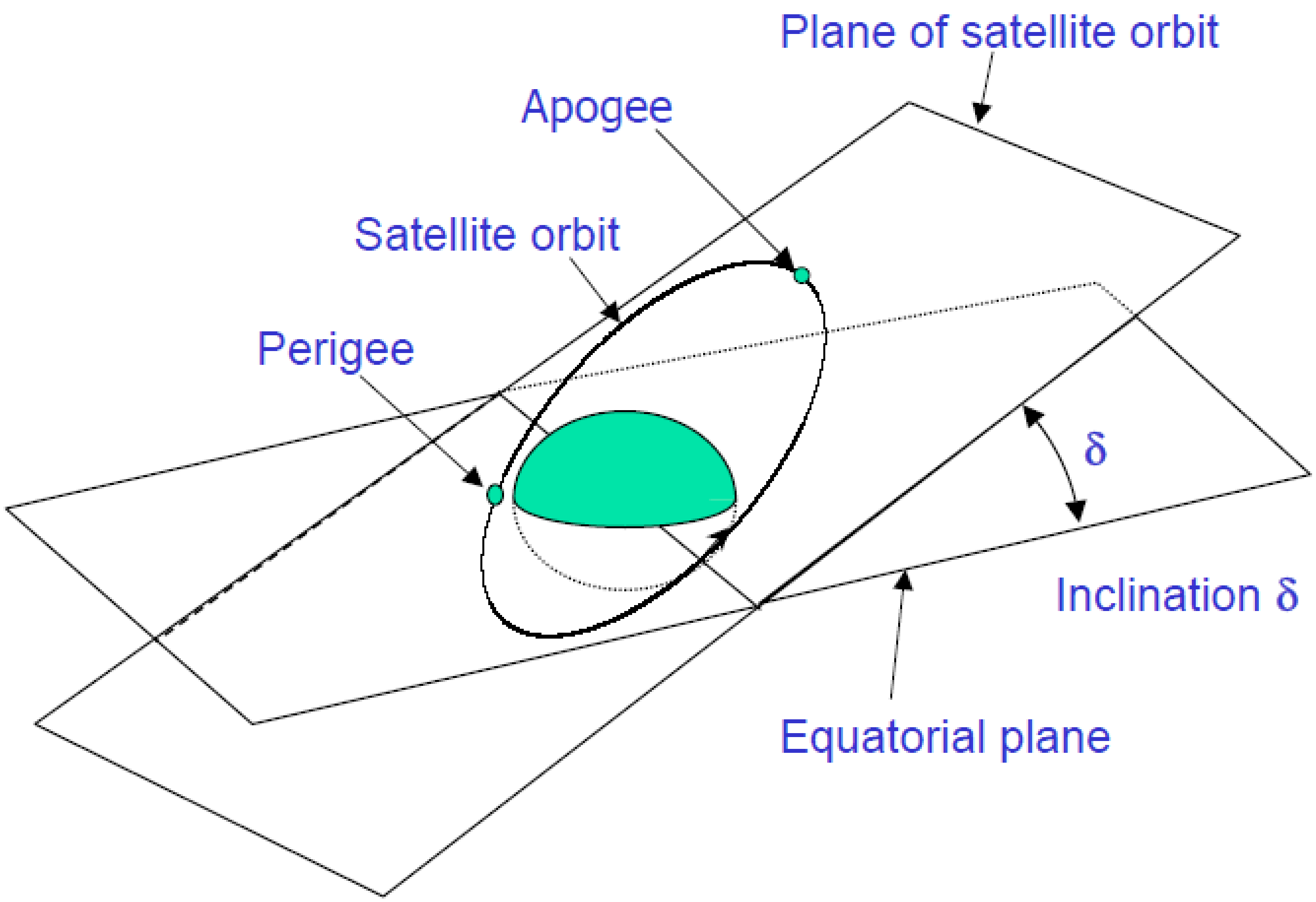
Earth-Satellite Parameters

- For the orbit of the satellite to be stable, we need to equate the two forces:
  $mg\,(R/r)^2 = mr\omega^2$, where $\omega = 2\pi f$

  Thus,

$$r = \sqrt[3]{\frac{gR^2}{(2\pi f)^2}}$$

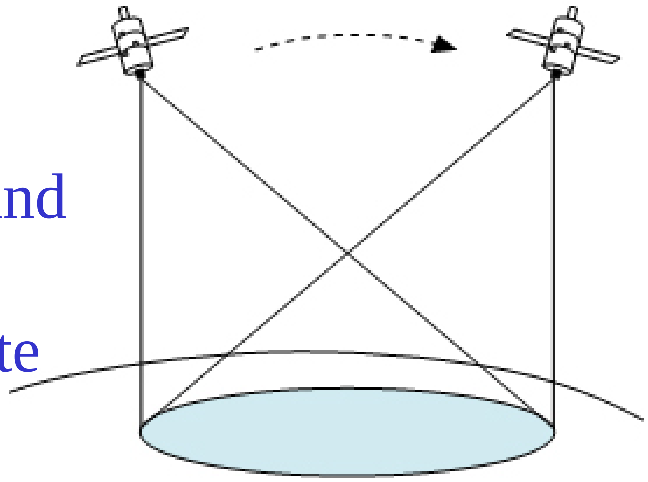
Inclination of satellite orbit plane



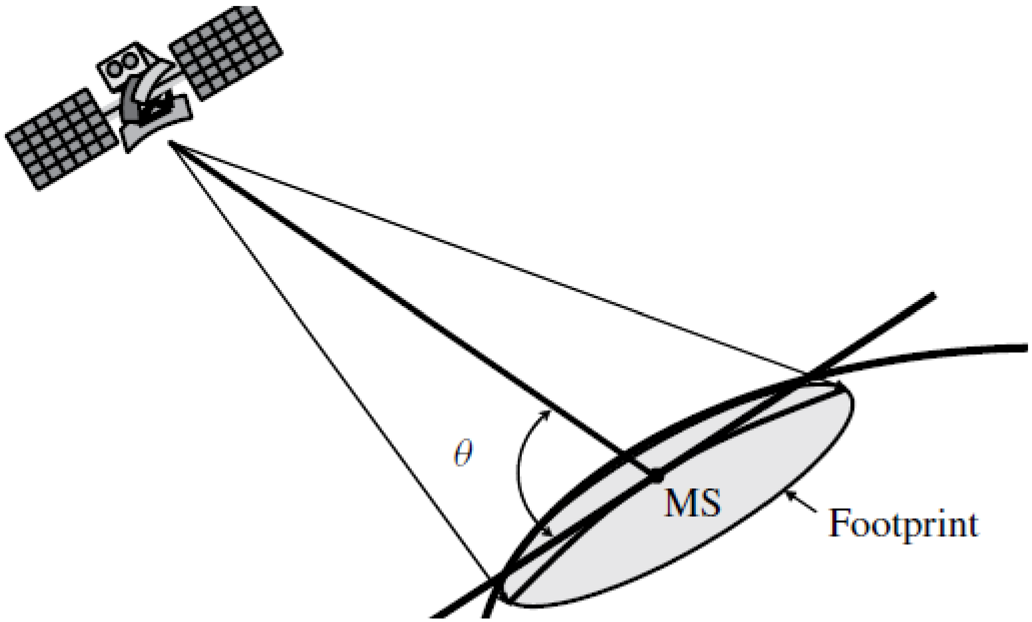
The plane of the satellite orbit with respect to earth

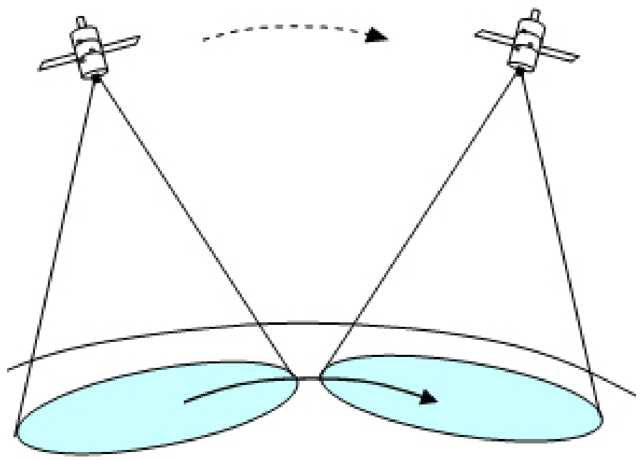
Footprint and Elevation Angle

- The area inside the circle on earth is called the footprint of the beam.
- There are two types of footprint: moving footprint and fixed footprint (fixed only for a period of time).
- Elevation angle θ: Angle θ between center of satellite beam and targeted area on earth, $0 \le \theta \le 90^o$.
- Minimal elevation angle: minimal θ that is required for a satellite to communicate with earth.



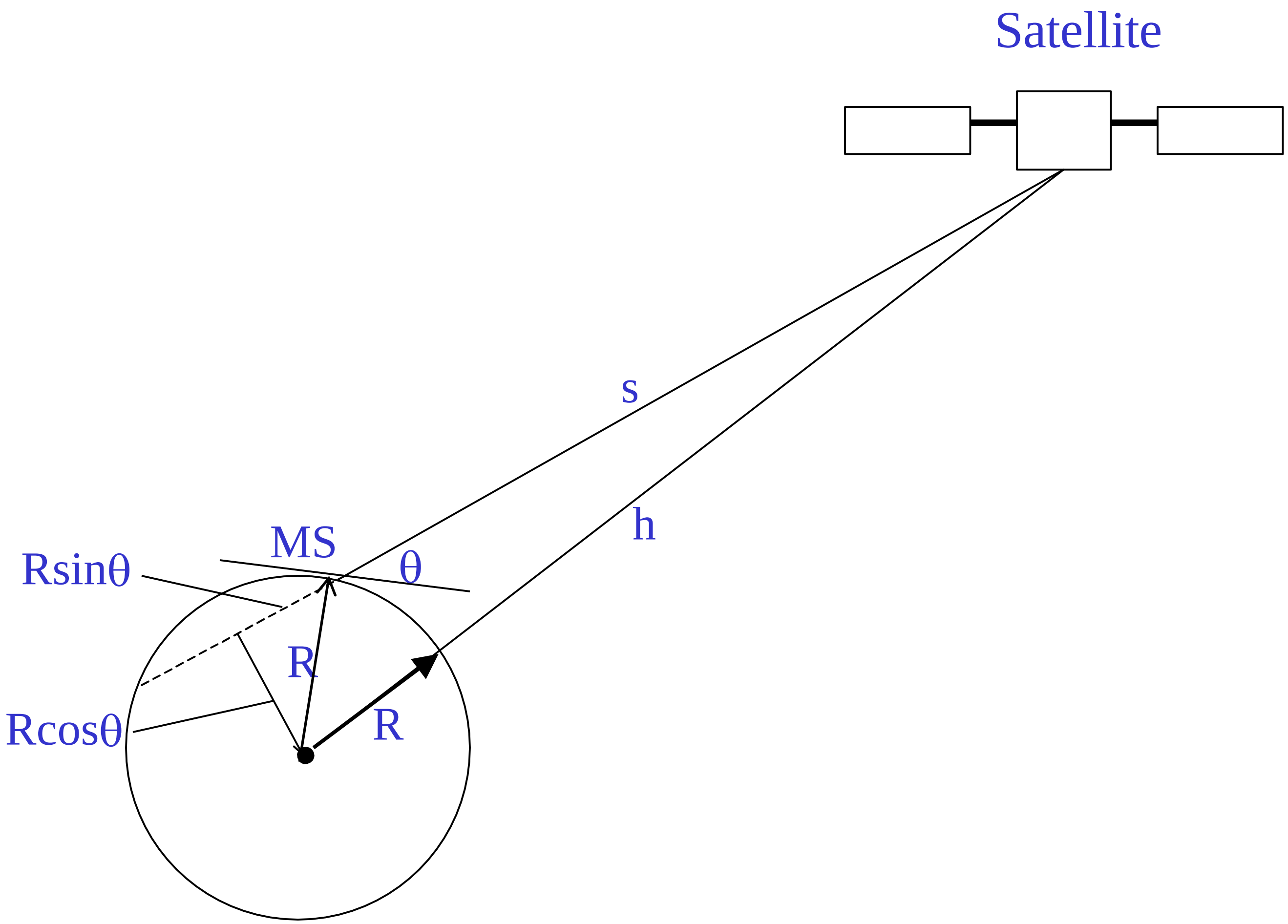
Fixed footprint





Moving footprint

Distance from Satellite to MS



$$Delay = \frac{s}{c} = \frac{1}{c}\left(\sqrt{(R+h)^2 - R^2\cos^2\theta} - R\sin\theta\right)$$

Communication Delay between Satellite and MS

- The figure shows the path *s* taken for communication from a MS to the satellite.
- The time delay is a function of various parameters and is given by:

$$Delay = \frac{s}{c} = \frac{1}{c}\left(\sqrt{(R+h)^2 - R^2 \cos^2\theta} - R\sin\theta\right)$$

where, R= radius of the earth

h = orbital altitude

θ = satellite elevation angle

c= speed of light

Frequency Bands for Up/Down links

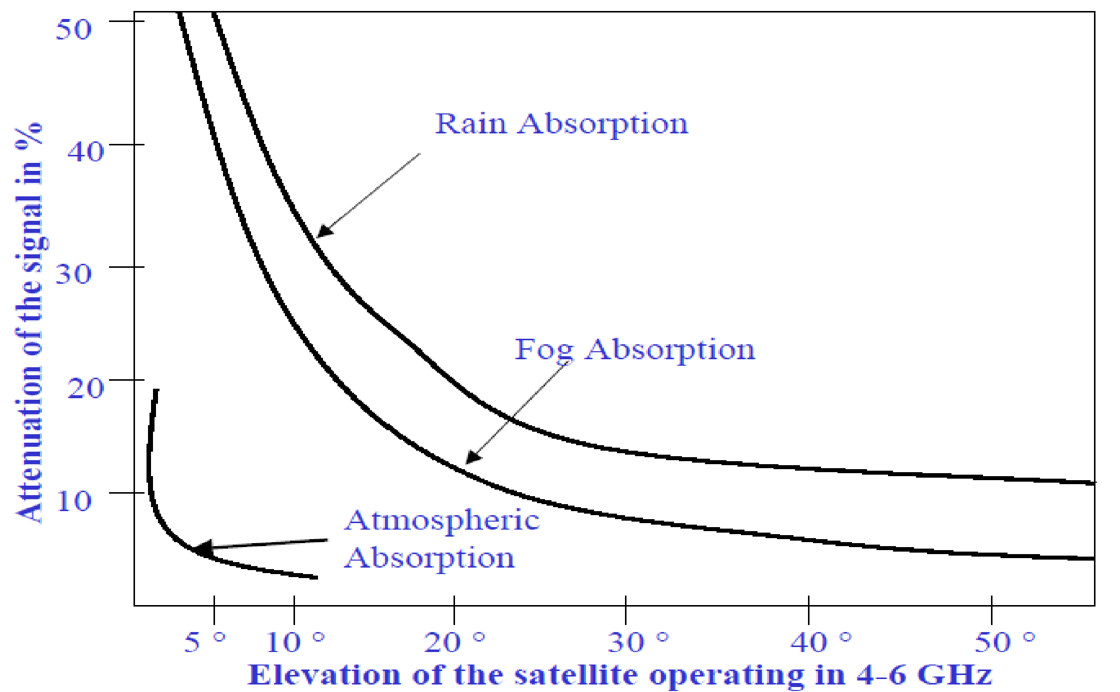
The satellites operate in different frequencies for up/down links

Band	Uplink (GHz)	Downlink (GHz)
C	3.7-4.2	5.925-6.425
Ku	11.7-12.2	14.0-14.5
Ka	17.7-21.7	27.5-30.5
L and S	1.610-1.625	2.483-2.50

- C band frequencies have been used in the first generation satellites and has become overcrowded because of terrestrial microwave networks using these frequencies.
- Ku and Ka bands are becoming more popular, even though they suffer from higher attenuation due to rain
- L and S bands are used by GEO/LEO satellites (GPS)

Transmission Power Characteristics

- Satellites receive signals at very low power levels (less than 100 pico-watts), one to two orders of magnitude lower than the terrestrial receivers (1 to 100 micro-watts)
- Received power is determined by the following parameters:
  - Transmitting Power
  - Distance between transmitter and receiver
  - Gain of transmitting / receiving antennas
  - Elevation angle
  - Weather conditions



Basic Parameters of Satellite Systems

- Satellites weigh around 2,500kg.
- A satellite typically has a large footprint – 34% of earth's surface is covered.
- When a satellite is close to north/south pole, it is undesirable to relay communication, as it is far away from the equator (elevation angle is too small and signal quality is poor).
- Ku band frequencies (11 GHz and 13 GHz) are allocated for connection between the ES and the satellites.

Characteristics of Satellite Systems

- LEO satellites are classified into little and big satellites:
  - Little LEO satellites are smaller in size, in the frequency range 148-150.05MHz (uplink) and 137-138MHz (downlink). Support only low bit rates (in the order of 1 kb/s) for bi-directional communication (non-voice).
  - Big LEO satellites have adequate power and bandwidth to provide mobile services like data transmission, paging etc. It uses frequency range 1,610-1,626.5MHz (uplink) and 2,483.5-2,500MHz (downlink).
- LEOs orbit around 500-1,500km above the earth surface and have latency around 5-10ms.
- MEOs orbit at a height of about 5,000 – 12,000km, and have a latency around 70-80ms.
- GEO satellites are at an altitude of 35,768 km and rotate exactly one round per day.
  - Orbits are in equatorial plane with 0 degree inclination (synchronous)
  - Use 1,634.5-1,660.5MHz (uplink) and 1,530-1,559MHz (downlink)
  - Latency?

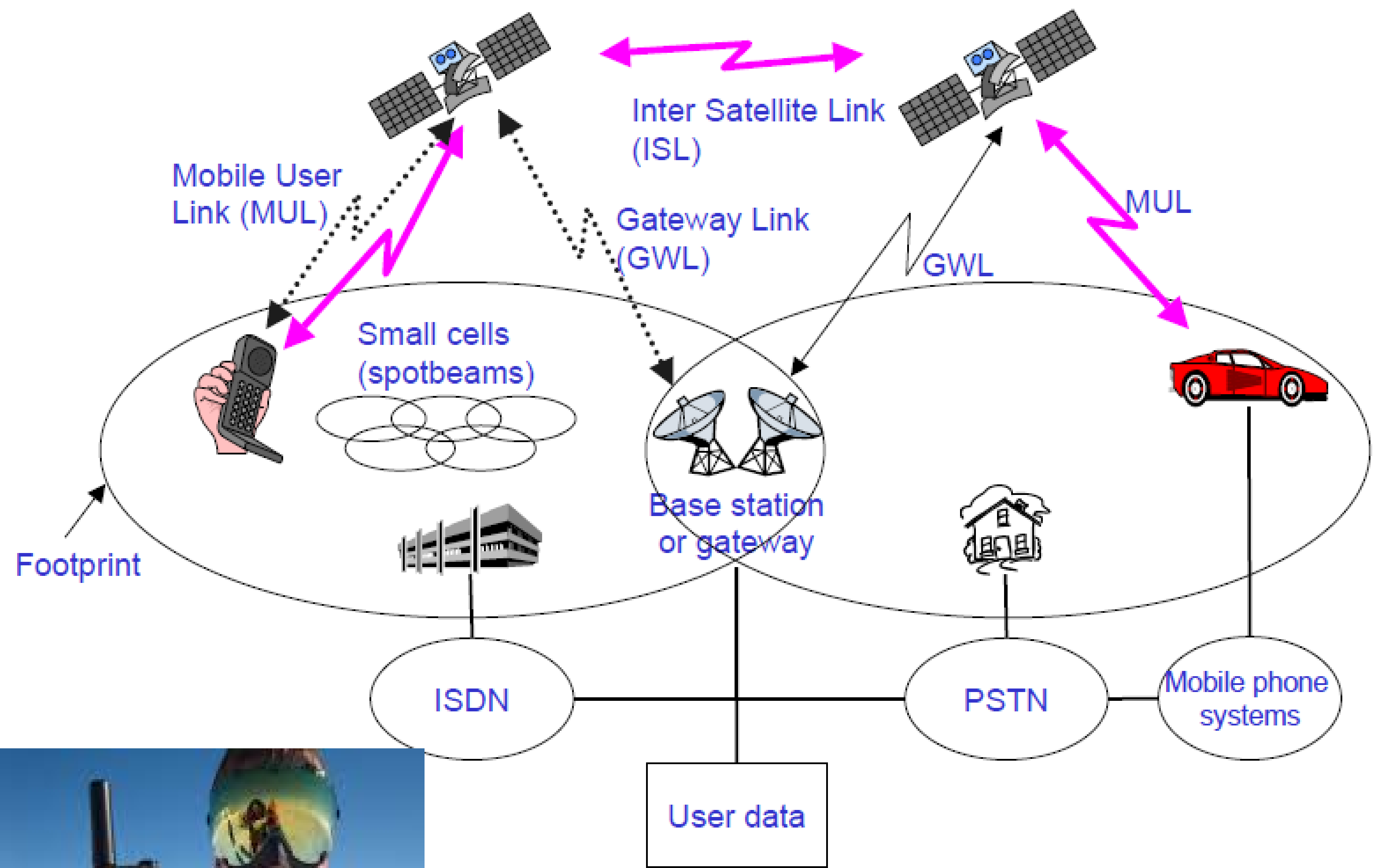
Little LEOs

System	Orbcomm	LEO One	Final Analysis
Company	Orbcomm, Orbital Sciences	LEO One	Final Analysis, General Dynamics Info Systems
Service Types	messaging, paging, e-mail	messaging, paging, e-mail	messaging, e-mail, file transfer
Voice (kbps)	-----	-----	-----
Data Rate	2.4 kbps uplink 4.8 kbps downlink	2.4-9.6 kbps uplink 24 kbps downlink	TBD
Orbit Altitude (km)	825	950	1000
No. of Satellites	48	48	38
No. of Orbit Planes	3	8	7
Earth Stations	10	20	7
Mobile Uplink	148-150 MHz	148-150 MHz	VHF/UHF
Mobile Downlink	137-138 MHz, 400 MHz	137-138 MHz	137-138 MHz
Feeder Uplink	148-150 MHz	148-150.5 MHz	VHF/UHF
Feeder Downlink	137-138 MHz, 400 MHz	400.15-401 MHz	VHF/UHF
ISL	No	No	No
Service Date	1996	2002	2001

Big LEOs

System	Iridium	Globalstar	Constellation Communications
Company	Motorola	Loral, Alcatel, Qualcomm	Orbital Sciences, Bell Atlantic, Raytheon
Service Types	voice, data, fax, paging, messaging	voice, data, fax, paging, messaging	voice, data, fax
Voice (kbps)	2.4	adaptive 2.4 / 4.8 / 9.6	2.4
Data (kbps)	2.4	7.2	28.8
Orbit Altitude (km)	780	1410	2000
Number of Satellites	66	48	46
Orbit Planes	6	8	8
Earth Stations	15 - 20	100 - 210	TBD
Beams / Satellite	48	16	24/32
Footprint Dia. (km)	4700	5850	TBD
Mobile Uplink (MHz)	1616 - 1626.5 (L-band)	1610 - 1626.5 (L-band)	2483.5 - 2500 (S-band)
Mobile Downlink (MHz)	1616 - 1626.5 (L-band)	2483.5 - 2500.0 (S-band)	1610 - 1626.5 (L-band)
Feeder Uplink (GHz)	27.5 - 30.0 (Ka-band)	5.091 - 5.250 (C-band)	5.091 - 5.250 (C-band)
Feeder Downlink (GHz)	18.8 - 20.2 (Ka-band)	6.875 - 7.055 (C-band)	6.924 - 7.075 (C-band)
ISL	Yes (4)	No	No
Service Date	1998	2000	2001

Structure of a Satellite System

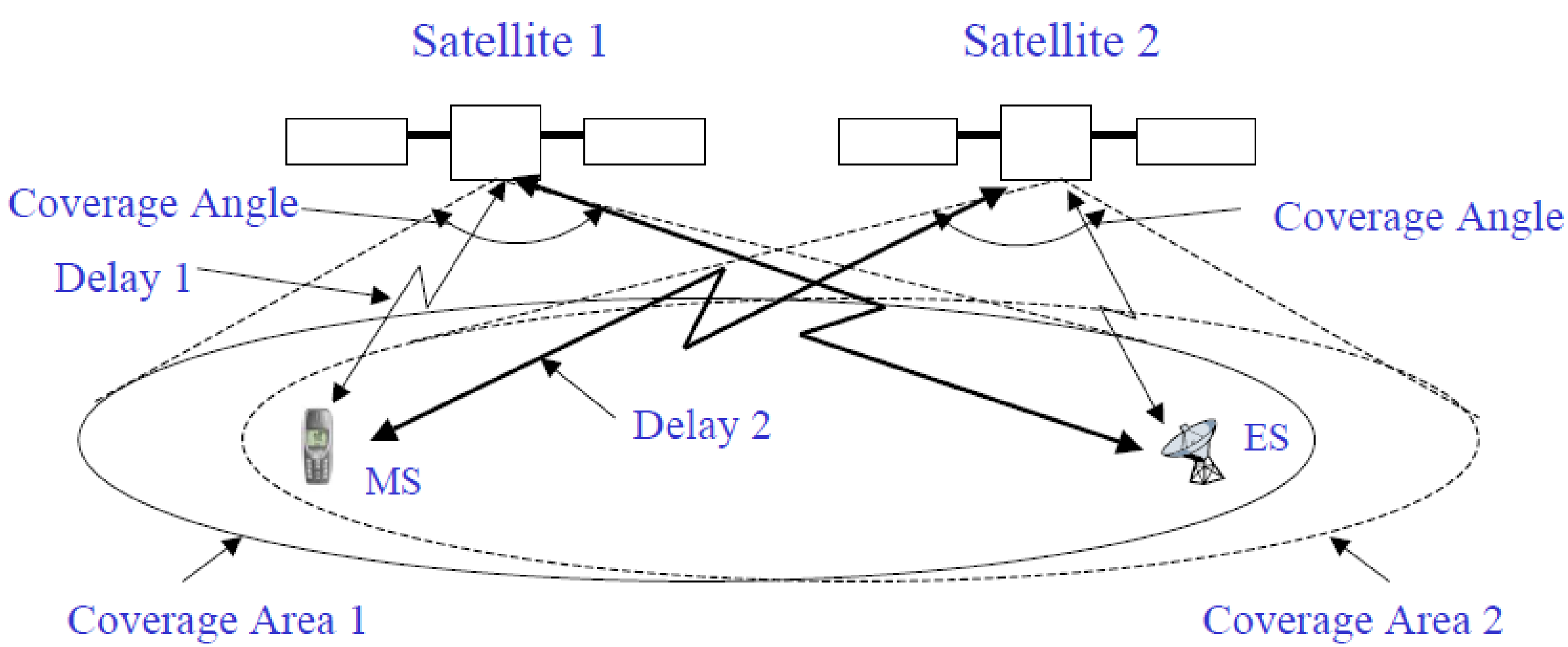


Satellite System Infrastructure

- When a MS establishes a connection with a satellite using a LoS beam, it connects the rest of the world by the satellite infrastructure and the backbone network.
  - The footprint of a satellite beam is the area where a MS can communicate with the satellite.
- ES (or BS) on the ground controls satellite communication and serves as a gateway to connect satellites (and MS) to the Internet or PSTN.
- Inter satellite links (ISL) is used to relay data from one satellite to another.

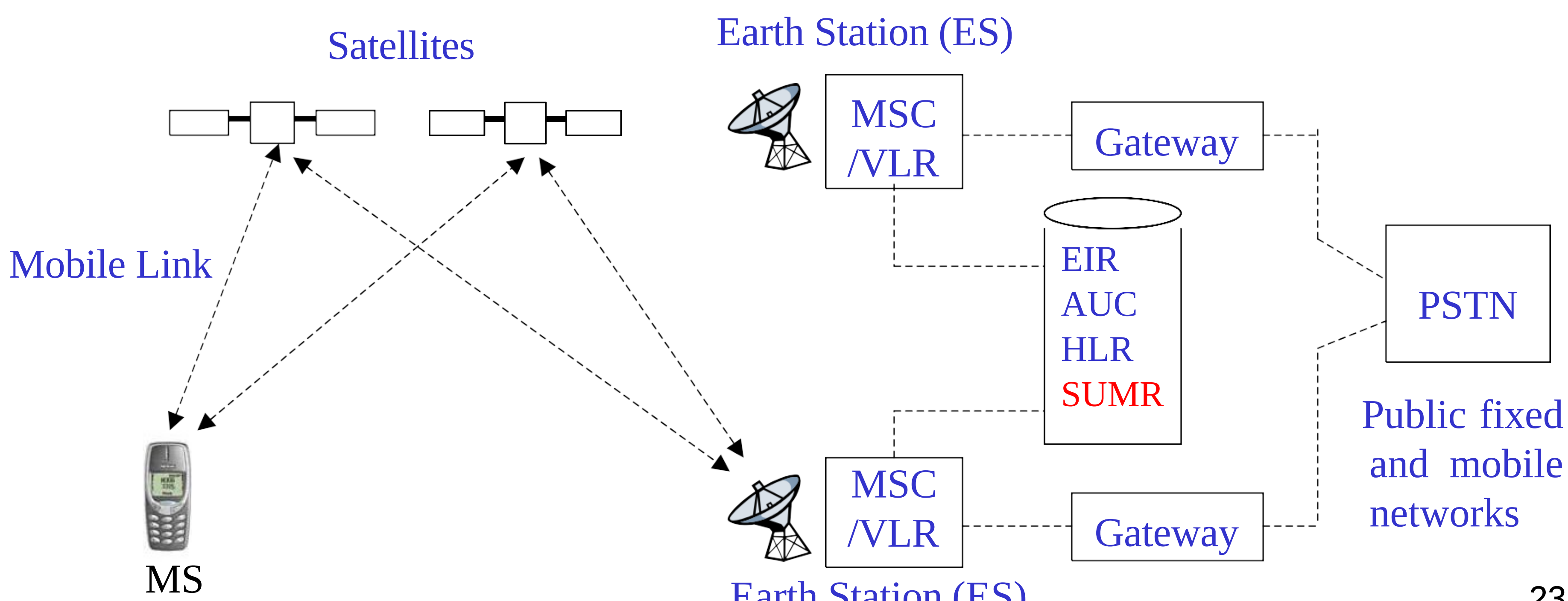
Signal Loss and Path Diversity

- There are losses in free space and also due to atmospheric absorption of the satellite beams and bad weather (e.g., rain).
- The satellite's beam may be temporarily blocked due to flying objects or the terrain of the earth surface.
- Therefore, a concept known as "diversity" is used to transmit the same message through more than one satellite.

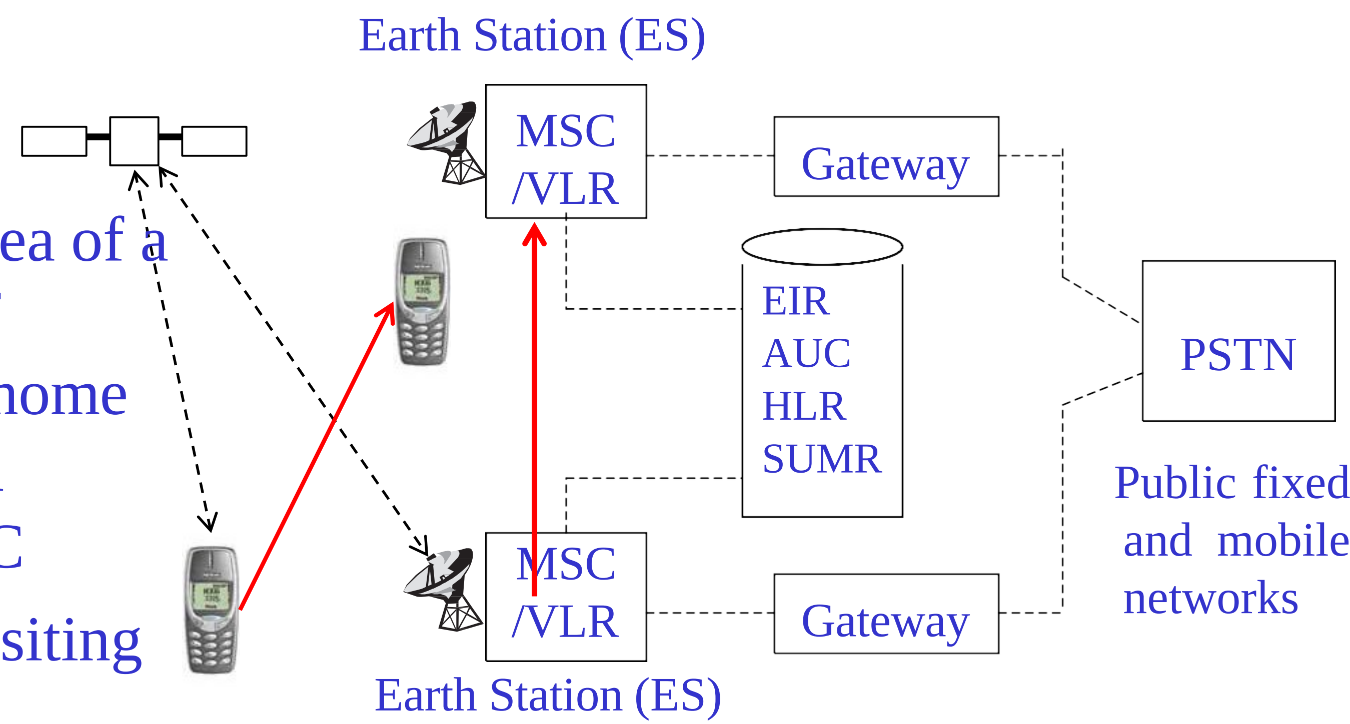


MS, Satellite, ES and PSTN

- Satellite acts as a relay node between MSs and ES
- ES performs similar functions as Mobile Switching Center (MSC)
  - keep track of MS's location by VLR-HLR (visitor location register – home location register)
- MSs are connected to the PSTN backbone via satellites
  - calls to/from PSTN phones can also be established via satellites

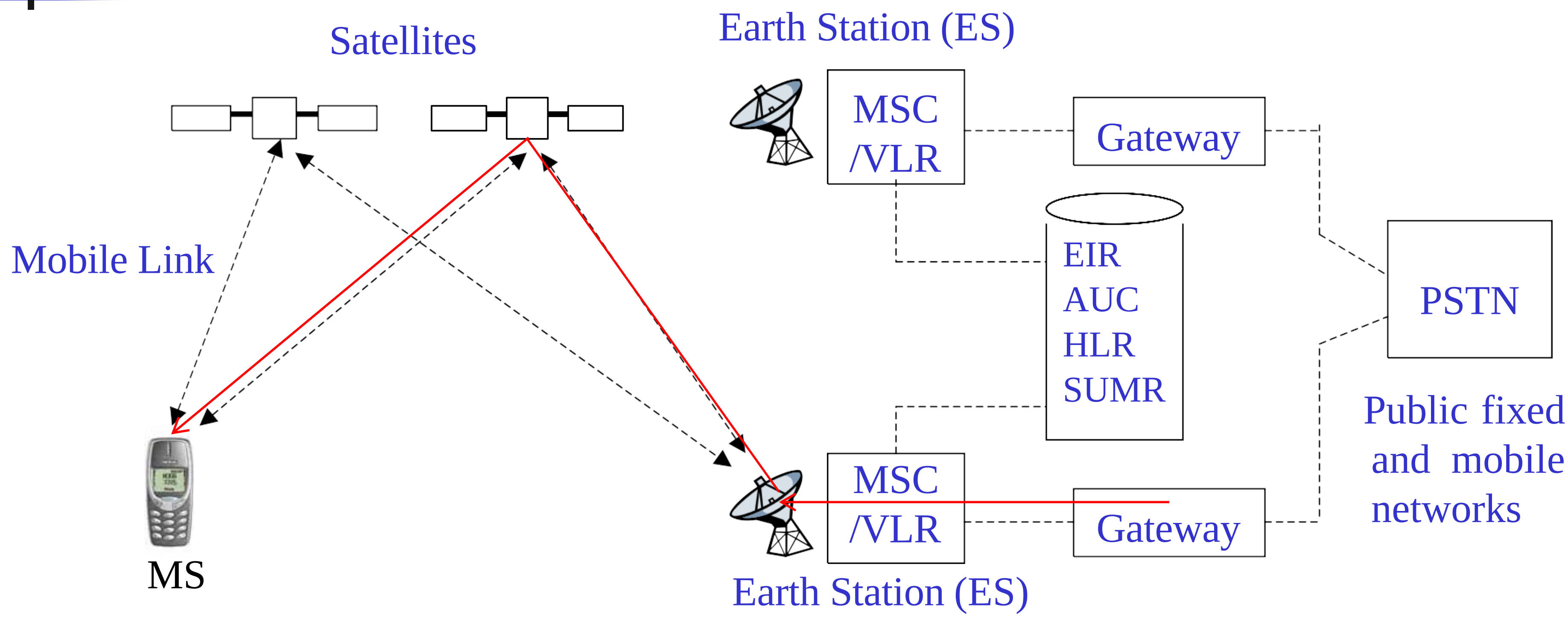


MS Roams from one ES (MSC) to another ES



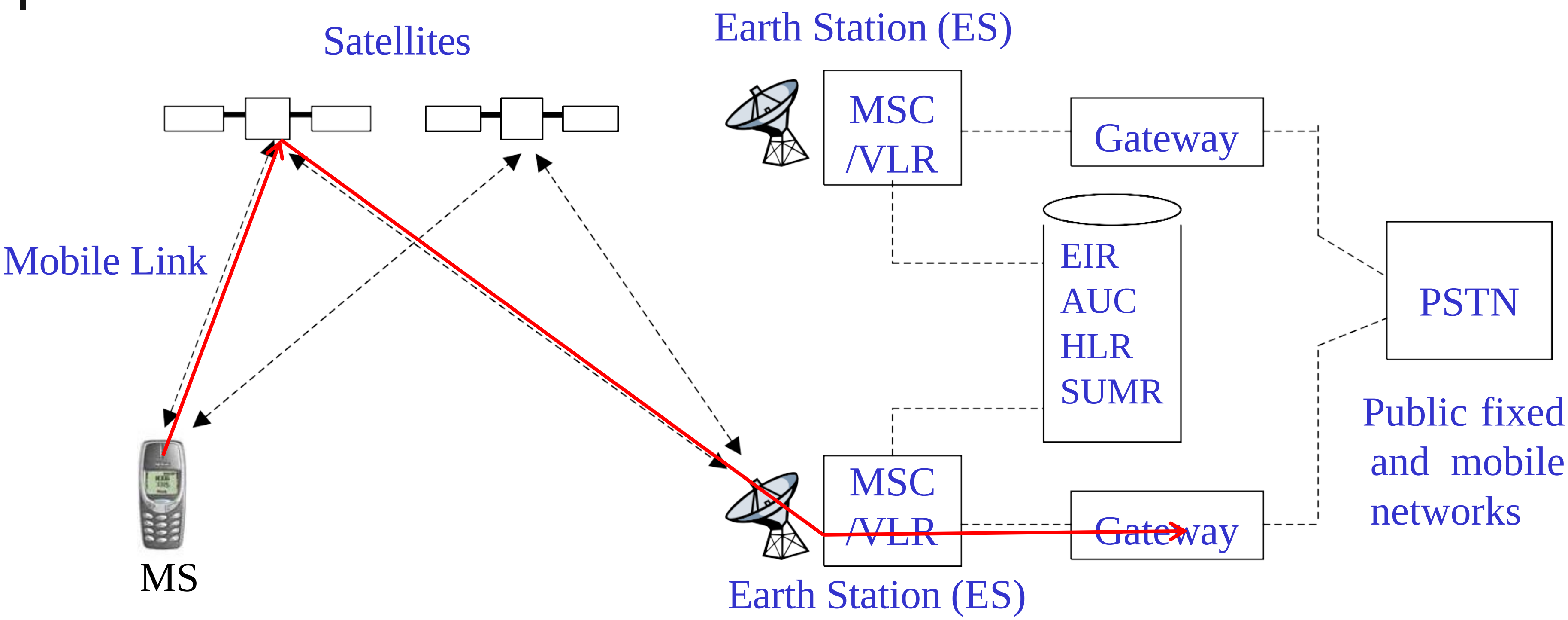
- When a MS moves to area of a new ES, a MSC handoff occurs: requesting MS' home MSC to update the HLR pointing to the new MSC
- New MSC allocates a visiting address to the MS
- Each ES maintains a database SUMR (Satellite-User Mapping Register) via communication with satellites.
  - SUMR records the satellites currently within the sight of this ES
  - SUMR maps MSs (users) to satellites under the area of this ES

Setup of Calls Incoming to MS



1. When a call from PSTN to an MS supported by satellites, the call is routed to the current visiting MSC (i.e., the ES) via MS's home MSC (similar to the cellular system)
2. The MSC of ES finds the satellite currently serving the MS using SUMR
3. The satellite uses a paging channel to inform the MS about the incoming call and the channels for up/downlink connection (allocation done by ES)
4. The connection is established between the MS and the PSTN phone

Setup of Calls Initiated from MS



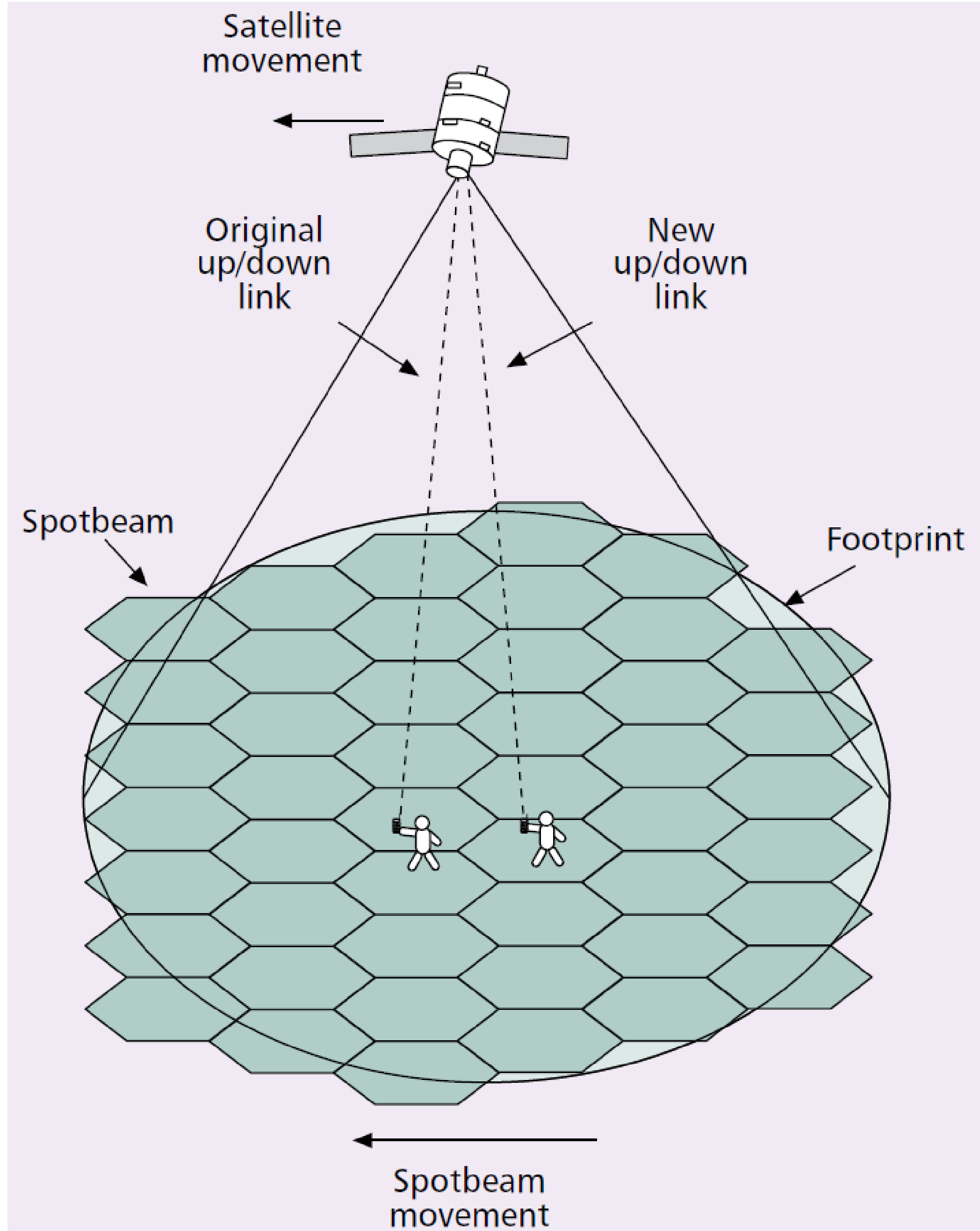
1. For a call originated from a MS, the MS uses the shared control channel of an overhead satellite (it tracks the MS via beacon signals)
2. The satellite informs the ES (MSC) of the call set-up request from the MS
3. The ES performs authentication and billing, then allocates data channels to the MS via the satellite (resource allocation is done by ES, not satellite!)
4. The call set-up from the ES's MSC to PSTN is the same as cellular system

Types of Handoff

- Spotbeam handoff (within a satellite): Spotbeam/cell handoff. A satellite's footprint is divided into spotbeams/cells. Handoff occurs when MS moves from one cell to another
- Inter-Satellite handoff: As most satellites are not geo-synchronous, handoff occurs from one satellite to another when a MS's coverage is changed from one satellite's footprint to another (satellite moves)
- Satellite-ES handoff: As satellite moves relative to the ground, Satellite-ES handoff occurs when a satellite's footprint area is moved from one ES to another
- Inter-Satellite Link (ISL) handoff: Due to the change of connectivity among satellites, the links connecting satellites are up and down. When a links is about to be down, ISL handoff occurs. Many satellite systems don't have ISLs, thus no ISL handoff (no discuss of it further)

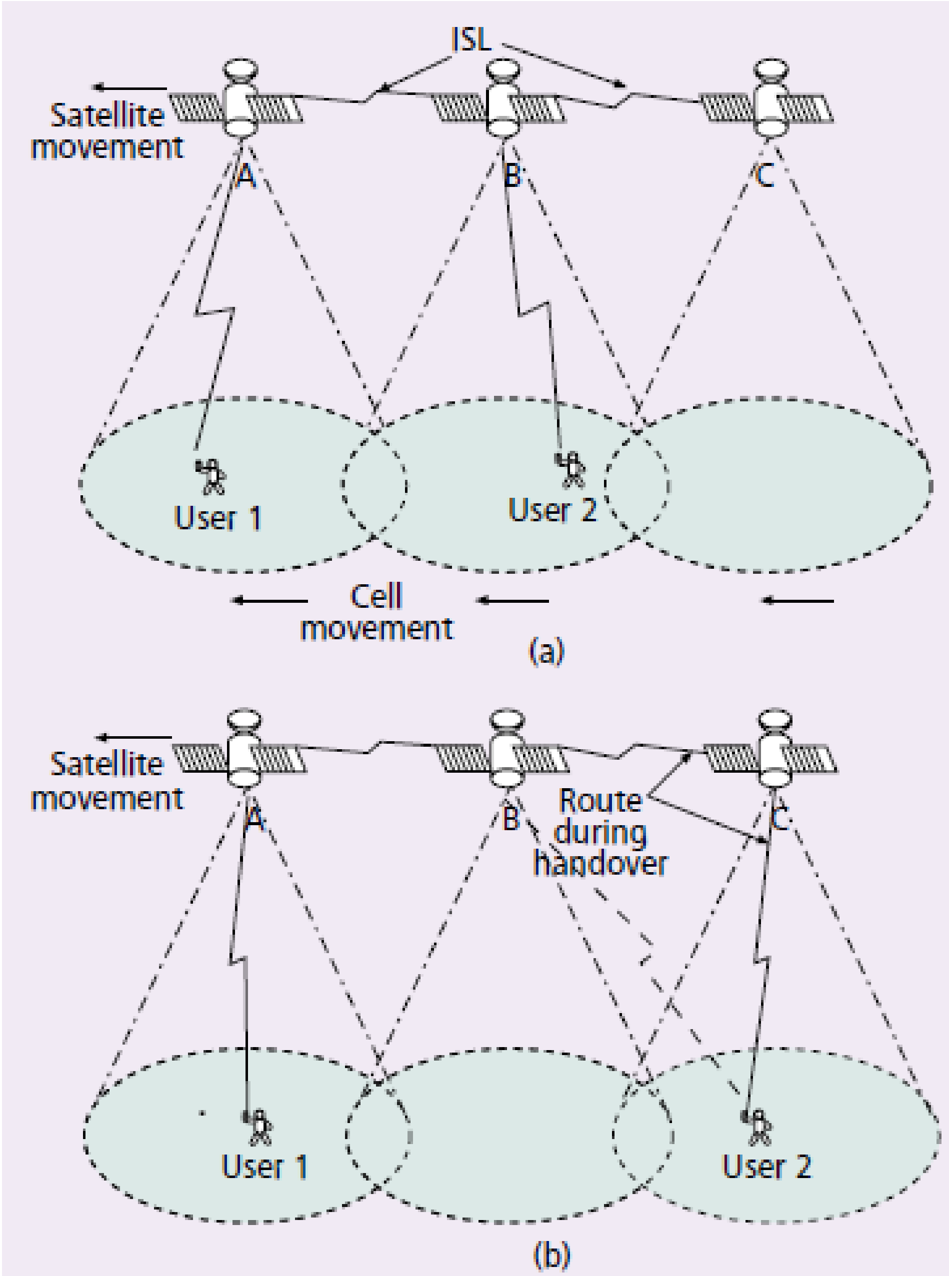
Spotbeam/cell Handoff (IntraSatellite)

- The footprint (a large area) of a satellite is divided into spotbeams (cells) for frequency reuse (the same frequency can be reused in non-neighboring cells)
- As satellite moves, a MS changes from one cell to another, handoff occurs (a new frequency need be assigned if it's on a call). MS' mobility is negligible compared with ground speed of satellites
- As spotbeam is small, this handoff occurs very frequent (usually every 1~2 min), but predictable
- It's within a satellite, handled fast



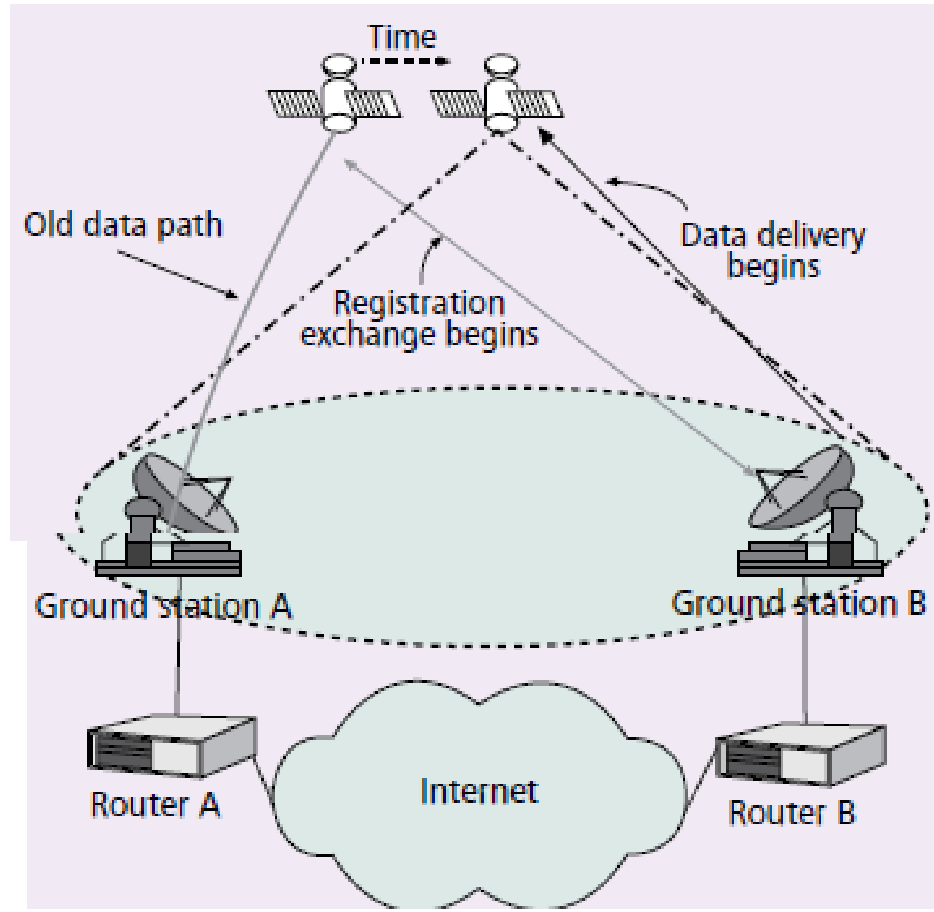
Inter-Satellite Handoff

- When a MS (e.g., user2 in Fig.) changes the area from one satellite's footprint to another due to satellite's movement, the MS is handoff to another satellite
- Each satellite keeps beaconing MSs inside its footprint, and updates the ES about the information in SUMR
- All decision-making and radio resource management is done by ES, leaving satellite light-weighted



Satellite-ES handoff

- When a satellite's footprint moves from one ES to another, handoff occurs
  - all MSs currently under the footprint of it are also handoff to the new ES
- Both the old and new ESs need to update the information of SUMR
  - each ES keeps track of the MSs and mapping of satellites to MSs in its area
- It also involves the change of IP address of MSs currently served by this satellite (ES *A* and ES *B* are in different networks and allocate different IP addresses!)

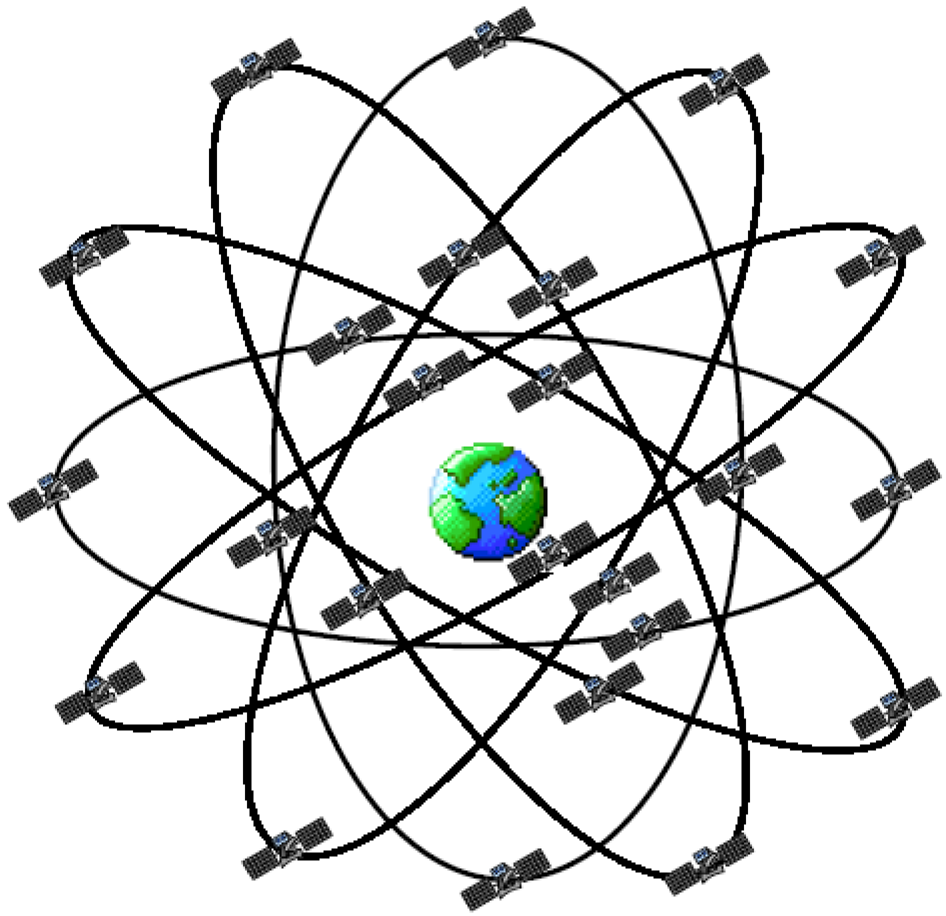


Global Positioning System (GPS)

- Used in applications such as military targeting, navigation, tracking down stolen vehicles, locating the callers for E-911 emergency….
- GPS system consists of a network of 24 orbiting satellites called “NAVSTAR” placed in 6 different orbital planes with 4 satellites in each orbital plane.
- The orbital period of these satellites is 12 hours.
- The first GPS satellite was launched in Feb. 1978.
- Each satellite is expected to last approx. 7.5 years.

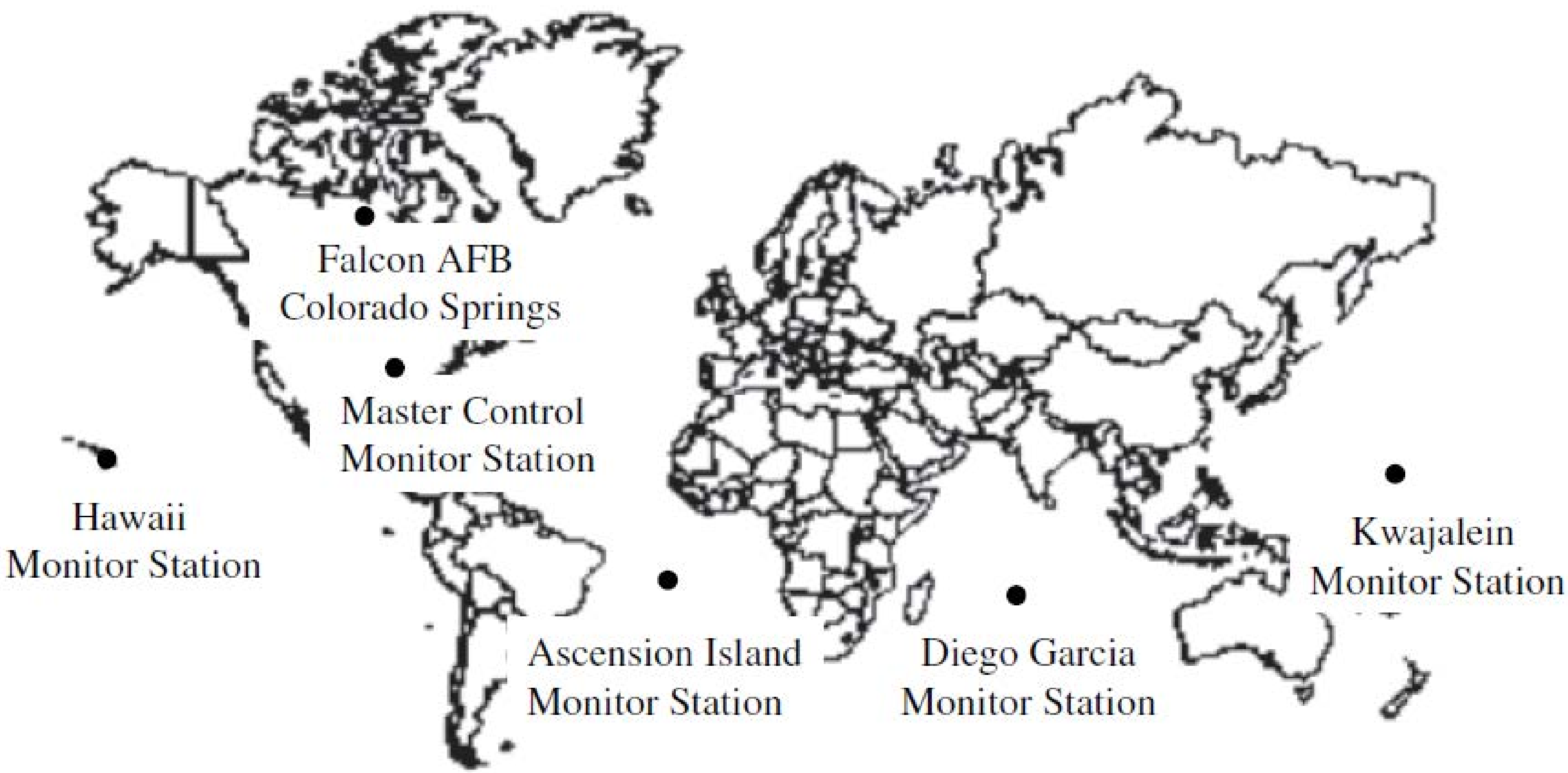
GPS Nominal Constellation
24 Satellites in 6 Orbital Planes

- 6 orbital planes, each with 4 satellites
- http://gps.fas.gov

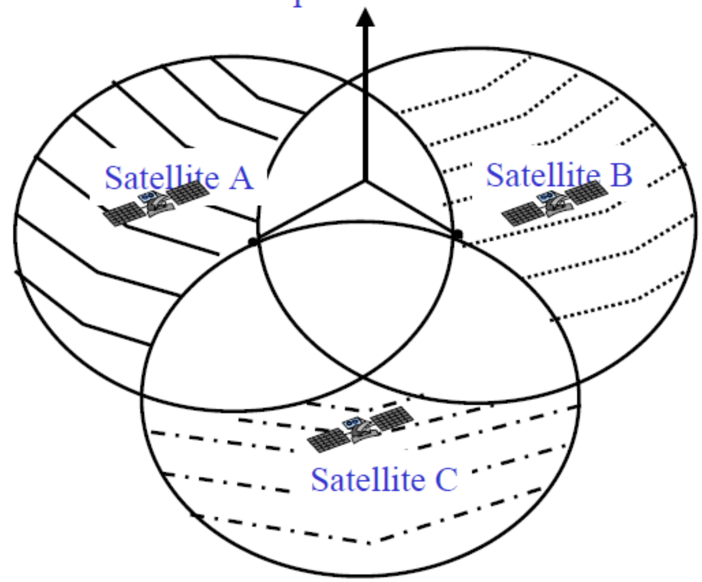


GPS Monitor Stations

- 5 Ground stations (one in Colorado) monitor and track the GPS satellites (they broadcast signals to satellites)
- They compute precise orbital data (ephemeris) and clock corrections for each satellite (used for GPS calculation)



Principle of GPS Localization



GPS is based on Triangulation Technique:

- Satellites broadcast their GPS signals periodically, containing a timestamp t
- A GPS receiver (MS) receives signal at t+δ. It can calculate its distance *d* to satellite by δ. It knows it is on the sphere centered from satellite *A* with radius *d*
- The MS is also a point on another sphere centered at a second satellite *B*. The MS is somewhere on the circle formed by the intersection of the 2 spheres
- With the measurement of distance from a third satellite *C*, the position of the MS is narrowed down to just 2 points on the circle: the one under the layer of satellites is the MS; the other is eliminated.
- The GPS coordinates of the 3 satellites are known, the GPS coordinates of the MS on earth can thus be determined

Principle of GPS Localization (Cont'd)

- The GPS signal (message) consists of a 'Pseudo-Random Number' (PRN), ephemeris and navigation data.
- Satellites are identified by their PRN ranging from 1-32. The PRN identifies which satellite is transmitting (this is the number displayed on the GPS receiver).
- Ephemeris is the data used by the user to calculate the current positions of the satellites in orbit (it needs to correct errors caused by gravitational pulls from the moon and the sun on the satellite).
- Navigation data is about the time and status of the entire satellite constellation, called the *almanac*.

Some Typical Applications of GPS

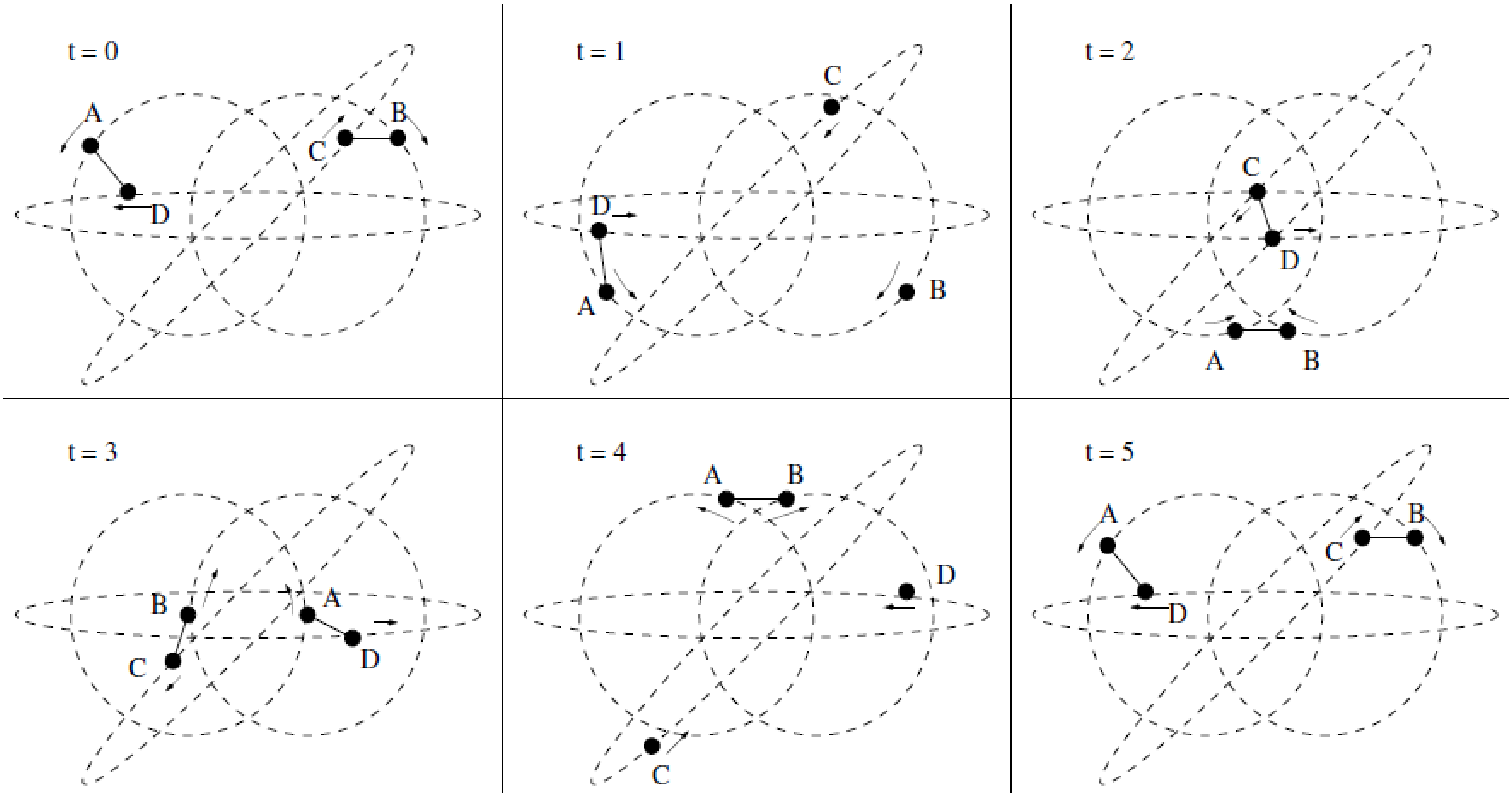
User Group	Application Area
U.S. Military	Maneuvering in extreme conditions and navigating planes, ships, etc.
Building the English channel	Checking positions along the way and making sure that they meet in the middle
General aviation and commercial aircrafts	Navigation
Recreational boaters and commercial fishermen	Navigation
Surveyors	Reduces setup time at survey site and offers precise measurements

Limitations of GPS

- Distance measurements may vary as the values of signal speed vary in atmosphere
  - Propagation delay due to atmospheric condition affects accuracy
- Effects of Multi-path fading and shadowing are significant
  - Multi-path fading occurs when the signal bounces off a building or terrain
- No GPS signals inside a building

Inter-Satellite Routing

Challenges: Graph is connected over time by links



Inter-Satellite Routing and Traditional Routing

Destination	Next Hop Node
$\vdots$	$\vdots$
d_i	h_i
$\vdots$	$\vdots$

(a) Traditional Routing Table

Destination Address	Time of Message Forwarding Lookup							
	0	$\ldots$	$(t-2)$	$(t-1)$	t	$\ldots$	t'	$\ldots$
$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$
d_i			Carry 2 Forward H	Carry 1 Forward H	Carry 0 Forward H		Carry 0 Forward L	
$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$

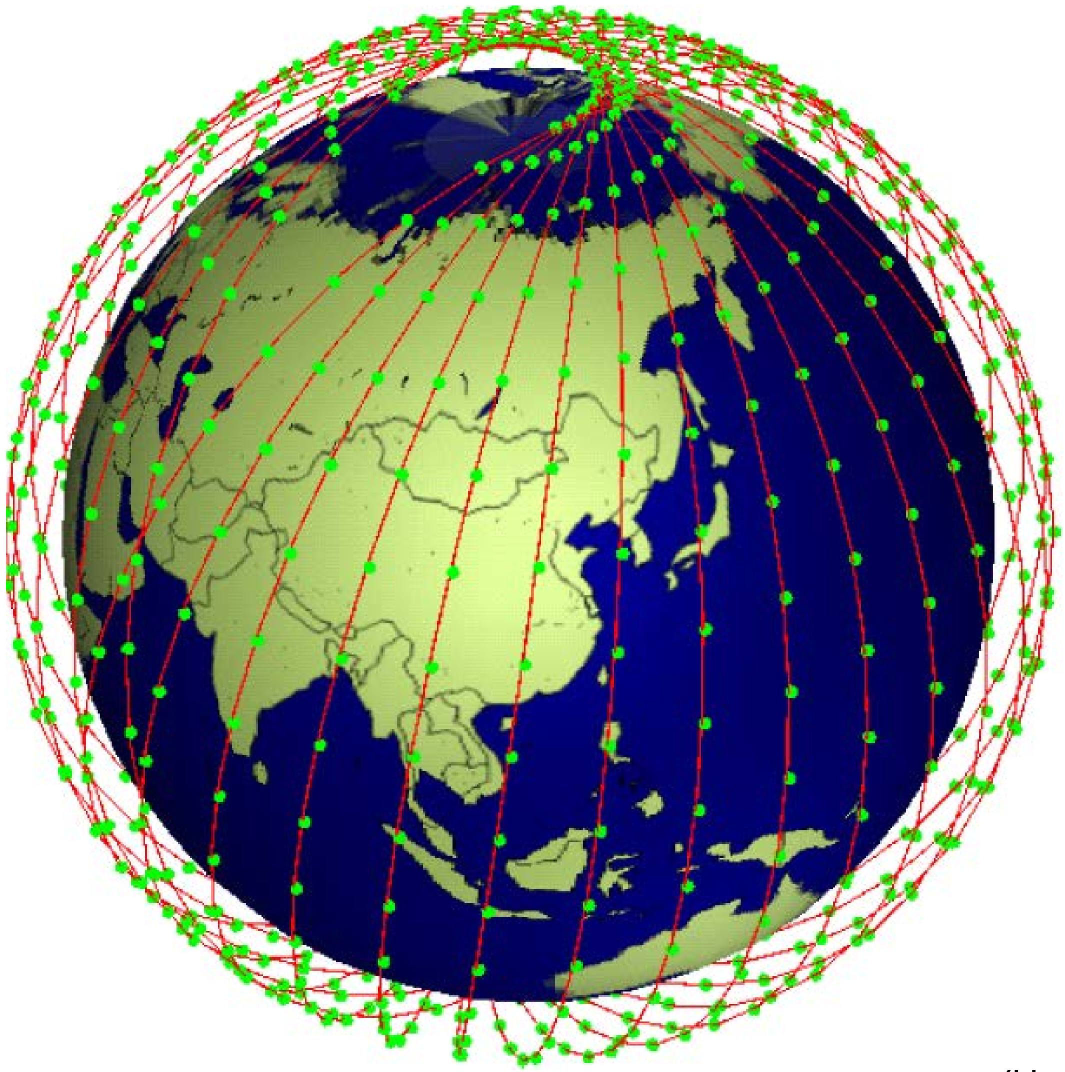
(b) Space-Time Routing Table

ISL Routing Schemes

- Characteristics of satellite networks
  - Highly dynamic topology changes
  - Predictable and periodical movement along orbits
- Two routing schemes: grid based routing and space-time graph routing
- Grid-based routing: assumes a logical grid structure and maps satellites to their closest nodes in the grid
  - For LEO satellites only
  - All satellites in the same constellation
- Space-time graph routing: a more general method that uses the space-time graph to represent the changing topologies of the satellite network over time

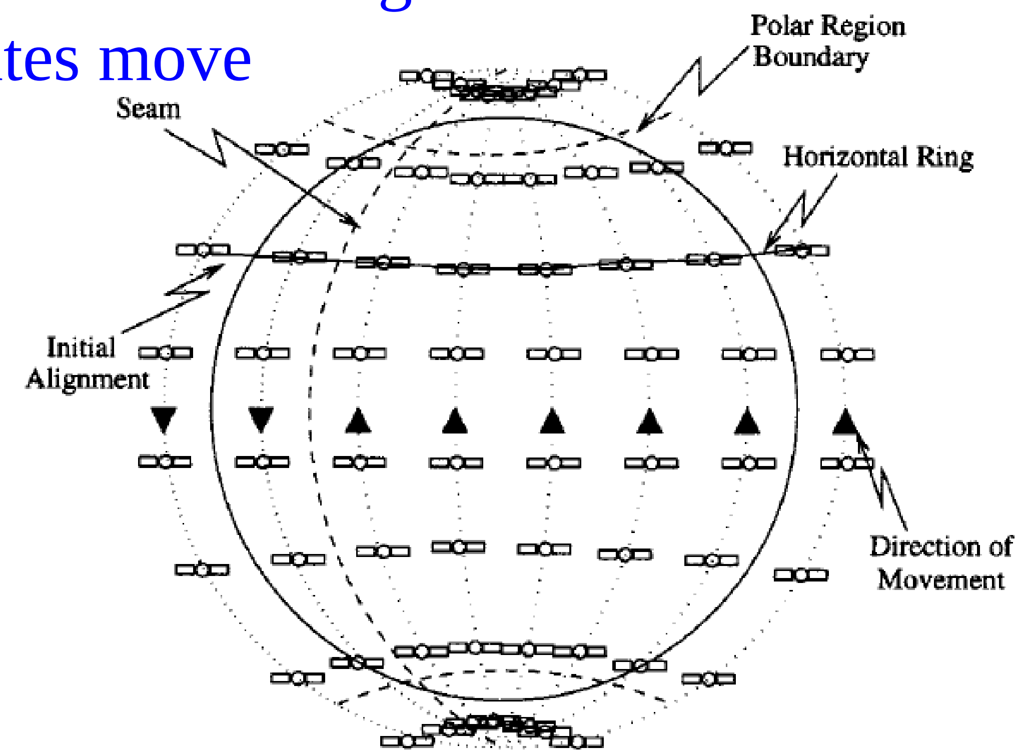
Example: Grid Satellite Constellation

- Teledesic: combined efforts with Celestri (1998)
  - Motorola: prime partner of Teledesic
- Aim: Internet-in-the-sky
- Teledesic constellation



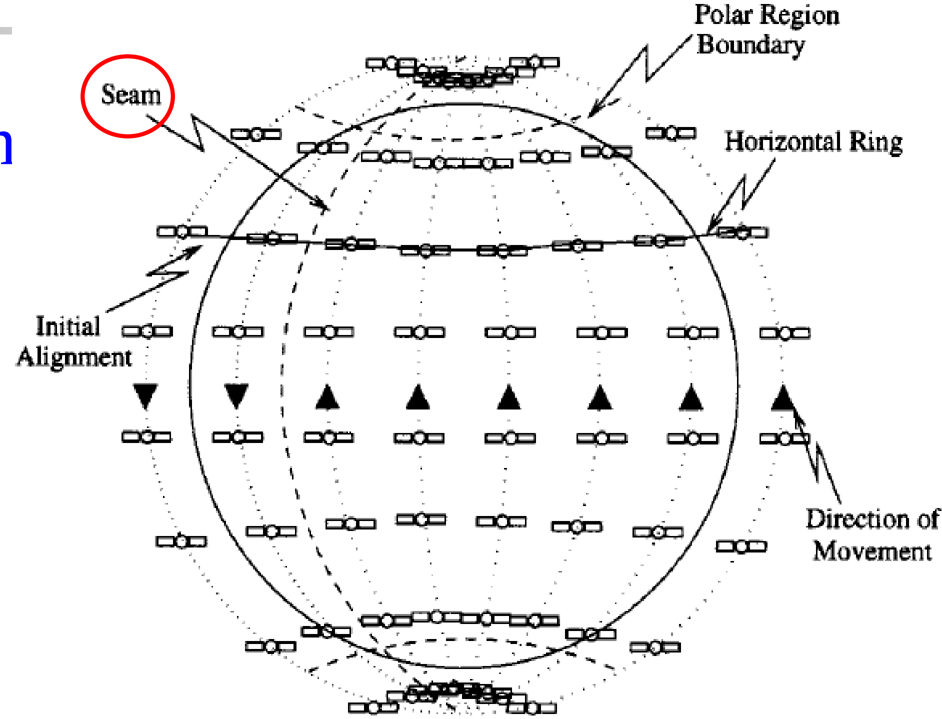
Logical Grid Based Routing

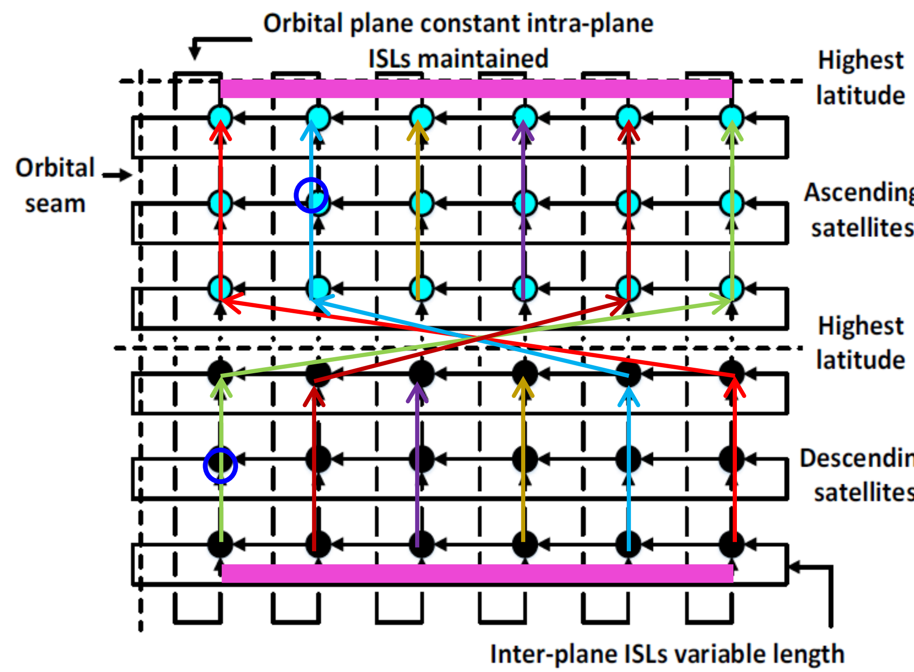
- The satellite network is composed of N polar orbits (planes), each with M satellites
- Satellites are mapped to the logical locations of a grid (each logical location is filled by its nearest satellites)
- The relative locations of a satellite with its neighbors in this Grid do not change as satellites move
- Each satellite has 4 neighbors (except those at border of the seam), two (up and down) in the same plane and two in the left and right planes
- Intra-plane links (up & down) and inter-plane links (left & right)



Two Special Features of Satellite Logical Grid

- No horizontal links crossing the seam
  - All satellites rotate around the earth in the same direction, creating a seam that divides the globe into two hemispheres
  - No inter-plane links between two planes at the border of the seam due to satellites moving in opposite directions (high speed)
- Large variance of inter-plane link distance
  - inter-plane link distance becomes larger when close to equator, and smaller when close to the poles

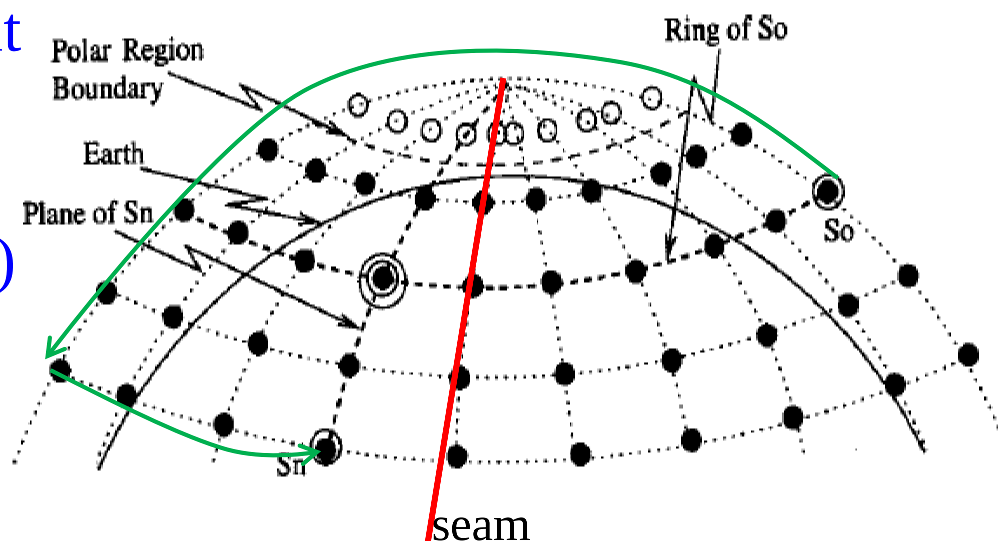




Routing on the Logical Grid

- The geo-location of a satellite is represented by coordinate [longitude, latitude]
  - The logical location of a satellite is represented by pair (*p*, *s*), where *p* is the plane number and *s* the satellite number
- Suppose a message is sent from source satellite S_0 at logical point (p_0, s_0) to destination satellite S_n at point (p_n, s_n)
- The routing takes the shortest (distance) path on the logical grid

1) If S_0 and S_n are on different hemisphere (need cross the seam), it takes vertical links to the same hemisphere as S_n via the pole, then horizontally to reach S_n (green line)
2) If S_0 is at higher latitude than S_n, it goes horizontal first, than vertical to reach S_n, otherwise vertical first

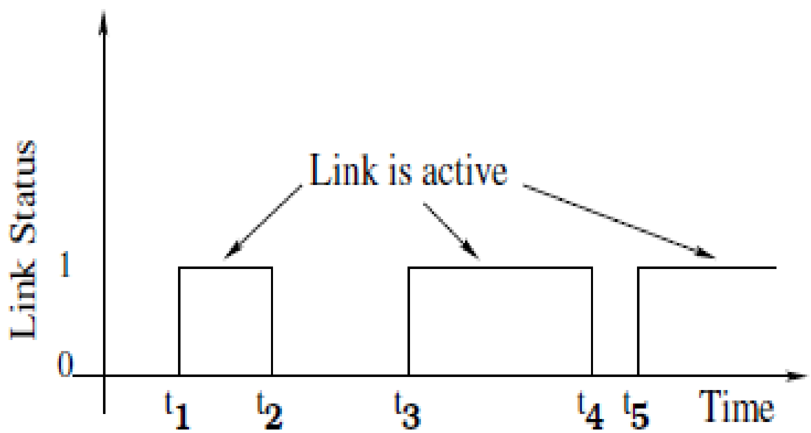


Space-time Graph Based Routing

- G(t) = (V, E(t)), where V is the set of nodes and E(t) is a time-varying set of links between these nodes
- $L_{ij}(t)$ represents whether a communication link is present between nodes v_i and v_j at time t

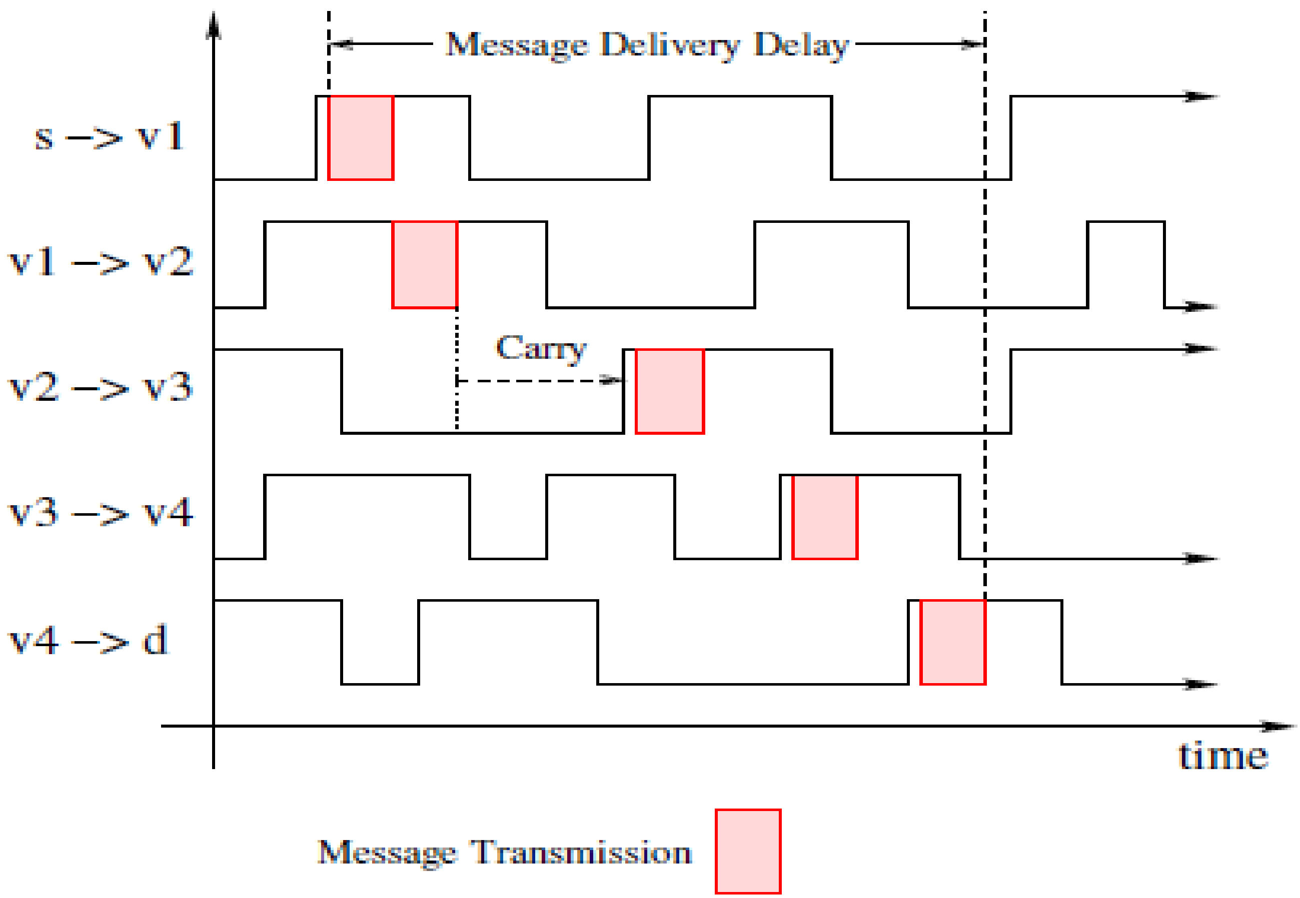
$$L_{ij}(t) = \begin{cases} 1 & \text{if } \; |P_i(t) - P_j(t)| \leq \gamma \\ 0 & \text{otherwise} \end{cases}$$

where γ is transmission range of satellites, $P_i(t)$ is the geographic position of node v_i at time t



Message Transfer: carry & forward

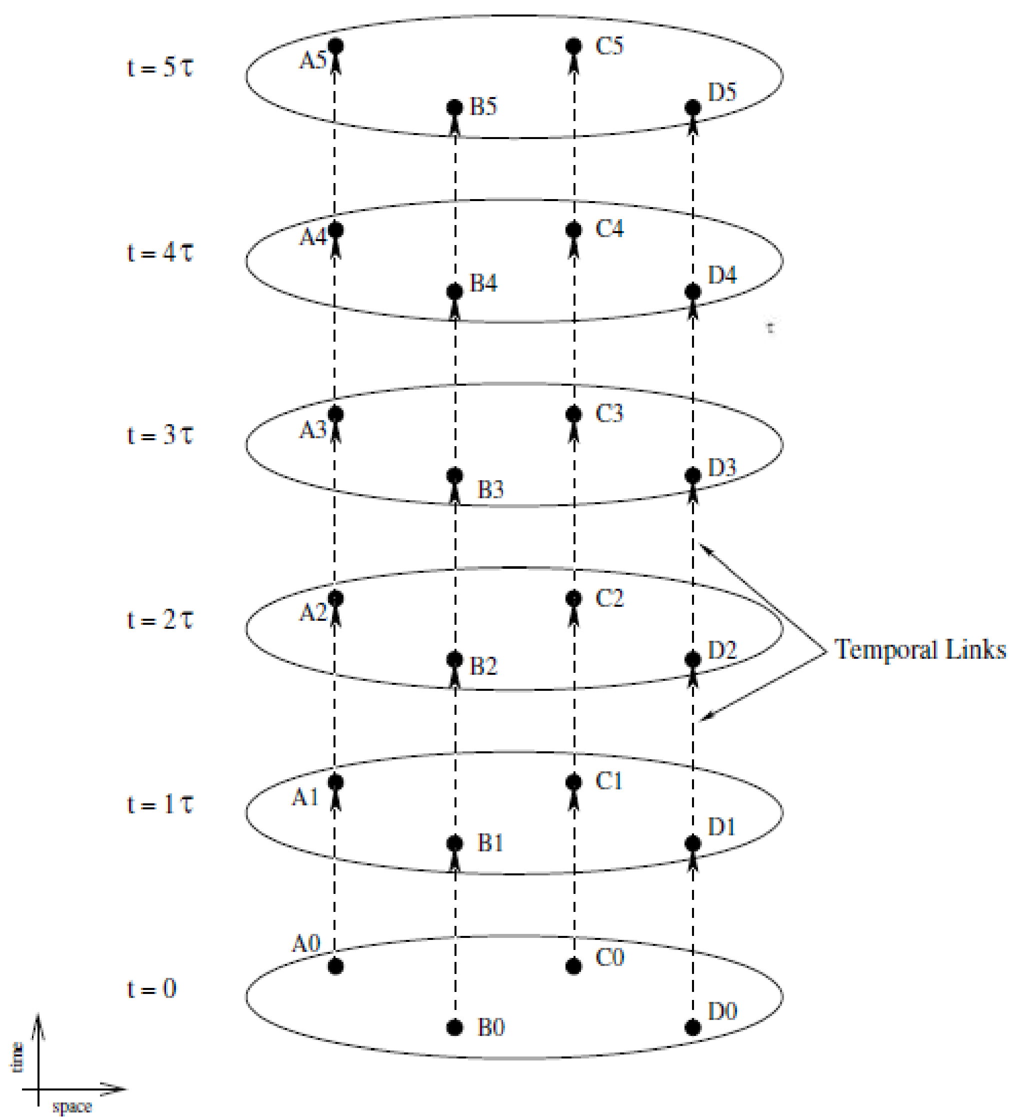
- Message transmission s → v1 → v2 → v3 → v4 → d



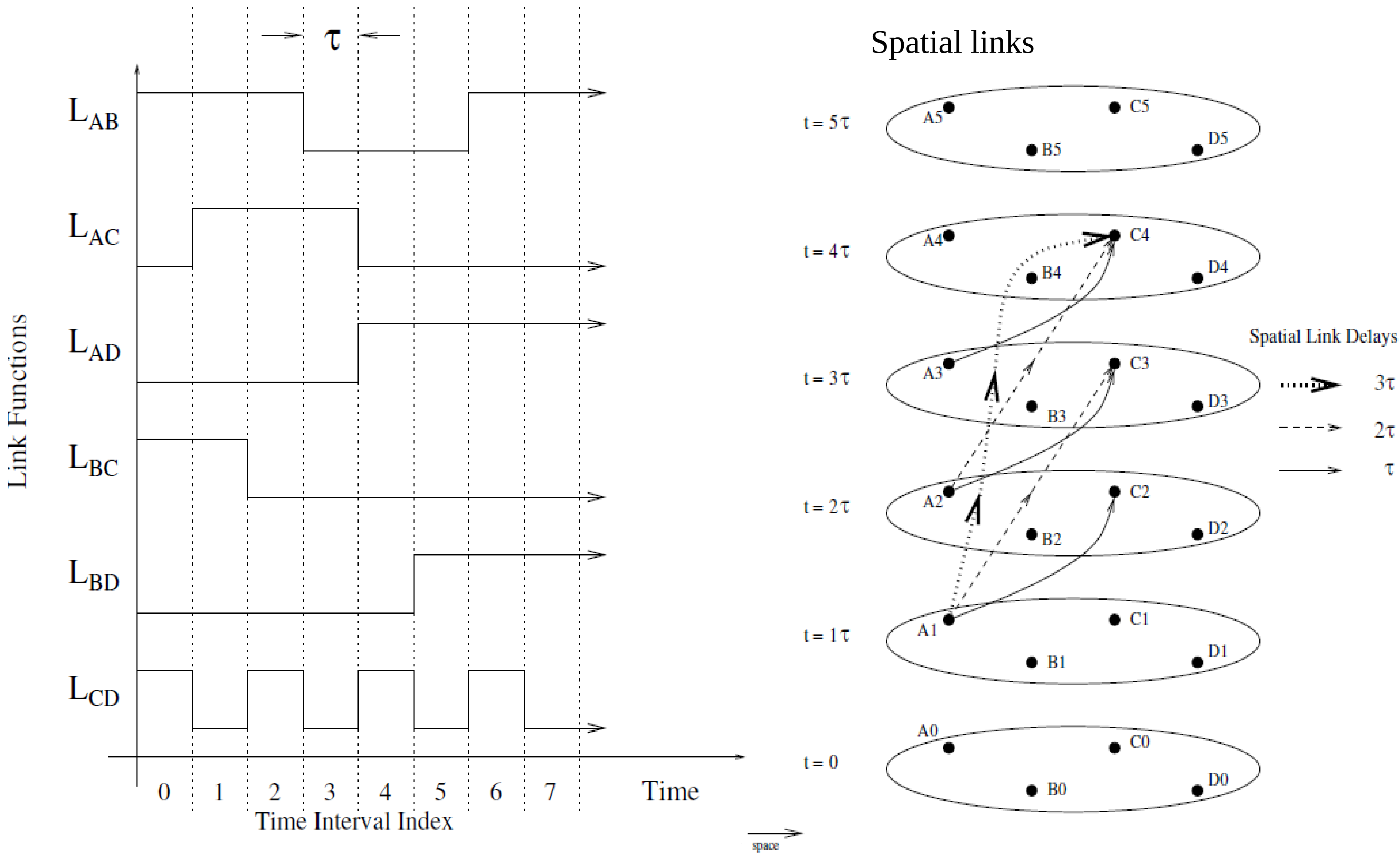
Spatial-Temporal Links

- Each layer of the graph has one copy of every node in the network and a column of vertices corresponds to the same node.
- Temporal links: connect “time-copies” of the same node between consecutive intervals of time.
  - Traversing a temporal link denotes “carrying” a message by a node from one time to another time
- Spatial links: connect different nodes in space (and across time planes)
  - Represent connectivity between two nodes during the time for a duration

Temporal links

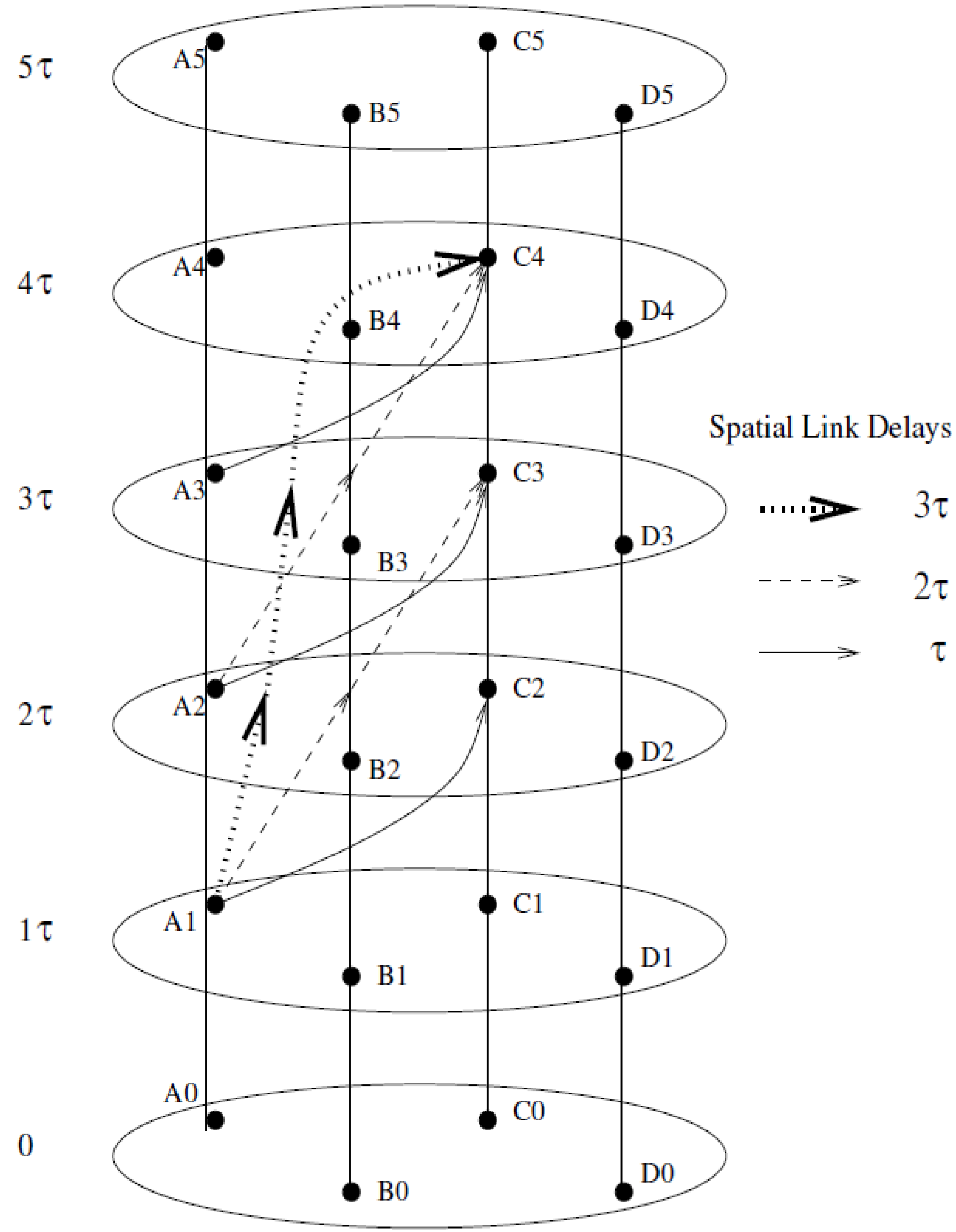


Spatial Link L_{AC} with different length of time



Routing using Space-Time Graph

- Given a request (v_i, v_j, t, m) to route a message of size m (in the unit of transmission time) from v_i to v_j at time t
- Find a path in the space-time graph from vertex v_{it} to $v_{jt'}$ of color c (size c), $(c-1)\tau < m < c\tau$. Note: t' is unknown
- The shortest path is the path that produces the shortest delay $|t' - t|$
- The shortest path computation is based on dynamic programming
  - Dijkstra's algorithm can compute it, but too costly



Shortest Path Routing by Dynamic Programming

- $D^k(i,j,t,c)$: delay of the shortest path from v_i and v_j at t in k^{th} iteration
- Initialization:
  - for each direct edge $(v_{it}, v_{j(t+c)})$:

    $D^0(i, j, t, c) = c;$
  - if no direct edge from v_i to v_j at t, but $D^0(i,j,t+1,c) \neq 0$:

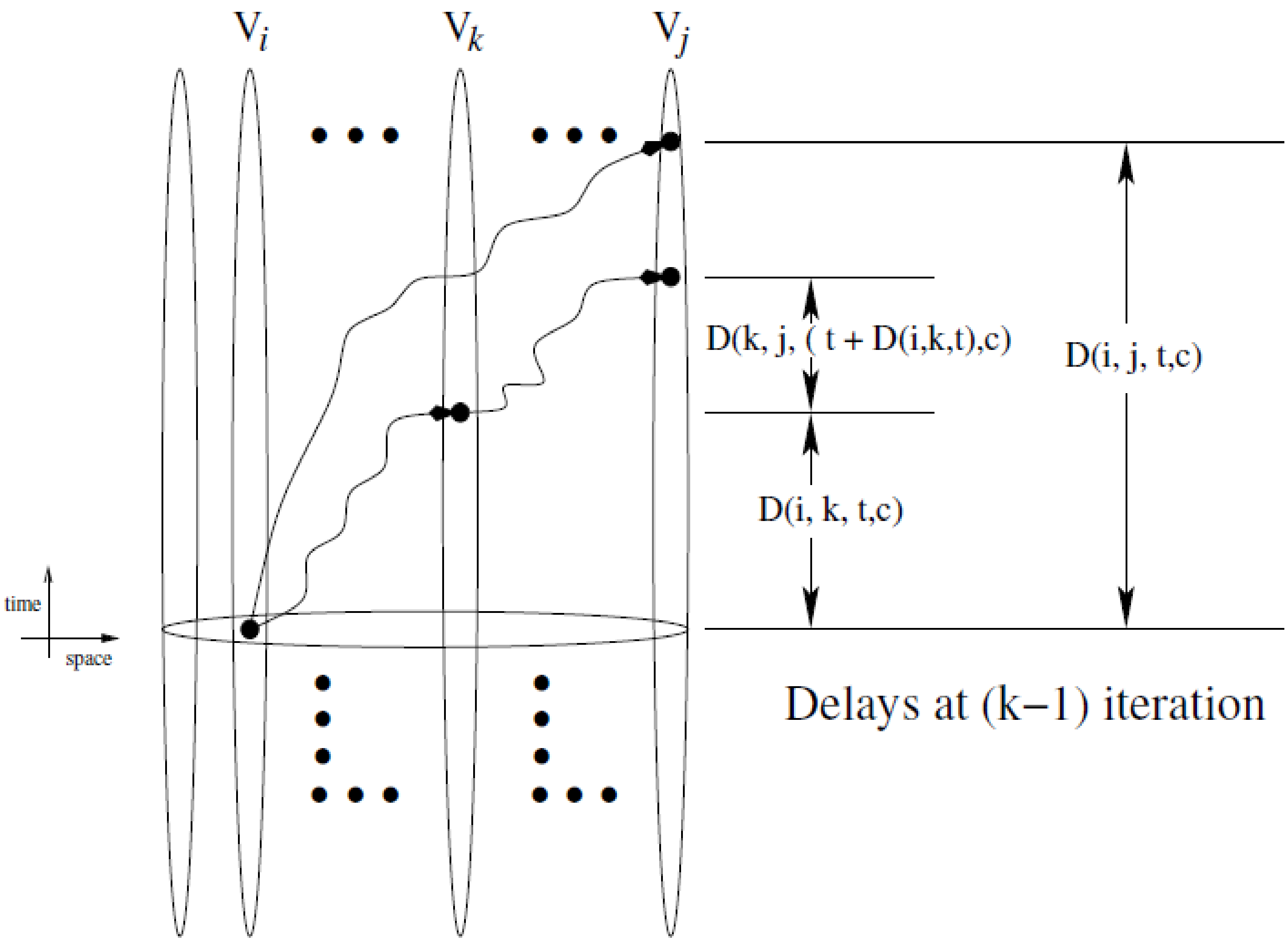
    $D^0(i,j,t,c) = D^0(i,j,t+1,c) + 1;$ // v_i carries from t to t+1, then gives to v_j

    else $D^0(i,j,t,c) = \infty$
- Dynamic programming: iteratively find a shorter path via an intermediate node w at any time in the space-time graph

$$D^k(i,j,t,c) = \min\{D^{k-1}(i,j,t,c),\ D^{k-1}(i,w,t,c) + D^{k-1}(w,j, D^{k-1}(i,w,t,c),c)\}$$

Dynamic Programming Formulation for shortest path

$$\mathcal{D}^{(k)}(i,j,t,c) \leftarrow \min \begin{cases} \mathcal{D}^{(k-1)}(i,j,t,c) \\ \\ \mathcal{D}^{(k-1)}(i,k,t,c) + \\ \mathcal{D}^{(k-1)}(k,j,(t+\mathcal{D}^{(k-1)}(i,k,t)),c) \end{cases}$$



The Shortest Path Routing Algorithm

Routine 1 Shortest_Delay_Path

Input: Space-time graph $G' = (V', E')$ with colored edges, number of vertices n, time period $\mathbf{T}$, message color c

Output: Shortest path length from node v_i at time t to node v_j of color c $\mathcal{D}(i, j, t, c)$, $1 \leq i, j, < n$; $0 \leq t < \mathbf{T}$

Method:

$\mathcal{D}$ = Initialize_Delay $(G', n, \mathbf{T}, c)$
for $k = 1$ **to** n **do**
    for $i = 1$ **to** n **do**
        for $j = 1$ **to** n **do**
            for $t = 1$ **to** $\mathbf{T}$ **do**
                $d_{curr} = \mathcal{D}(i, j, t, c)$
                $d_1 = \mathcal{D}(i, k, t, c)$
                $d_2 = \mathcal{D}(i, k, (t + d_1), c)$
                $d_{alt} = d_1 + d_2$
                if $(d_{alt} < d_{curr})$ **then**
                    $\mathcal{D}(i, j, t, c) = d_{alt}$
                    intHop$[v_i][v_j][t] = v_k$

Summary

- Satellite System Infrastructures
- Call Setup for satellite phones
  - Incoming call to and outgoing call from a satellite phone
- Handoff in Satellite Systems
  - Intra-satellite handoff (cross spotbeams)
  - Inter-satellite handoff (cross footprint of satellites)
  - Satellite-ES handoff (satellite switching from one ES to another)
- GPS
- Inter-Satellite Link Routing
  - Logical grid based routing
  - Space-time graph routing

Exercise

- How is a call connected with a satellite phone?
- Estimate the error range of the GPS system if the error of clock synchronization is ± 10-3. Assume the satellite is 20,000km above the earth and a GPS receiver is currently at 30^{o} from the upright line between the earth and the satellite. The speed of radio signal is 300,000 km/s.
- Hierarchical routing is another satellite routing scheme, which organizes satellites into hierarchies according to their height above the earth (e.g., a GEO satellite becomes a head of a cluster of MEO satellites, and a MEO satellite is a head of a cluster of LEO satellites). Can this hierarchical structure of satellites be modeled by the logical grid, or by the space-time graph?