Satellite Networks — Satelite Communications

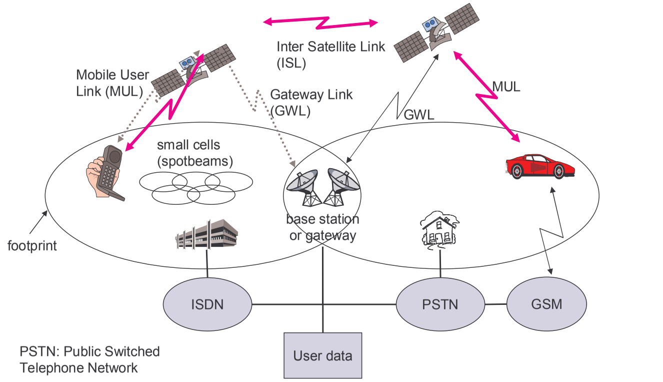
- 1945 Arthur C. Clarke essay on "Extra Terrestrial Relays"
- 1957 First satellite SPUTNIK
- 1960 First reflecting communication satellite ECHO
- 1963 First geostationary satellite SYNCOM
- 1965 First commercial geostationary satellite Satellit "Early Bird" (INTELSAT I)
  - 240 duplex telephone channels or 1 TV channel, 1.5 years lifetime
- 1976 Three MARISAT satellites for maritime communication
- 1982 First mobile satellite telephone system INMARSAT-A
- 1988 First satellite system for mobile phones and data communication INMARSAT-C
- 1993 First digital satellite telephone system
- 1998 Global satellite systems for small mobile phones

Satellite Networks — Applications

- Traditionally
  - weather satellites
  - radio and TV broadcast satellites
  - military satellites
  - satellites for navigation and localization (e.g., GPS)
- Telecommunication
  - global telephone connections } replaced by fiber optics
  - backbone for global networks } replaced by fiber optics
  - connections for communication in remote places or underdeveloped areas
  - global mobile communication

→ satellite systems to extend cellular phone systems (e.g., GSM or AMPS)

Satellite Networks — Classical satellite systems

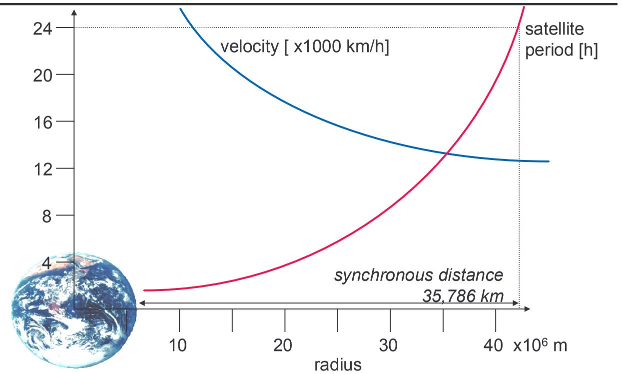


Satellite Networks — Basics

- Satellites in circular orbits
  - attractive force $F_g = m\, g\, (R/r)^2$
  - centrifugal force $F_c = m\, r\, \omega^2$
  - m: mass of the satellite
  - R: radius of the earth (R = 6370 km)
  - r: distance to the center of the earth
  - g: acceleration of gravity (g = 9.81 m/s²)
  - ω: angular velocity ($\omega = 2\,\pi\, f$, f: rotationfrequency)
- Stable orbit $F_g = F_c$

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

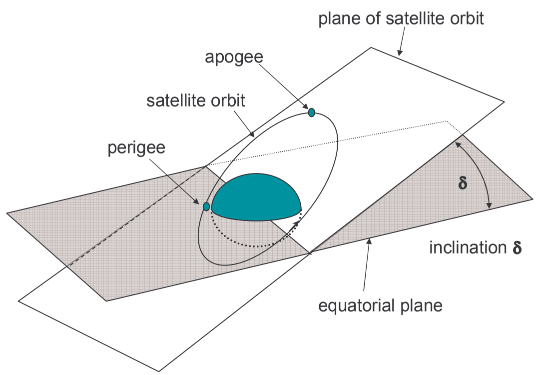
Satellite Networks — Satellite period and orbits



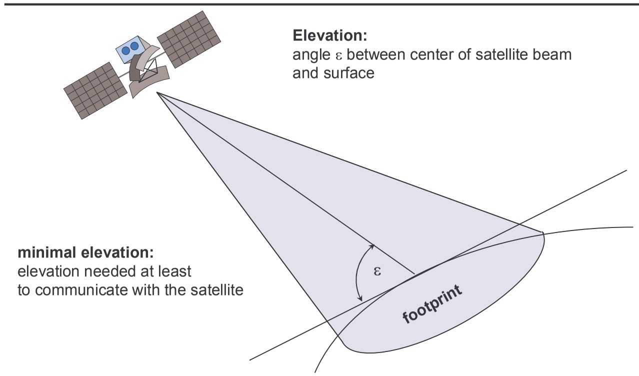
Satellite Networks — Basics

- elliptical or circular orbits
- complete rotation time depends on distance satellite-earth
- inclination: angle between orbit and equator
- elevation: angle between satellite and horizon
- LOS (Line of Sight) to the satellite necessary for connection
  ➔ high elevation needed, less absorption due to e.g. buildings
- Uplink: connection base station - satellite
- Downlink: connection satellite - base station
- typically separated frequencies for uplink and downlink
  - transponder used for sending/receiving and shifting of frequencies
  - transparent transponder: only shift of frequencies
  - regenerative transponder: additionally signal regeneration

Satellite Networks — Inclination



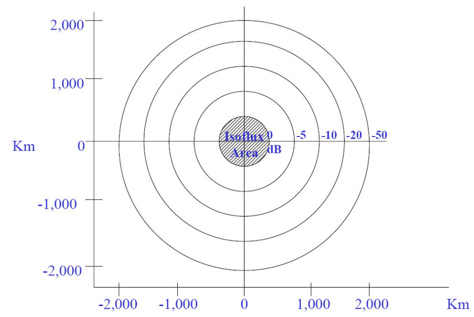
Satellite Networks — Elevation



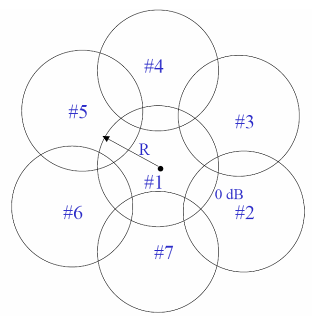
Footprint

- The area inside the circle is considered to be an isoflux area and this constant intensity area is taken as the footprint of the beam
- A satellite consists of several illuminated beams. These beams can be seen like cells in a conventional wireless system.
- The elevation angle between the satellite beam and the surface of the earth has an impact on the illuminated area (footprint).

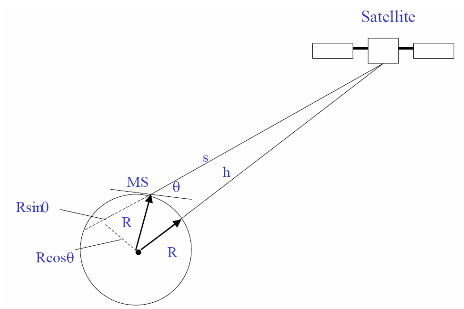
Intensity Level of the Footprint of GEO Satellites



Satellite Beam Geometry



Satellite Communication



Satellite Networks

Satellite Communication

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

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

where, R = radius of the earth

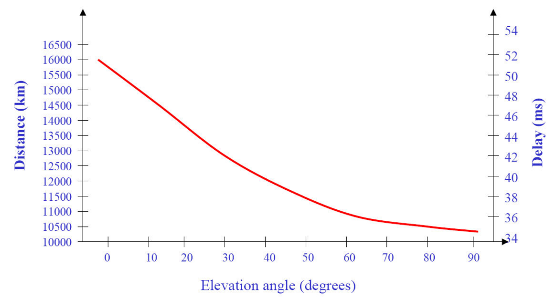
h = orbital altitude

θ= satellite elevation angle

c = speed of light

Satellite Networks

Delay variation in MS as a function of elevation angle



Variation of delay in MS as a function of elevation angle when the satellite is at an elevation of 10,355 kms.

Satellite Networks

Frequency Bands

- The satellites operate in different frequencies for the uplink and the downlink

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
LIS	1.610 – 1.625	2.483 – 2.50

Satellite Networks

Different Frequency Bands

- C band frequencies have been used in the first generation satellites and has become overcrowded because of terrestrial microwave networks employing these frequencies.
- Ku and Ka bands are becoming more popular, even though they suffer from higher attenuation due to rain

Satellite Networks — Link budget of satellites

Parameters like attenuation or received power determined by four parameters:

- sending power
- gain of sending antenna
- distance between sender and receiver
- gain of receiving antenna

L: Loss
f: carrier frequency
r: distance
c: speed of light

$$L = \left(\frac{4\pi r f}{c}\right)^2$$

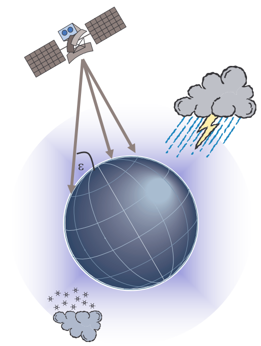
Problems:

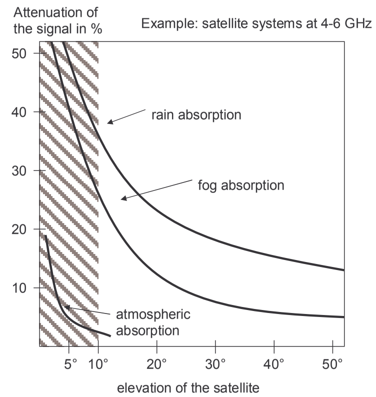
- varying strength of received signal due to multipath propagation
- interruptions due to shadowing of signal (no LOS)

Possible solutions:

- Link Margin to eliminate variations in signal strength
- satellite diversity (usage of several visible satellites at the same time) helps to use less sending power

Satellite Networks — Atmospheric attenuation





Satellite Networks — Characteristics of Satellite Systems

- Satellites weigh around 2,500 kgs.
- The GEO satellites are at an altitude of 35,768 kms which orbit in equatorial plane with 0 degree inclination.
- They complete exactly one rotation per day.
- The antennas are at fixed positions and use an uplink band of 1,634.5-1,660.5 MHz and downlink in the range of 1,530-1,559 MHz.
- Ku band frequencies (11 GHz and 13 GHz) are employed for connection between the BS and the satellites.

Satellite Networks — Characteristics of Satellite Systems

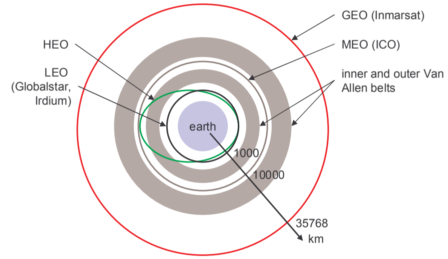
- A satellite typically has a large footprint –34% of earth's surface is covered. Therefore it is difficult to reuse frequencies.
- There is a high latency (about 275 ms) due to global coverage of mobile phones.
- LEO satellites are divided into little and big satellites.
- Little LEO satellites are smaller in size, in the frequency range 148-150.05 MHz (uplink) and 137-138 MHz (downlink). They support only low bit rates (1 kb/s) for two way messaging.
- Big LEO satellites have adequate power and bandwidth to provide various global mobile services like data transmission, paging etc.
- Big LEO satellites transmit in the frequency range of 1,610-1,626.5 MHz (uplink) and 2,483.5-2,500 MHz (downlink).
- It orbits around 500-1,500 kms above the earth's surface.
- The latency is around 5-10 ms and the satellite is visible for 10-40 min

Satellite Networks — Orbits I

Four different types of satellite orbits can be identified depending on the shape and diameter of the orbit:

- GEO: geostationary orbit, ca. 36000 km above earth surface
- LEO (Low Earth Orbit): ca. 500 - 1500 km
- MEO (Medium Earth Orbit) or ICO (Intermediate Circular Orbit): ca. 6000 - 20000 km
- HEO (Highly Elliptical Orbit) elliptical orbits

Satellite Networks — Orbits II



Van-Allen-Belts:
ionized particles
2000 - 6000 km and
15000 - 30000 km
above earth surface

Satellite Networks — Geostationary satellites

- Orbit 35,786 km distance to earth surface, orbit in equatorial plane (inclination 0°)
- ➔ complete rotation exactly one day, satellite is synchronous to earth rotation
- fix antenna positions, no adjusting necessary
- satellites typically have a large footprint (up to 34% of earth surface!), therefore difficult to reuse frequencies
- bad elevations in areas with latitude above 60° due to fixed position above the equator
- high transmit power needed
- high latency due to long distance (ca. 275 ms)

➔ not useful for global coverage for small mobile phones and data transmission, typically used for radio and TV transmission

Satellite Networks — LEO systems

- Orbit ca. 500 - 1500 km above earth surface
- visibility of a satellite ca. 10 - 40 minutes
- global radio coverage possible
- latency comparable with terrestrial long distance connections, ca. 5 - 10 ms
- smaller footprints, better frequency reuse
- but now handover necessary from one satellite to another
- many satellites necessary for global coverage
- more complex systems due to moving satellites

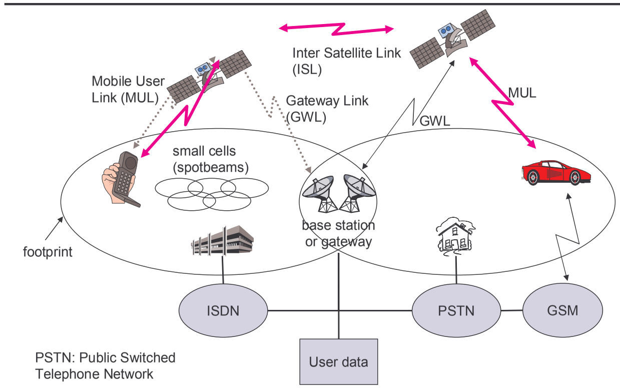
- Examples:
- Iridium (start 1998, 66 satellites)
  - Bankruptcy in 2000, deal with US DoD (free use, saving from "deorbiting")
- Globalstar (start 1999, 48 satellites)
  - Not many customers (2001: 44000), low stand-by times for mobiles

Satellite Networks — MEO systems

- Orbit ca. 5000 - 20000 km above earth surface
- comparison with LEO systems:
- slower moving satellites
- less satellites needed
- simpler system design
- for many connections no hand-over needed
- higher latency, ca. 70 - 80 ms
- higher sending power needed
- special antennas for small footprints needed

- Example:
- ICO (Intermediate Circular Orbit, Inmarsat) start ca. 2000
  - Bankruptcy, planned joint ventures with Teledesic, Ellipso – cancelled again, start planned for 2003

Satellite Networks — Typical satellite systems



PSTN: Public Switched Telephone Network

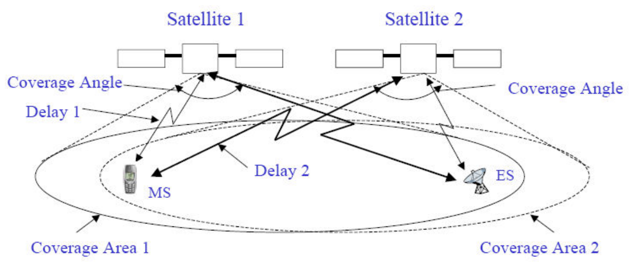
Satellite Networks — Satellite System Infrastructure

- Once contact has been established between a MS and a satellite using a LOS beam, the rest of the world can be accessed using the underlying wired backbone network.
- The satellites are controlled by the BS located at the surface of the earth which serves as a gateway.
- Inter satellite links can be used to relay information from one satellite to another, but they are still controlled by the ground BS.
- The illuminated area of a satellite beam, called the footprint, is the area where a mobile user can communicate with the satellite.

Satellite Networks — Infrastructure II

- There are losses in free space and also due to atmospheric absorption of the satellite beams.
- Rain also causes attenuation to signal strength when 12-14 GHz and 20-30 GHz bands are used to avoid orbital congestion.
- The satellite’s beam may be temporarily blocked due to flying objects or the terrain of the earth’s surface.
- Therefore a concept known as “diversity” is used to transmit the same message through more than one satellite

Satellite Path Diversity



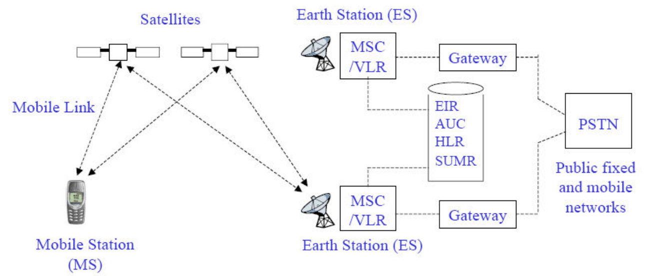
Satellite Path Diversity

- Idea behind diversity is to provide a mechanism that combines two or more correlated information signals.
- These signals have uncorrected noise and/or fading characteristics.
- A combination of the two signals improves the signal quality.
- The receiving end has the flexibility to select one of the better signals received while the other is lost due to temporary LOS problem, or attenuated because of excessive absorption in the atmosphere.
- The net effect of diversity is to utilize twice the bandwidth and therefore it is desirable to employ this in as small a fraction of time as possible.

Satellite Path Diversity

- The use of diversity can be initiated by either the MS or BS located on the earth.
- The use of a satellite path diversity is done due to the following conditions:
  - Elevation Angle: Higher elevation angle decreases shadowing problems. So, one approach is to initiate path diversity when the elevation angle is less than some predefined threshold value.
  - Signal Quality: If the average signal level quality fades beyond some threshold, then this could force the use of path diversity.
  - Stand-by option: A channel could be selected and reserved as a stand by option, when obstruction of the primary channel occurs. Several MSs can share the same stand-by channel.
  - Emergency Handoff: Whenever the connection of an MS with a satellite is lost, the MS tries to have an emergency handoff.

Satellite System Architecture



Satellite Networks

Routing

One solution: inter satellite links (ISL)

- reduced number of gateways needed
- forward connections or data packets within the satellite network as long as possible
- only one uplink and one downlink per direction needed for the connection of two mobile phones

Problems:

- more complex focusing of antennas between satellites
- high system complexity due to moving routers
- higher fuel consumption
- thus shorter lifetime
- Iridium and Teledesic planned with ISL
- Other systems use gateways and additionally terrestrial networks

Satellite Networks

Localisation of mobile stations

]Mechanisms similar to GSM

- Earth Stations (ES) maintain registers with user data
  - HLR (Home Location Register): static user data
  - VLR (Visitor Location Register): (last known) location of the mobile station
  - SUMR (Satellite User Mapping Register):
    - satellite assigned to a mobile station
    - positions of all satellites
- Registration of mobile stations
    - Localization of the mobile station via the satellite's position
    - requesting user data from HLR
    - updating VLR and SUMR
- Calling a mobile station
    - Localization using HLR/VLR similar to GSM
    - connection setup using the appropriate satellite

Satellite Networks

Handover in satellite systems

Several additional situations for handover in satellite systems compared to cellular terrestrial mobile phone networks caused by the movement of the satellites

- Intra satellite handover
  - handover from one spot beam to another
  - mobile station still in the footprint of the satellite, but in another cell
- Inter satellite handover
  - handover from one satellite to another satellite
  - mobile station leaves the footprint of one satellite
- Gateway handover
  - Handover from one gateway to another
  - mobile station still in the footprint of a satellite, but gateway leaves the footprint
- Inter system handover
  - Handover from the satellite network to a terrestrial cellular network
  - mobile station can reach a terrestrial network again which might be cheaper, has a lower latency etc.

Satellite Networks

Overview of LEO/MEO systems

	Iridium	Globalstar	ICO	Teledesic
# satellites	66 + 6	48 + 4	10 + 2	288
altitude (km)	780	1414	10390	ca. 700
coverage	global	±70° latitude	global	global
min. elevation	8°	20°	20°	40°
frequencies [GHz (circa)]	1.6 MS 29.2 ↑ 19.5 ↓ 23.3 ISL	1.6 MS ↑ 2.5 MS ↓ 5.1 ↑ 6.9 ↓	2 MS ↑ 2.2 MS ↓ 5.2 ↑ 7 ↓	19 ↓ 28.8 ↑ 62 ISL
access method	FDMA/TDMA	CDMA	FDMA/TDMA	FDMA/TDMA
ISL	yes	no	no	yes
bit rate	2.4 kbit/s	9.6 kbit/s	4.8 kbit/s	64 Mbit/s ↓ 2/64 Mbit/s ↑
# channels	4000	2700	4500	2500
Lifetime [years]	5-8	7.5	12	10
cost estimation	4.4 B$	2.9 B$	4.5 B$	9 B$

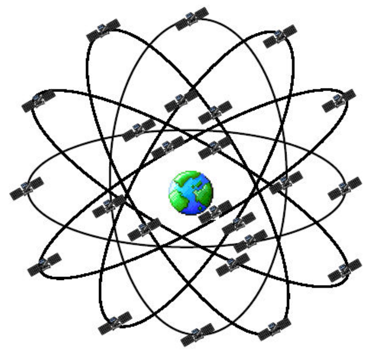
Satellite Networks

Global Positioning System (GPS)

- Used in applications such as military targeting, navigation, tracking down stolen vehicles, guiding civilians to the nearest hospital, exact location of the callers to the emergency services.
- GPS system consists of a network of 24 orbiting satellites called “NAVSTAR” placed in 6 different orbital paths with 4 satellites in 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.

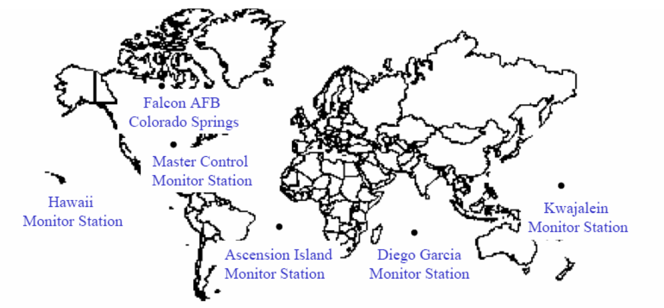
Satellite Networks

GPS Nominal Constellation of 24 Satellites in 6 Orbital Planes



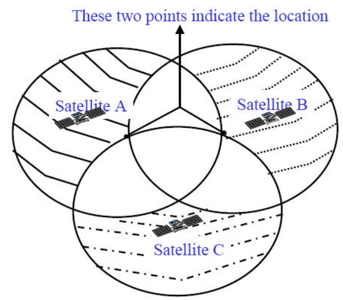
Satellite Networks

GPS Master Control and Monitor Station Network



Satellite Networks

Triangulation



GPS

- GPS is based on the “Triangulation Technique”.
- Consider the GPS receiver (MS) to be placed at a point on an imaginary sphere of radius equal to the distance between Satellite ‘A’ and the receiver on the ground.
- The GPS receiver MS is also a point on another imaginary sphere with a second satellite ‘B’ at its centre.
- The GPS receiver is somewhere on the circle formed by the intersection of 2 spheres.
- Then with the measurement of distance from a third satellite ‘C’ the position of the receiver is narrowed down to just 2 points on the circle.
- One of these points is imaginary and is eliminated.
- Therefore the distance measured from 3 satellites is sufficient to determine the position of the GPS receiver on earth.

GPS

- The GPS signal consists of a ‘Pseudo-Random Code’ (PRN), ephemeris and navigation data.
- The ephemeris data corrects errors caused by gravitational pulls from the moon and sun on the satellites.
- The navigation data is the information about the located position of the GPS receiver.
- The pseudo-random code identifies which satellite is transmitting.
- Satellites are referred to by their PRN ranging from 1-32.

Limitations of GPS

- Distance measurements may vary as the values of signal speed vary in atmosphere.
- Effects of Multi-path fading and shadowing are significant.
- In GPS, multi-path fading occurs when the signal bounces off a building or terrain.
- Propagation delay due to atmospheric condition affects accuracy.

Beneficiaries of GPS

- GPS has become important for nearly all military operations and weapons systems.
- It is used on satellites to obtain highly accurate orbit data and to control spacecraft orientation.
- GPS can be used everywhere except where it is impossible to receive the signal such as inside most buildings, in caves and other subterranean locations.
- There are airborne, land and sea based applications of GPS.
- Anyone who needs to keep track of where he/she is and needs to find his/her way to a specified location, or know what direction and how fast they are going can utilize the GPS service.

Applications of GPS

User Group	Application Area
Military	Manoeuvring in extreme conditions and navigating planes, ships, etc.
The Channel Tunnel	Checking positions and making sure they meet in the middle
General aviation and commercial aircraft	Navigation
Recreational Sailors and Commercial Fishermen	Navigation
Surveyors	Reduces setup time at survey site and offers precise measurements

Applications of GPS

User Group	Application Area
Recreational users (Hikers, moutain bikers etc)	Keeping track of where they are and finding a specific location
Automobile services	Emergency roadside assistance
Fleet vehicles, public transport systes, delivery truckes and courier services	Monitor locations at all times
Emergency vehicles	Determine location of car, truck, or ambulance closest to the accident site
Car Manufactuers	SatNav systems

Differential GPS

- Involves 2 receivers (one that's stationary and one that's moving around making position measurements).
- Stationary one provides a solid local reference
- GPS uses timing signals from 4 satellites
- Each signal will have some error
- Distance to satellite is much greater than distances travelled on earth – receivers within a few km of each other see the same signal

Differential GPS

- Idea: eliminate all errors common to both reference and roving receiver i.e. everything but multipath and receiver errors.

Typical Error in Meters (per satellite)	Standard GPS	Differential GPS
Satellite Clocks	1.5	0
Orbit Errors	2.5	0
Ionosphere	5.0	0.4
Troposphere	0.5	0.2
Receiver Noise	0.3	0.3
Multipath	0.6	0.6
SA	30	0
Typical Position Accuracy		
Horizontal	50	1.3
Vertical	78	2.0
3-D	93	2.8

Satellite Networks

DGPS

- Reference receiver, or base station (in accurately known location), computes corrections for each satellite signal
- Works in reverse, calculating what the timing should be based on a known location
- Transmits errors for all visible satellites to the roving receiver and also rate of change of error.
- Position accuracies of 1-10 meters are possible
- Corrections may be used in real-time or with post-processing techniques
- Information transmitted as radio beacons (usually in 300kHz range)

Satellite Networks

Post Processing DGPS

- Radio link for DGPS not always needed.
- For some applications (e.g. when building a new road) it is not necessary to use DGPS as the measurements are being taken
- Buses could relay information to a tracking office which could do the DGPS calculations

Satellite Networks

Wide Area Augmentation System (WAAS)

- Idea: a continental DGPS system.
- If a problem occurs with a satellite this can take a few minutes to be corrected: clearly not good enough for the aviation industry.
- Geosynchronous satellite over the US which alerts aircarft when there is a problem.
- ~24 reference receivers across the IS
- Allows Category 1 landings (very close to the runway but not zero visibility).

Satellite Networks

DGPS

- Gives DGPS corrections in the US for everyone
- European version: EGNOS
- Russian: GLOMASS
- FAA in the US has set up Local Area Augmentation Systems (LASS) near runways.
- These work like WASS, but on a local scale allows for Category 3 (zero visibility) landings.

Satellite Networks

Positioning/ Location Based Services

Need to consider these in terms of:
- Performance
- Complexity
- Implementation Requirements
- Investment

Satellite Networks

Techniques

1. GPS (Global Positioning System)
2. Cell-ID (Cell Identity).
3. AOA (Angle of Arrival).
4. TOA (Time-of-arrival).
5. OTD (Observed Time Difference).
6. A-GPS (Assisted Global Positioning System).

Satellite Networks

Cell-ID (Cell Identity)

- Typically used in GSM networks
- Based on Cell-ID, may also use timing advance (TA) information and network measurement reports (NMR)
- Cell provides information to handsets
- Timing Advance measures the range from the MS to the BTS – works best in rural areas with large cells.

Satellite Networks

E-CGI (Enhanced Cell Global Identity)

- Handsets provide info on visible cells for handover decisions. This includes power level estimates
- These are used to estimate BTS-MS distance using simple propagation models and/or network planning tools.
- Power measurements for adjacent sectors of the same cell site can provide information on angle of the MS from the site.
- Problems: only as good as model used, cell density etc

Satellite Networks

(AoA) Angle of Arrival

- Calculates relative angles of arrival at MS of 3 Base Stations, or the absolute AoA of the MS at 2 or 3 BSs.
- Uses antenna arrays, these provide direction finding capabilities to the receiver.
- Either:
  - Measure phase differences across the array (phase interferometry)
  - Measure power density across the array (beamforming)
- Simple triangulation is then used.
- Field trials suggest this is impractical in a city environment.

Satellite Networks

TOA (Time of Arrival)

- Bounce signal from MS to BS and back (or vice versa).
- Propagation time is half the time delay between transmitting + receiving.
- Needs a duplex transmission
- Accuracy not great (less than 125m, 67% of the time)

Satellite Networks

Time Difference of Arrival (TDOA)

- Measure relative arrival time at the MS of signals from 3 base stations (at the same time, or a known offset).
- Leading candidate for LBS provision
- Maximum timing resolution will depend on the sampling rate of the receiver
- Requires precise synchronisation of BS;s.
- Estimate got from intersection of two hyperboloides.
- Accuracy of less than 50m possible .

Satellite Networks

E-OTD (Enhanced – Observed Time Difference)

- Handset measure arrival time of signals transmitted by 3 (or more) BTSs.
- MS-assisted: timing measurements made by the handset are transferred to the serving MSC using standard Location Services (LCS) signalling.
- MS-based: handset does calculations and informs serving MSC using standard Location Services (LCS) signalling.
- Transmission times of BTSs must be accurately known, so network synchronisation is needed.

E-OTD

- Works well in high BTS density areas and performs well indoors.
- Not so good in low BTS density areas
- Used in UMTS networks (Observed Time difference of Arrival Idle Period Down Link – OTDOA – IPDL). Not as good as E-OTD in GSM (yet!).
- Rural: 50-150m, Suburban: 50-150m, Urban: 50-150m, Indoor: Good

A-GPS (Assisted GPS)

- Adding GPS functionality can add to cost and complexity of handsets.
- Idea is to provide support at the Serving MSC.
- GPS information sent to MS through the radio network – increases battery life and reduces time to first fix.
- No need to find and decode satellite signals.
- Rural: 10m, Suburban: 10-20m, Urban: 10-100m, Indoor: Variable