CHAPTER 11
Satellite Communication

11.1 Types of Satellites:

The idea for satellite communications was proposed by Clarke in 1945. He envisioned placing three satellites in a geosynchronous (geostationary) orbit at a height of 35780 km and separated by 120^0 to provide global coverage for communication (Fig. 11.1). Such satellites can provide voice, video, TV and data services all over the world. Satellites are not limited to communications only. Other satellites are used in remote sensing, research, global positioning system (GPS), military applications, space probes and weather forecasting. In early days, the moon was used as a passive repeater. Today all communication satellites are active repeaters. In general, satellite systems are classified into four major categories

1. geosynchronous
2. polar
3. mobile
4. defense

Geostationary satellites are mainly used for international and regional services including domestic services, such as local TV distribution, regional communications as well as monitoring weather patterns. Polar satellites orbiting at higher altitudes are used for meteorological, oceanic, space and environmental studies as well as data collection.

A geostationary satellite must be placed at its orbit and closely monitored from the ground and must function efficiently for its entire operating life. Thrusters are required for positioning, altitude control and reorientation. Solar arrays provide the power needed on board, while dry cells are usually supplied as back up during eclipses.

The placement of a satellite to a geosynchronous orbit is achieved through three main sequences (Fig. 11.2):

a) injection into space
b) placement into temporary orbit
c) transfer into permanent orbit

At a height of approximately 36000 km, the angular velocity of the satellite is 11068 km/hr (3.07 km/s). This combination of satellite height and angular velocity satisfies the fundamental laws (Kepler's, and Newton's laws of planetary motions) in maintaining orbit without the need for further propulsion requirements except for minor orbital adjustments.

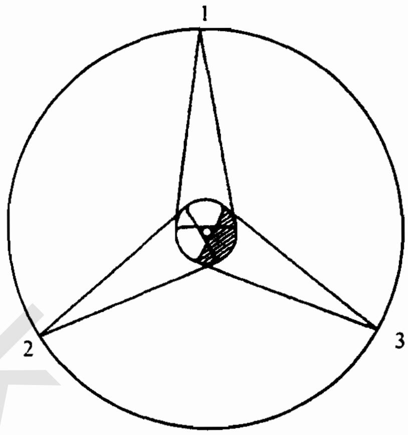

Fig. (11.1) Geostationary satellites – Clarke's model

The 24 hour orbital period of the satellite is exactly the same as earth's period around its axis. Thus, the satellite seems to be stationary at a reference point on the surface of the earth. Kepler's laws state that

1. The motion of a planet around the sun is an ellipse with the sun at one focal point.
2. The area covered by the axis connecting the planet and the sun during the orbital trajectory of the planet is equal at equal time intervals.
3. The ratio of the cube of the distance between a planet and the sun to the square of its period is constant.

A communication satellite is launched into space via a launching vehicle. This vehicle can be either a rocket or a space shuttle. In either case, to reach the geosynchronous orbit, the satellite must undergo 4 sequences

a) ascent
b) placement into parking orbit
c) transfer orbit
d) placement into a permanent circular geostationary orbit.

The primary mission of a geostationary communication satellite is to be used as an active repeater, i.e., to be able to receive signals transmitted from the earth, amplify these signals, translate (frequency convert) reamplify and transmit back to earth.

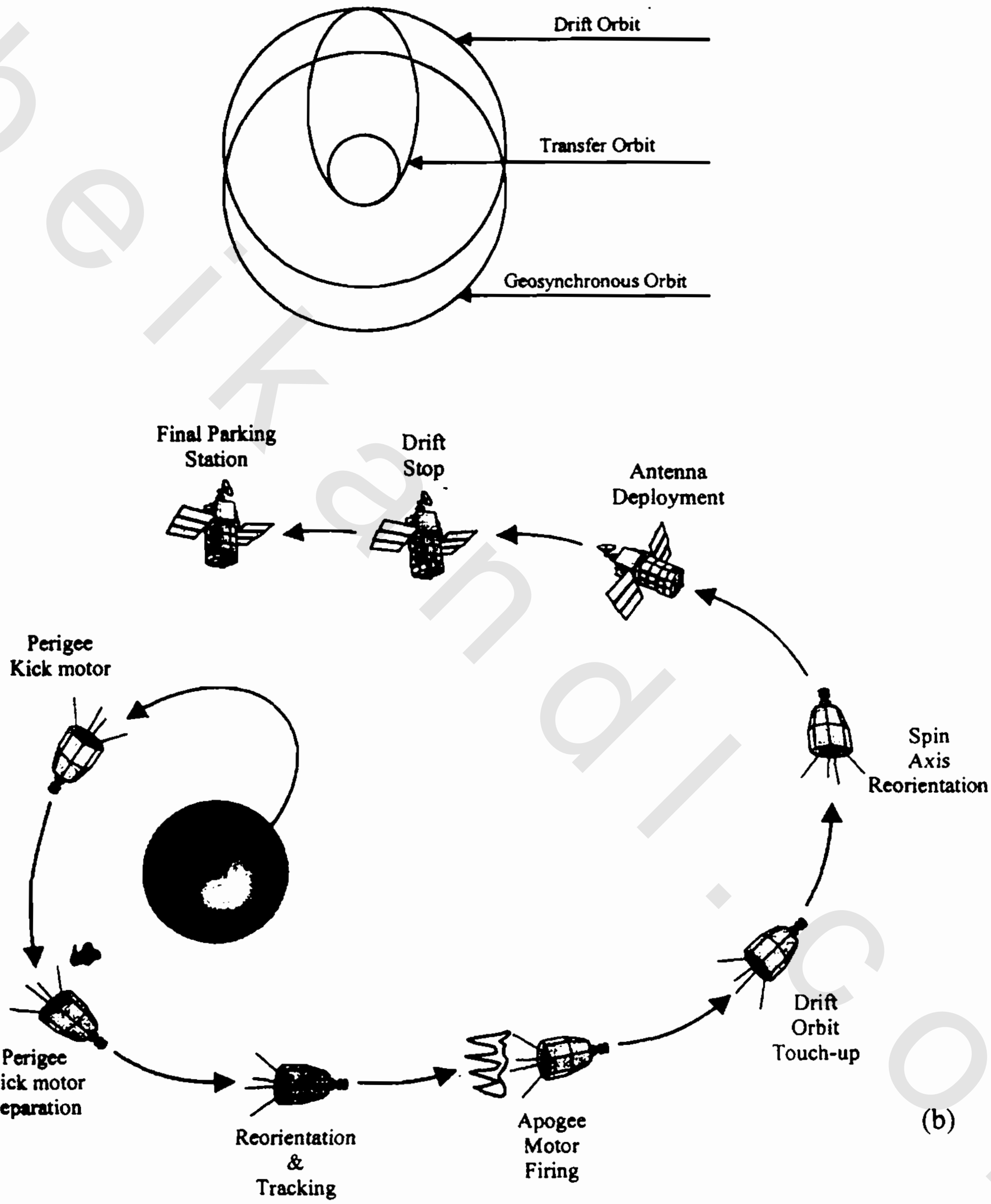

Fig. (11.2) Satellite launching
a) orbits *b) launching steps*

11.2 The Transponder:

The communication subsystem on board the satellite (repeater) consists of the following main units (Fig. 11.3)

1) Low noise amplifier (LNA)
2) Local oscillator (LO)
3) Mixer
4) Input multiplexer (MUX)
5) High power amplified (HPA)
6) Output multiplexer

The information carrying electromagnetic beam transmitted by the earth station is intercepted by the receiver antenna on board the satellite. This microwave beam has traveled an approximate distance of $40000\ km$ through space and is heavily attenuated. The LNA provides the necessary gain prior to the mixer. The mixer and the local oscillator perform the frequency translation from the uplink to the downlink frequencies.

The $6/4\ GHz$ C band is fairly congested and new systems are being implemented at $14/11\ GHz$ (Ku-band) and $30/20\ GHz$ (Ka-band). The frequency allocation at $12\ GHz$ is mainly for direct broadcast satellite (DBS). The higher of the two frequencies allocated for a satellite communication system is invariably the up link frequency. This is because the satellite has limited antenna size. The reason for using two frequencies in the first place is to achieve isolation between the satellite transmit and receive antenna. This is particularly important since the satellite transponder has enormous gain and limited space; hence the possibility of positive feedback and oscillation is serious.

The number of satellites that can be accommodated in the geostationary orbit is limited by the need to illuminate only one satellite when transmitting signals from a given earth station. If other satellites are illuminated then interference may result. For practical antenna sizes 4^{o} spacing is required between satellites in the $6/4\ GHz$. Since narrower beam widths are achievable in the $14/11\ GHz$ band, 3^{0} spacing is permissible, and in the $30/20\ GHz$ band spacing can approach 1^{0}.

11.3 FDM / FM / FDMA System:

Transponder bandwidth ($36\ MHz$) is subdivided into several transmission bands ($3\ MHz$), each allocated to one of the participating earth stations (Fig. 11.4).

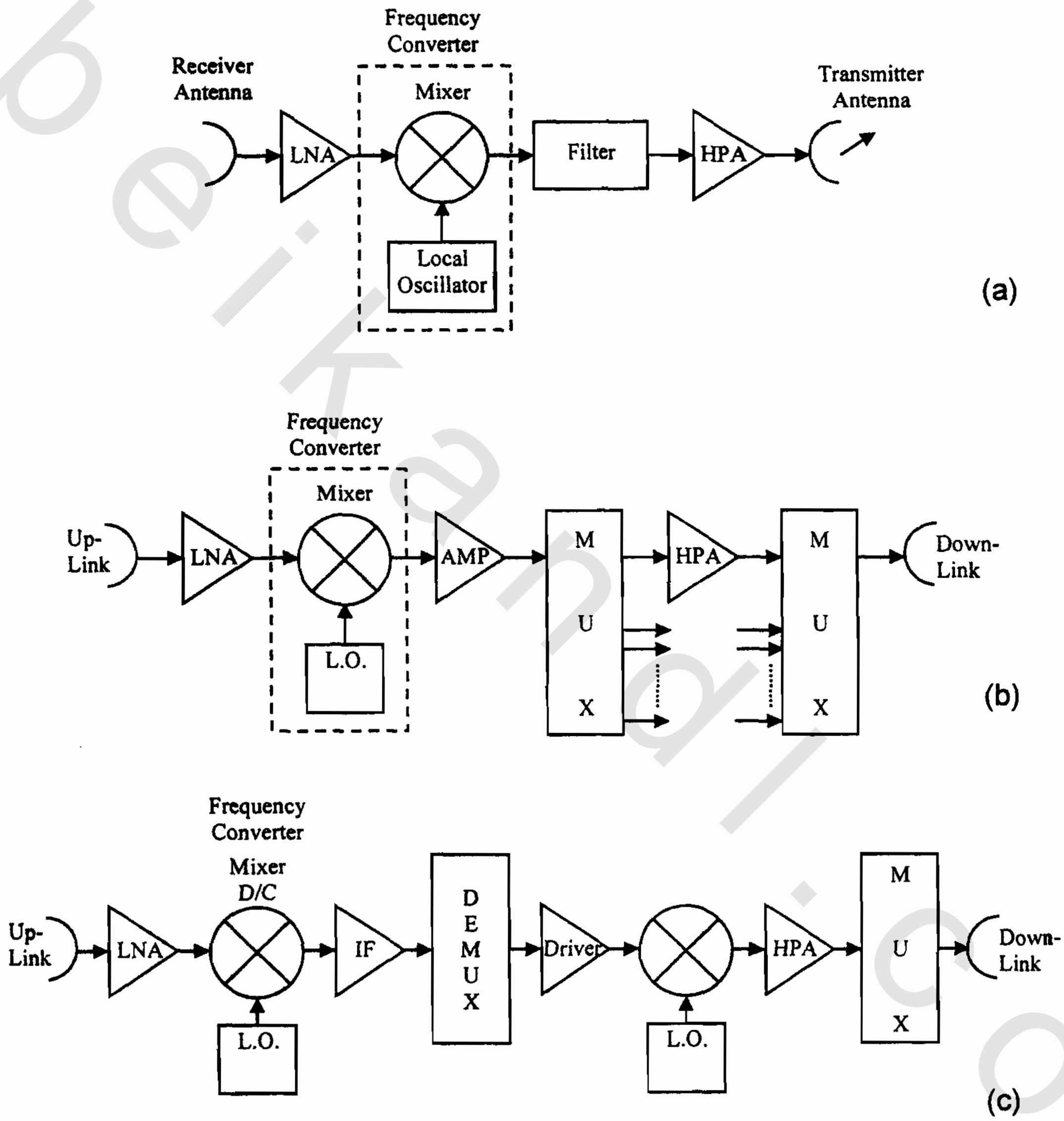

Fig. (11.3) Transponder

a) block diagram of a simplified satellite repeater
b) satellite repeater block diagram.
c) Ku-band dual-frequency converting satellite repeater

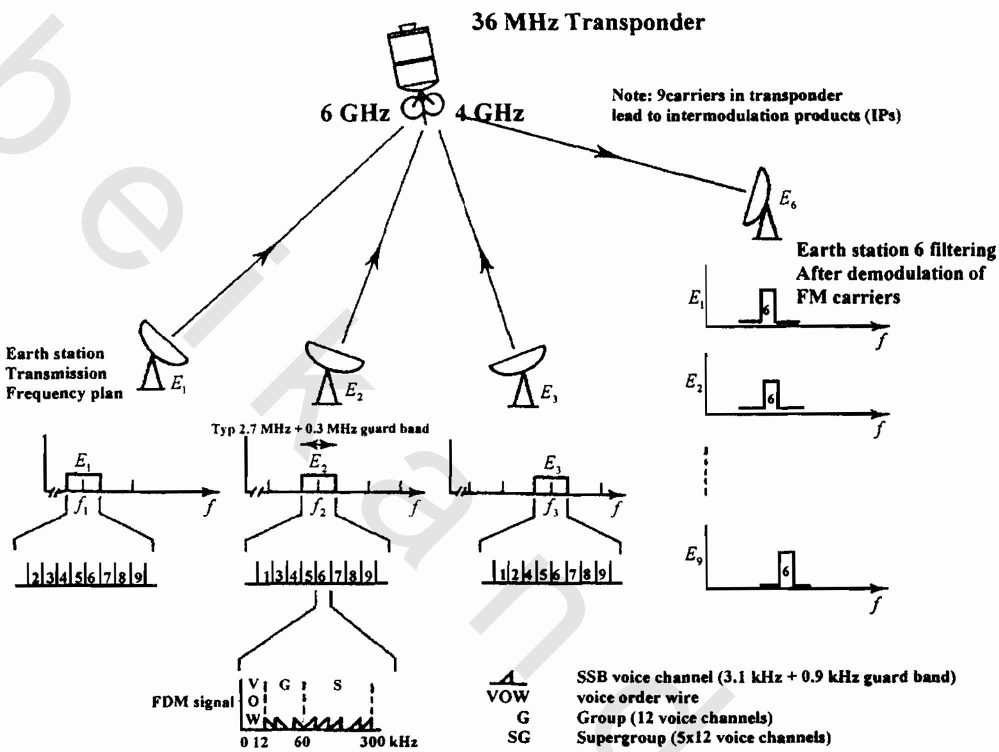

Fig. (11.4) FDM / FM / FDMA transponder satellite network

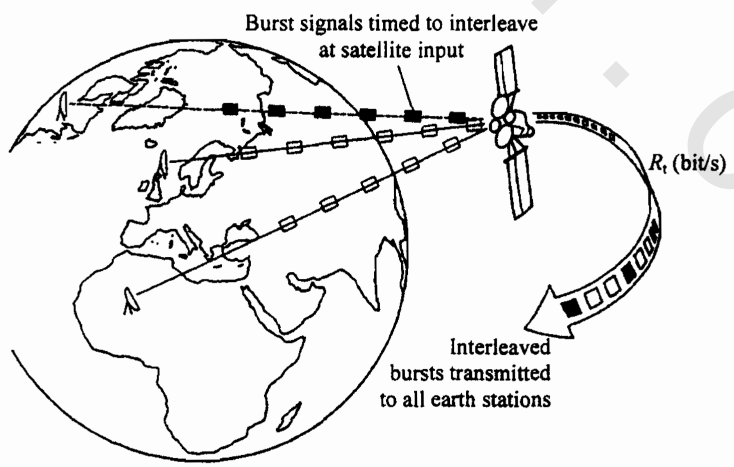

Fig. (11.5) TDMA

All the signals transmitted by a given earth station occupy that station's transmission band. Individual SSB voice signals arriving from the PSTN at an earth station are frequency division multiplexed into a position in the transmission band depending on the signal's destination. Thus, all signals arriving for transmission at earth station 2 and destined for earth station 6 are multiplexed together into sub band 6 of transmission band 2

The FDM signal consisting of all subbands is then frequency modulated onto the earth station's IF carrier. The FDM / FM signal is subsequently up converted to the $6\,GHz$ RF carrier, amplified and transmitted. A receiving earth station demodulates the carriers from all the other earth stations in the network. Each earth station therefore requires $N-1$ receivers where N is the number of participating earth stations. It then filters out the subband of each transmission band designated to itself and discards all other subbands. The subband signals are then demultiplexed and the resulting SSB signals are demodulated i.e. translated back to baseband and interfaced again with the PSTN. This method of transponder resource sharing between earth stations is called frequency division multiple access (FDMA).

11.4 TDM / PSK / TDMA System:

The time division multiplex access (TDMA) is an alternative to FDMA for transponder resource sharing between earth stations. Fig. (11.5) shows the essential TDMA principle. Each earth station is allocated a time slot – in contrast to FDMA frequency slot – within which it has access to the entire transponder bandwidth. The earth station time slots or bursts are interleaved on the uplink frequency, shifted, amplified and transmitted by the satellite to all participating earth stations. One earth station periodically transmits a reference burst in addition to its information burst in order to synchronize the bursts of all the other earth stations in the TDMA system where digital modulation is used. Fig. (11.6) shows a schematic diagram of a TDM / PSK / TDMA earth station.

A typical frame structure showing the TDMA slots allocated to different earth stations is shown in Fig. (11.7). Two reference bursts are often included (provided by different earth stations) so that the system can continue to function in the event of losing one reference station due to equipment failure. The frame period T_F is of the order of $5\,ms$. The traffic bursts each consists of a preamble followed by the subscriber traffic. The preamble which might be 280 QPSK symbols long is used for carrier recovery, symbol timing, frame synchronization and station identification.

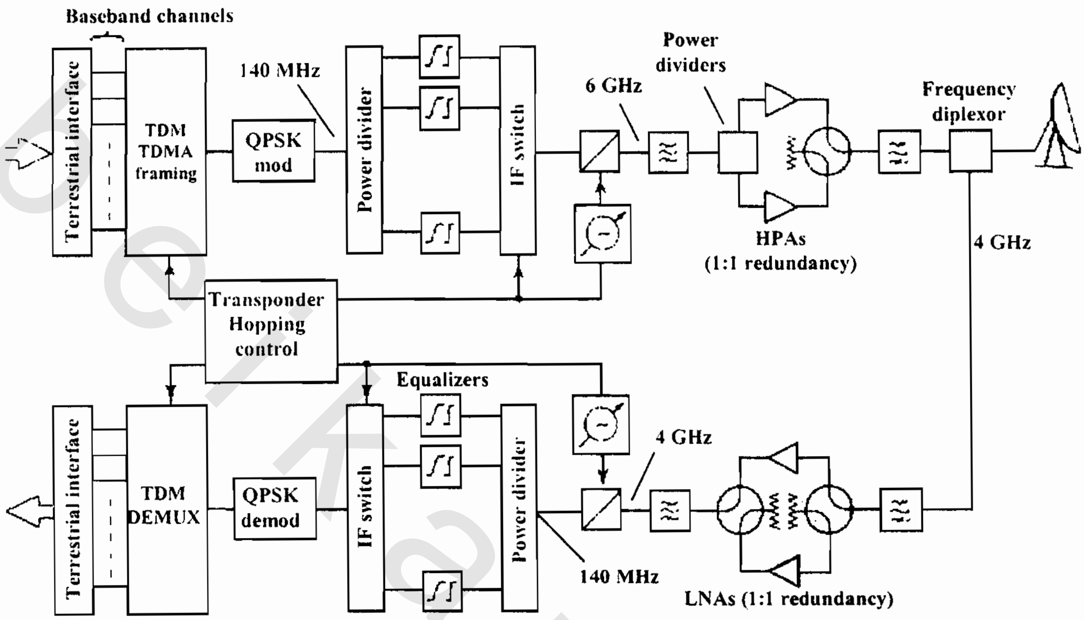

Fig. (11.6) Block diagram of TDM / QPSK / TDMA earth station

Reference bursts have the same preamble as the traffic bursts followed by control and delay signals (typically 8 symbols in duration) which ensure that the TDMA bursts from participating earth stations are timed to interleave correctly at the transponder input. Subscriber traffic is divided into 128 satellite channels. In conventional preassigned (PA) systems, the satellite channels are predivided into groups, each group being assigned to a given destination earth station. Each satellite channel carries 128 bits (64 QPSK symbols) representing 16 consecutive 8 bit PCM samples from a single voice channel. For a conventional $8\ kHz$ PCM sampling rate ($2\times 4\ kHz$ when bandwidth is $4\ kHz$), this corresponds to $16\times 125\ \mu s = 2\ ms$. In this case, the frame durations would therefore be limited in length to $2\ ms$ so that the next frame could convey the next $2\ ms$ of each voice channel. Channels carrying non voice high data rate information is composed of multiple voice channels. Thus, a $320\ kb$ would be $5\times 64\ kb/s$ voice channels.

We define the frame efficiency η_F of TDM/PSK/TDMA system as the portion of frame bits which carry revenue earning traffic

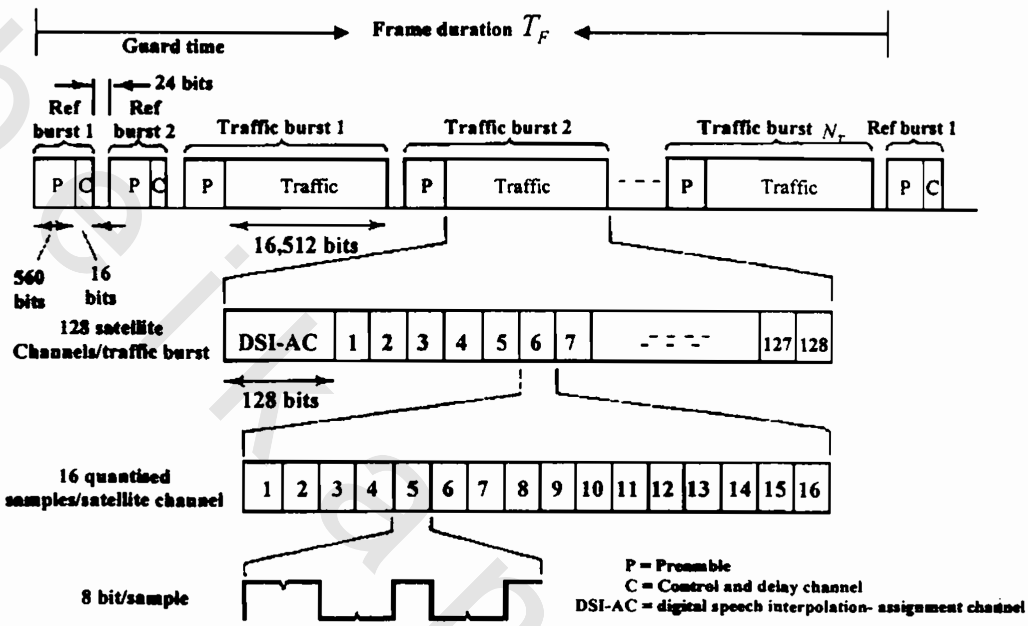

Fig. (11.7) TDMA frame structure

$$\eta_F = (b_F - b_0)/b \qquad (11\text{-}1)$$

where b is the total number of frame bits and b_0 is the number of overhead (non revenue earning) bits. The total number of frame bits is given by

$$b_F = R_b T_F \qquad (11\text{-}2)$$

Where R_b is the TDMA bit rate and T_F is the frame duration. The number of voice channels which a TDMA system can support in called voice channel capacity X

$$X = R_b / R_v \qquad (11\text{-}3)$$

where R_v is the rate of a single voice channel.

The information bit rate R_b is given by

$$R_b = (b_F - b_0)/T_F \qquad (11\text{-}4)$$

$$= \eta_F R_T \quad \text{b/s} \qquad (11\text{-}5)$$

The bit rate of a single voice channel is given by

$$R_v = f_s n \quad \text{b/s} \qquad (11\text{-}6)$$

where f_s is the sampling rate (usually 8 k Hz), and n is the number of PCM bits/sample (usually 8) and R_v (32 kb/s). The average number of voice channels per each station access X_A is

$$X_A = X / \nu \quad (11\text{-}7)$$

where ν is the number of accesses per frame

11.5 DAMA:

I intelsat uses, TDM/PSK/TDMA modulator where QPSK is standard, nominal symbol rate 60.416 M baud, nominal bit rate 120.832 Mb/s. It may well happen in preassigned TDMA (PA-TDMA) that at a certain earth station all the satellite channels assigned to a given destination station are occupied while free capacity exists in channels assigned to other destination channels. Demand assigned TDMA (DA -TDMA or DAMA) allows the reallocation of satellite channels in the traffic burst as the relative demand between earth station varies.

In addition to demand assignment of satellite channels within the earth station's traffic burst, DA-TDMA may also allow the number of traffic bursts per frame and/or the duration of the traffic bursts allocated for a given earth station to be varied.

Digital speech interpolation (DSI) is another technique employed to maximize the use made of available transponder capacity. An average speaker engaged in conversation actually talks for only 35%of the time, while the rest is consumed in listening and pausing. DSI automatically detects where the speech is present in the channel, and during speech absence reallocate the channel to another user. The inevitable clipping at the beginning of speech which occurs as the channel is being allocated is too short to be noticed. DAMA requires extra overhead in the frame structure to control the allocation of satellite channels and the relative number per frame and lengths of each earth station's traffic bursts. For systems with large numbers of earth stations, each contributing short bursty traffic at random times, then random access (RA) systems may use transponder resources more efficiently than DAMA, The earth stations of RA systems attempt to access the transponder, i.e., transmit bursts (packets) at will. There is a possibility of traffic bursts colliding with transponder causing errors in the received data. Such collisions can be detected by transmitting and receiving stations and may then let packets be retransmitted.

EX. 11.1

The frame length in a pure TDMA system is 2 ms. If QPSK symbol rate is 60.136 M baud and all traffic bursts are of equal length, determine

i) maximum number of earth stations which the system can serve

ii) the frame efficiency

Solution

$$R_b = 2xQPSK \text{ Baud rate}$$
$$= 2x60.136x10^6 = 1.20272x10^8 \text{ b/s}$$
$$b_F = R_b T_F = 1.20272x\,10^8 x\; 2x\,10^{-3}$$
$$=240544 \text{ bits}$$

The overhead

$$b_0 = N_R b_R + N_T(b_P + b_{AC}) + (N_R + N_T)b_G$$

where N_R = the number of participating reference stations, N_T is the number of participating traffic stations , b_R is the number of bits in a reference burst, b_P is the number of preamble bits in a traffic burst, b_{AC} is the number of digital speech interpolation-assignment channel bits per traffic burst and b_G is the number of guard bits per reference or traffic of burst.

In this example, we take b_R=560+16 bit reference $N_R = 2$, preamble b_P=560 bit, guard interval b_G-24 bit, DSI assignment (128 bit)

$$b_o = 2(560+16) + (560+128)N_T + (2+N_T)24$$
$$=1200 + 712N_T$$
$$b_F - b_0 = 240544 - (1200 + 712N_T)$$
$$= 239344 - 712N_T$$

(i)
$$N_T = (b_F - b_0)/(16512-128)$$
$$= (239344 - 712N_T)/16384$$
$$N_T(16384 + 712) = 239344$$
$$N_T = 14$$

Thus, a maximum of 14 earth stations may participate

(ii)
$$\eta_F = (b_F - b_0)/b_F$$
$$= \frac{240544 - (1200 + 712\times 14)}{240544} = 0.954$$

Thus, the frame efficiency is 95.4%

11.6 VSAT:

In addition to international point to point multiplex telephony, low data rates (2.4 to 64 kb/s) width narrow signal bandwidth may employ satellites width very small aperture (1m diameter antenna) terminals (VSATs) and modest power (0.1 to 10W) Thus many remote terminals can access a central computer data base. VSAT systems may employ up to 10000 earth station terminals in a single network. Satellites may also use switched TDMA on board processing (SS-TDMA), where many small spot beams are used (Fig. 11.8) A switching matrix on board controls the connectivity with different earth stations. The various sub bursts destined for different receiving stations of a transmitting station's traffic burst can be directed by the matrix switch to the correct downlink spot beams (Fig. 11.9). Beams may be hopped from area to area

11.7 Satellite TV Bands:

Radio waves above 50 MHz used to carry TV signals do not propagate far above the horizon. At high frequencies they propagate similar to light. This is unlike radio waves of greater wavelength (500 kHz-30MHz) which are reflected by the ionosphere: Geostationary satellites are used. Two main parameters have to be taken into account for the choice of frequency bands used for satellite communication

1. Noise level All sources of noise (atmospheric, galactic or artificial) decrease almost linearly with frequency and become negligible above 5 GHz (except for background noise due to the Big Bang).
2. Attenuation due to the atmosphere and atmospheric disturbances (rain, clouds and fog): atmospheric attenuation by clear weather is low below 15 GHz and then increase with frequency with remarkable peaks at 22 GHz (due to absorption by water vapor) and 60 GHz (due to absorption by oxygen).

Attenuation due to rain is very limited below 3 GHz and increase progressively up to 80 GHz where it reaches a stable maximum. Thus the most appropriate frequencies seem to be between 3 and 5 GHz. The first band used (C band) is from 3.7 to 4.2 GHz while Ku band used is from 10.95-11.7 GHz (uplink) and 12.5-12.75 GHz (downlink).

Two different levels of polarization are used for satellite transmissions. Linear polarization means that the direction of the electric field vector is fixed. Thus we can transmit two waves of identical frequency and of orthogonal polarizations (horizontal and vertical) modulated by different signals without interference. Circular polarization means the electric field rotates clockwise or counter clockwise.

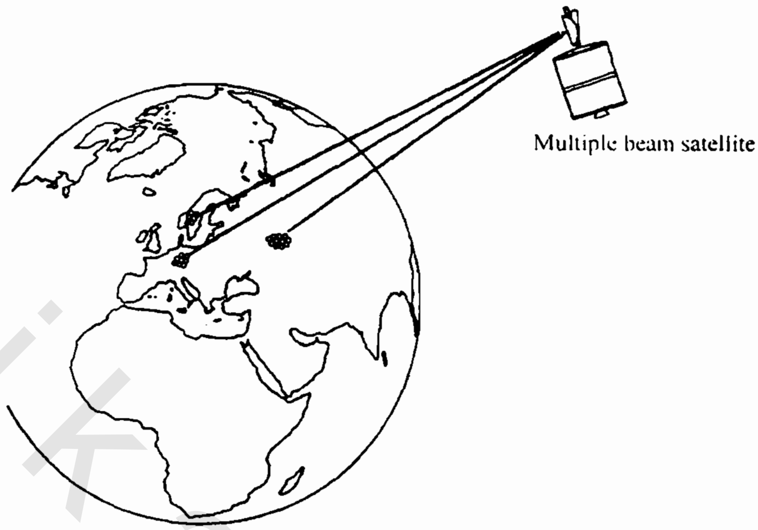

Fig. (11.8) SSTDMA

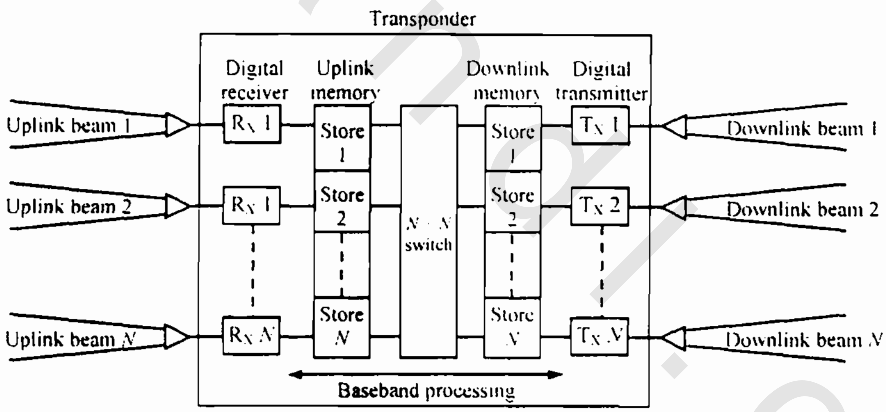

Fig. (11.9) SSTDMA transponder

11.8 EIRP:

Let us assume a transmitter with radiated power P located in free space at a distance R form a receiver and radiating uniformly in all directions. Such an ideal transmitter is called isotropic source. Since there is no loss of energy in vacuum, at a distance R from the source, the energy will be uniformly distributed on a sphere of radius R. The flux density I (W/m^2) is given by

$$I = \frac{P}{4\pi R^2} \quad (11\text{-}8)$$

The total power P_A received by area A, is given by

$$P_A = \frac{PA}{4\pi R^2} \quad (11\text{-}9)$$

Sine the power on board the satellite is limited, it is important to concentrate as precisely as possible on the target service area by means of a directive transmission antenna. The equivalent isotropic radiant power (EIRP) in dBW of a satellite at a given reception point is the power relative to 1 W that would be required from an isotopic source situated at the same place as the satellite to produce the same flux density as that received from the satellite at the same reception point. This figure is made up of two components. It is the sum of the gain G_E in radiated electric power ratio between the satellite's transmitter and 1 W transmitted, and the transmitting antenna gain due to the directivity relative to the isotopic antenna

$$EIRP = G_E + G_A \text{ (in } dBW\text{)} \quad (11\text{-}10)$$

Ex.11.2

An ideal satellite radiating power 100 W uniformly on a circular area 1000km radius on the earth centered on the equator just below the satellite at approximately 36000 km from the satellite. (Fig. 10.10). Find

i) $EIRP$

ii) Power received by a parabolic antenna of diameter 1 m and efficiency 100%

Solution

$$G_E = 10\log(P_E / P_I) = 10\log 100 = 20dB$$

An ideal isotopic transmitter would radiate uniformly its whole power in a spherical area at radius 36000. The total area is $S = 4\pi(36000)^2 km^2$. The directional satellite radiates, all its power in a cone which at the level of the earth cuts a circular area of radius $r_z = 1000km$. The area of the circular zone is $S_z = \pi r_z^2 = \pi(1000)^2 km^2$

The gain G_A brought by the directivity of the transmitting antenna represents the power ratio that would be necessary to obtain the same power flux density with an isotropic transmitting antenna.

$$G_A = 10\log(\frac{S}{S_z}) = 10\log[4x\,36^2]$$

$$= 37.1dB$$

$$EIRP = G_E + G_A = 20 + 57.1 \; dBW$$

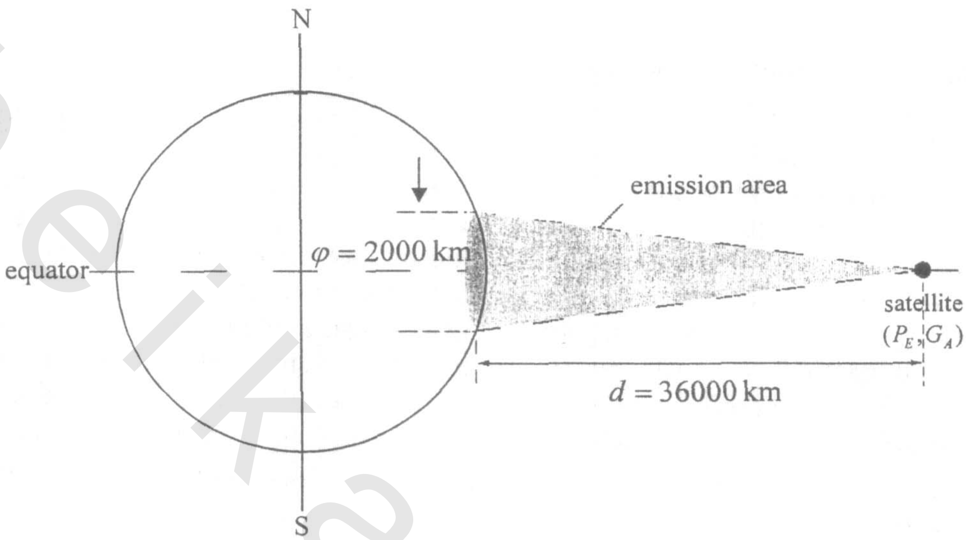

Fig. (11.10) $EIRP$ **calculation transmission**

The power received by an antenna P_R to the transmission power P_E uniformly spread over the illuminated area is equal to the ratio of the apparent area of the antenna (0.5m) and the area of the illuminated zone. S_z

$$S_R = \pi r_R^2 = \pi(0.5)^2$$
$$= 0.25\pi \quad m^2$$
$$\frac{P_R}{P_E} = \frac{S_R}{S_z} = 0.25x\,10^{-12}$$

We calculate the directional attenuation A_d in dB

$$A_d = -10\log\frac{P_R}{P_E} = -10\log(0.25x10^{-12})$$
$$= 126dB$$

In this case, with100W transmitter, $P'_E = 20dBW$ The power of the received signal P_R' (dBW) would be

$$P_R' = P_E' - A_d$$
$$= 20 - 126 = -106dBW$$

In other words, the received signal is 106dB below 1W corresponding to $0.25\text{x}10^{-10}W$

Problems

1. A satellite radiates power 200 W uniformly on a circular area 2000 km radius on earth Calculate $EIRP$.

2. In the problem above, for an antenna 2m diam, find the directional attenuation and the received power, use data in Ex. 11.2

3. A terrestrial station has power 1 kW and antenna gain 60 dB and radius 10 m. Find $EIRP$ and compare it with $EIRP$ of the transponder if the terrestrial antenna is treated as a receiving antenna for the same value in problem(1).

4. Derive relations in TDM between bandwidth, frame time and number of stations for Nyquist criterion.

5. In a digital link, derive the relations between symbol rate, clock speed bandwidth, number of channels, number of bits/symbol, and bit rate for both Nyquist criterion and ISI raised cosine condition. Show the effect of using the raised cosine filter on the number of allowable channels for the same baseband bandwidth.

6. Design a frequency synthesizer programmable between 16.2 and 19.2 MHz to give IF signal at 10.7 MHz with 250 kHz bandwidth.

7. Verify Clarke's vision of geostationary satellites at 36000 km above the surface of the earth. Take the radius of the earth to be 6200 km.

8. Redo Ex. 11.1 for 16-PSK.

References

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