Chapter 6 Solution to Problems

1. You are designing an FDM/FM/FDMA analog link that will occupy 36 MHz of an INTELSAT VI transponder. The uplink and downlink center frequencies of the occupied band are 5985.5 MHz and 3760.5 MHz. The distance from the satellite to your earth station is 40,000 km. The saturation uplink flux density for your uplink is - 75 dBW/m^2 and the satellite's G/T is = -11.6 dBK^{-1}. At saturation the transponder EIRP for your downlink is 29 dBW and the earth station's G/T is 41 dBK^{-1}. The transponder is linear in that the EIRP in dBW is BO dB below the saturation value when the uplink flux density is backed off BO dB below saturation. The intermodulation carrier to noise ratio, (C/N), in dB, is related to the back-off BO in dB by

$$(C/N)_I = 7.86 + 0.714 \times BO$$

In other words, at saturation the value of $(C/N)_I$ is 7.86 dB. Find the maximum overall carrier-to-noise ratio (C/N), in dB that this link can achieve. What back-off must be used to achieve it? (When you need a frequency in your calculations, use the uplink or downlink center frequency as appropriate.) Make your calculations for beam center.

Answer: This problem specifies receive system G/T ratio for the satellite and the receiving earth station. The C/N ratio in the receiver for either uplink or downlink is calculated in dB units as

$$(C/N) = P_t + G_t + G_r / T_s - L_p – 10 \log k - 10 \log B_N$$

Since the uplink specification is given in terms of saturation flux density we need to convert path loss, L_p to flux density, F:

$$F = P_t / (4 \pi R^2) = P_t \times [\lambda / (4 \pi R)]^2 \times 4 \pi / \lambda^2 = P_t \times L_p \times 4 \pi / \lambda^2$$

In decibel units

$$F = P_t + L_p – 10 \log (4 \pi / \lambda^2)$$

Analyze the uplink first. For saturation of the transponder at f = 5985.5 MHz,

$\lambda = 0.050121$ m

$$(C/N)_{up\ sat} = F_{sat} – 10 \log (4 \pi / \lambda^2) + G_r / T_s - 10 \log k - 10 \log B_N$$

$$= -75.0 – 36.99 – 11.6 + 228.6 – 75.56 = 29.45 \text{ dB}$$

The operating $(C/N)_{up}$ value of the transponder is set by the transponder input back off BO

$$(C/N)_{up\ op} = 29.45 – BO \text{ dB}$$

Repeating the same analysis for the downlink at a frequency of 3760.5 MHz, $\lambda = 0.07978$ m and the saturated output power of the transponder

Path loss, $L_p = 20 \log (4 \pi R / \lambda) = 196.0$ dB

$(C/N)_{dn\ sat} = 29.0 + 41.0 – 196.0 + 228.6 – 75.56 = 27.04$ dB

The operating value of the downlink C/N ratio is

$(C/N)_{dn\ op} = 27.04 - BO$ dB

The intermodulation $(C/N)_I$ ratio is given by

$(C/N)_I = 7.86 + 0.714\ BO$ dB

The overall C/N ratio in the earth station receiver is found from the reciprocal formula

$(C/N)_o = 1 / [1 / (C/N)_{up} + 1 / (C/N)_{dn} + 1 / (C/N)_I]$

Tabulate the values of each C/N ratio and calculate overall C/N as a function of back-off BO. Some iteration is required to find the best value of $(C/N)_o$.

BO dB	$(C/N)_{up}$ dB	$(C/N)_{dn}$ dB	$(C/N)_I$ dB	$(C/N)_o$ dB
1.0	28.45	26.06	8.57	8.45
5.0	24.45	22.06	11.43	10.87
10.0	19.45	17.06	15.0	12.03
15.0	14.45	12.06	18.57	9.51
12.5	16.95	14.56	16.78	11.18
11.25	18.20	15.81	15.89	11.73
10.63	18.83	16.44	15.45	11.91

The maximum value of overall $(C/N)_o$ ratio of 11.9 dB in the earth station receiver occurs when the transponder backoff is set to 10.6 dB.

Problems 2 through 5 all involve a satellite and earth stations with the same specifications.

Five earth stations share one transponder of a 6/4 GHz satellite. The satellite and earth station characteristics are given below:

Satellite	Transponder BW	= 36 MHz
	Transponder gain	= 90 dB (max)
	Input noise temp.	= 550 K
	Saturated output power	= 20 W (max)
	4 GHz antenna gain	= 20.0 dB
	6 GHz antenna gain	= 22.0 dB
Earth station	4 GHz antenna gain	= 60.0 dB
	6 GHz antenna gain	= 63.0 dB
	Receive System Temp.	= 100 K
Path loss	At 4 GHz, L_p	= 196 dB
	At 6 GHz , L_p	= 200 dB

2. The stations all operate in a TDMA mode. Speech signals are sampled at 8 kHz, using 8 bits/sample. The sampled signals (PCM) are then multiplexed into 40 Mbps streams at each station, using QPSK**.**

a. Find the bit rate for each PCM signal.

Answer: Speech signals sampled at 8 kHz and digitized into 8 bit words form standard digital speech channels at 64 kbps (sometimes called PCM signals).

b. The number of speech signals (as PCM) that could be sent by each earth station, as a single access, with no overhead (i.e. no header or CRC, etc.). This is a TDM data stream.

Answer: Time Division Multiplexing sends many 64 kHz bit streams sequentially at a bit rate higher than 64 kbps by interleaving 8 bit words from different digital speech channels.

For R_b = 40 Mbps we can send $40 \times 10^6 / 64 \times 10^3 = 625$ channels

c. The shortest frame time for any TDMA scheme.

Answer: We must send one 8 bit word from each channel every 125 μs (125 μs = 1 / 8 kHz). Therefore the shortest TDMA frame that can be used with digital speech is 125 μs.

3. Assume that the TDMA system uses a 125 μs frame time. Find the number of channels that each earth station can send within the TDMA frame when:

a. No time is lost in overheads, preambles, and the like.

Answer: Each 125 μs frame sends a total of 40 Mbps × 125μs = 5,000 bits from multiple speech channels. Each digital speech channel sends 8 bits every 125 μs

N = 5,000 / 8 = 625 channels.

b. A 5 μs preamble is added to the beginning of each earth station's transmission.

Answer: Each speech channel in the 125 ms frame is now divided into two parts: a 5 μs preamble and 8/40 μs of speech bits, giving a total of $5 \times 40 + 8 = 208$ bits/ speech channel. . Each frame sends 40 Mbps × 125 μs = 5000 bits. Hence

N = 5000 / 208 = 24 channels.

c. A 5 μs preamble is added to each station's transmission and 2 μs guardband is allowed between every transmission.

Answer: Each speech channel is preceded by a 5 μs preamble and followed by a 2 μs gap when there is no transmission (the guard band). Overhead around each speech channel requires 7 μs transmission time; at 40 Mbps, the link sends 40 bits in 1 μs, so each speech channel now requires the equivalent of $7 \times 40 + 8 = 288$ bits. Hence

N = 5000 / 288 = 17 channels

(rounded down from N = 17.36 – we cannot send partial channels).

4. A 750 μs frame time is used instead of a 125 μs frame. Find the new channel capacities of the earth stations for the cases in Problem 3 above.

Answer: The longer frame reduces the impact of overhead, but requires more bits per speech channel in each frame. In 750 ms, each speech channel delivers $750 / 125 \times 8 = 48$ bits. Each frame must contain 48 bits from each speech channel. Each 750 μs frame delivers a total of 750 μs × 40 Mbps = 30,000 bits.

With no overhead, N = 30,000 / 48 = 625 channels.

With 5 μs lost to a preamble before each 48 bit speech transmission, , the frame can carry 30,000 / 248 = 120 channels

With 2 μs guard bands between speech transmissions and a 5 μs preamble before each transmission, 80 bits are lost in guard times and 200 bits are used for preamble, so each speech channel requires the equivalent of 200 + 48 + 80 = 328 bits.

Hence N = 30,000 / 328 = 91 channels. (N = 91.46, so there is an extended guard time at the end of each frame of $2 + 0.54 \times 328 / 40 = 6.428$ μs.)

The reduced effect of overhead is well illustrated in the last value of N. The 125 μs frame delivered only 17 channels.

5. Find the earth station transmitter power and received (C/N) when the system is operated:

a. In TDMA with the transponder saturated by each earth station in turn.

Answer: We will assume that the transponder is set to its maximum gain of 90 dB.

The transponder is accessed by each TDMA earth station in sequence, and outputs its saturated output power of 20 W = 13 dBW.. Thus each earth station must achieve a transponder input power $P_r = 13 – 90 = -77.0$ dBW.

The uplink power budget allows us to find transmitter power P_t for the 6 GHz uplink. Assuming an earth station in the center of the satellite antenna footprint and path loss $L_p = 200$ dB, with no other losses:

$$P_r = -77.0 = P_t + 63.0 + 22.0 - 200$$

$$P_t = 38 \text{ dBW or } 6310 \text{ W.}$$

Each of the transmitting stations must send bursts of signal at this high transmitter output power.

The transponder has a receiving system noise temperature of $T_s = 550$ K. The 40 Mbps signals are sent using QPSK, so the symbol rate is 20 Msps, and assuming ideal RRC filters in the receivers, $B_N = 20$ MHz. Hence

$$N_{xp} = k\, T_s\, B_N = -228.6 + 27.4 + 73 = -128.2 \text{ dBW.}$$

The received power level was – 77 dBW at the transponder input so

$$(C/N)_{up} = -77 + 128.2 = 51.2 \text{ dB.}$$

On the downlink, the transponder is operated at its saturated output power of 20 W or 13 dBW. The received power at the earth station input is found from the downlink power budget. Assuming again an earth station at the center of the satellite footprint

P_r = 13.0 + 20.0 + 61.0 – 196.0 = -102.0 dBW

The system noise temperature of the receiver is 100 K, hence

N_{es} = -228.6 + 20.0 + 73.0 = -135.6 dBW

$(C/N)_{dn}$ = -102.0 + 135.6 = 33.6 dB.

Combining the uplink and downlink C/N ratios

$(C/N)_o$ = 1 / ($1/(C/N)_{up}$ + $1/ (C/N)_{dn}$) = 2252 or 33.5 dB

b. In FDMA with 3-dB input and output back-off.

Answer: The frequency band is divided into five equal bands, each band allocated to a different earth station. The satellite transponder output power must also be divided equally between the five earth stations. Thus each earth station transmits a 40/5 = 8 Mbps bit stream using QPSK giving a 4 Msps symbol rate and receiver noise bandwidth of 4 MHz. With 3 dB output back off the transponder transmits a total of 10 W, or 2 W per earth station channel. With the same assumptions as for the TDMA system, the uplink earth station transmit power P_t and uplink C/N ratio are given by

P_r = 3.0 – 90.0 = -87.0 dBW = P_t + 63.0 + 22.0 - 200.0

P_t = 28.0 dBW or 631 W.

The noise power of a 4 MHz noise bandwidth channel on the satellite is 7 dB less than the noise power for a 20 MHz channel, so N = -128.2 - 7.0 = -135.2 dBW.

$(C/N)_{up}$ = -87.0 + 135.2 = 48.2 dB.

The downlink has transponder output power of 2 W per earth station channel and noise bandwidth of 4 MHz giving N_{es} = -135.6 – 7 = 142.6 dBW. Hence received power and $(C/N)_{dn}$ are

P_r = 3.0 + 20.0 + 60.0 - 196.0 = -113.0 dBW

$(C/N)_{dn}$ = -113.0 + 142.6 = 29.6 dB

Combining the uplink and downlink C/N ratios

$(C/N)_o$ = 1 / ($1/(C/N)_{up}$ + $1/ (C/N)_{dn}$) = 900 or 29.5 dB

6. A digital communication system uses a satellite transponder with a bandwidth of 54 MHz. Several earth stations share the transponder using QPSK modulation using either FDMA or TDMA. Standard message data rates used in the system are 80 kbps and 2.0 Mbps. The transmitters and receivers in the system all use ideal RRC filters with $\alpha = 0.25$, and FDMA channels in the satellite are separated by 100 kHz guard bands. When TDMA is used, the TDMA frame is 125 μs in length, and a 2 μs guard time is required between each access. A preamble of 148 bits must be sent by each earth station at the start of each transmitted data burst.

a. What are the symbol rates for the 80 kbps and 2.0 Mbps QPSK signals sent using FDMA?

Answer: Symbol rates for QPSK are one half the bit rate.

For R_b = 80 kbps, R_s = 40 ksps

R_b = 2.0 Mbps, R_s = 1.0 Msps

b. What is the symbol rate of each earth station's transmitted data burst when TDMA is used?

Answer: Each earth station must transmit at a burst rate that occupies the transponder bandwidth of 54 MHz. Digital signals transmitted with RRC filters with $\alpha = 0.25$ have an occupied bandwidth $B_{occ} = R_s (1 + \alpha)$. Hence $R_s = B_{occ} / (1 + \alpha) = 54 / 1.25 = 43.2$ Msps. Each station must transmit QPSK signals at a symbol rate of 43.2 Msps, giving a bit rate of 86.4 Mbps.

c. Calculate the number of earth stations that can be served by the transponder when 80 kbps channels are sent using (i) FDMA and (ii) TDMA.

Answer: **FDMA:** Each station requires a RF bandwidth given by

$B_{RF} = 1.25 \times R_s + 100$ kHz

For R_b = 80 kbps, R_s = 40 ksps, B_{RF} = 50 + 100 = 150 kHz.

$N = 54.0 / 0.150 = 360$ channels

TDMA: All TDMA transmissions are made at a burst rate of 43.2 Msps, giving a bit rate of 86.4 Mbps. A 2 μs guard time is required after each transmission and 148 bits of preamble are sent at the start of each transmission. The 2 μs guard time is equivalent to $2 \times 86.4 = 172.8$ bits. The signal rate of 80 kbps requires 125 μs × 0.08 Mbps = 10 bits of data per frame.

Each station burst sends the equivalent of 148 + 10 + 172.8 = 330.8 bits.

Hence the number of channels in a 125 μs frame of $125 \times 86.4 = 10{,}800$ bits is

$N = 10,800 / 330.8 = 32$ stations.

d. Calculate the number of earth stations that can be served by the transponder when 2.0 Mbps channels are sent using (i) FDMA and (ii) TDMA.

Answer: FDMA: For $R_b = 2.0$ Mbps, $R_s = 1.0$ Msps. The RF bandwidth required for each channel is $B_{RF} = 1.0 + 0.1 = 1.1$ MHz. Hence the number of earth stations that can share the transponder is

$N = 54.0 / 1.1 = 49$ channels

TDMA: When the bit rate is 2.0 Mbps per station, each earth station transmission sends $125 \times 2 = 250$ data bits. Each transmission contains the equivalent of $148 + 250 + 172.8 = 570.8$ bits. Hence the number of earth stations that can share the transponder is

$N = 10,800 / 570.8 = 18$ stations

FDMA is clearly a much more effective method when the data transmission requirements of each station are small. The short frame time makes the system inefficient, even for the 2 Mbps data transmission rate.

7. The capacity of the TDMA system described in Problem 6 can be increased substantially by using satellite switched TDMA. In a group of earth stations, each station sends a 2.0 Mbps signal to every other earth station in every frame. It takes one microsecond to reposition the satellite antenna beam from one earth station to another. Only the downlink antenna beam is switched; the uplink uses a common zone beam. The frame length to be used is 1000 μs, with a 148 bit preamble and 2 μs guard times between transmissions arriving at the satellite The extra antenna gain at the satellite is traded for an increase in the data rate by using 16-QAM on the downlink. Other parameters of the system are unchanged.

a. Find the number of earth stations that can share the transponder.

Answer: Several parameters have changed from problem #6. The downlink is now using 16-QAM which sends 4 bits per symbol. Thus the bit rate for the downlinks is

$R_b = 43.2 \times 4 = 172.8$ Mbps.

Downlink frames consist of 1000 μs frames at 172.8 Mbps, giving 172,800 bits/frame. Each earth station is transmitting at 2.0 Mbps, so it must send 2000 bits in each 1000 μs frame.

Transmissions consist of bursts from N uplink stations, with each burst containing (N-1) transmissions of 2000 / (N-1) bits to each of the other (N-1) earth stations. Each uplink burst requires a guard time of 2 μs and each downlink transmission requires 148 bits of preamble at the start of each burst and a 1 μs beam repositioning time for each transmission to (N - 1) other earth stations. Using equivalent bits, the 2 μs guard time is equivalent to 345.6 bits and the 1 μs beam repositioning time is equivalent to 172.8 bits. There are 2000 / (N-1) data bits transmitted to each of the other (N-1) earth stations by each of the N earth stations in each frame. The preamble must be sent to each of the receiving earth stations so that it can synchronize its symbol and bit clocks to the received signal.

Hence the frame of 172,800 bits is built up as N bursts from the N transmitting stations. Each burst contains (N-1) packets. Each packet contains a transmission to the (N - 1) other stations, with a preamble of 148 bits, and a data transmission of 2000/(N-1) bits followed by a beam repositioning time equivalent to 172.8 bits. After each of the N bursts there is a guard time equivalent to 345.6 bits. Hence the frame equation is

$$172{,}800 = N \times [\ (N-1) \times (\ 148 + (2000 / (N - 1) + 172.8) + 345.6)\ ]$$

$$172{,}800 = 2024.8\ N + 320.8\ N^2$$

$$320.8\ N^2 + 2024.8\ N - 172{,}800 = 0$$

or $\quad N_2 + 6.312\ N - 538.65 = 0$

Solving the quadratic equation gives $N = 20$ (.266)

There are 20 stations in the network.

Check: It is easy to make errors in such calculation and therefore wise to check that the frame works correctly with 20 stations.

Each station transmits 2000 data bits in each frame, split into packets of 105 bits for each of the other 19 earth stations. Each 105 data bit packet has the equivalent of 148 bits of preamble and 172.8 bits to reposition the beam added to give a packet of 425.8 bits in duration. There are 19 of these packets in each burst from each earth station, so the burst consists of the equivalent of $19 \times 425.8 = 8090.2$. bits. There are 20 bursts of 8090.2 bits (equivalent) followed by a 2 μs guard time, equivalent to 345.6 bits. Hence the total number of bits in a frame is X where

$$X = 20 \times (8090.2 + 345.6) = 168{,}716 \text{ bits.}$$

The remaining 4084 bits form an additional guard time of 23 μs at the end of the TDMA frame.

There is not exact agreement between this check calculation and the original calculation with regard to the time at the end of the frame because of the use of fractional bits.

b. Find the total data throughput of the transponder after all preamble bits have been removed.

Answer: The data bits transmitted in each frame add up to twenty signals at 2 Mbps. Hence the total data bits transmitted each second is 20×2 Mbps = 40 Mbps.

Given that the downlink operates at 172.8 Mbps, the link is inefficient.

8. A LEO satellite system transmits compressed digital voice signals to handheld terminals (satphones). The satphones work in groups of ten. The inbound bit stream from the satphone to the satellite is at 10 kbps. The data are sent as a BPSK signal. The outbound bit stream from the satellite is at a bit rate of 100 kbps, and consists of packets addressed to each of ten satphones. This signal is sent using QPSK, and all ten satphones receive the 100 kbps bit stream.

The system operates in L-band where rain fading can be ignored, but blockage from buildings and trees is a significant factor. The satellite uses on-board processing and multi-beam antennas. The links use square root raised cosine (RRC) filters with $\alpha = 0.5$. In this question we will be concerned only with the links between the satellite and the satphones, and ideal RRC filters will be assumed.

a. What is the noise bandwidth of the narrowest bandpass filter in:

(i) the satphone receiver (ii) the satellite receiver for the inbound link

Answer: (i) The inbound channel from the satphone to the satellite carries a 10 kbps signal with BPSK modulation. Hence the symbol rate is R_s = 10 ksps and the noise bandwidth of the receiver RRC filter (in the satellite) is 10 kHz. This is a SCPC link.

(ii) The outbound channel from the satellite to the satphone carries a 100 kbps signal with QPSK modulation. Hence the symbol rate is R_s = 50 ksps and the noise bandwidth of the receiver RRC filter (in the satphone) is 50 kHz. This is a TDM link.

b. What is occupied RF bandwidth of the radio signals of:

(i) the inbound link (phone to satellite) (ii) the outbound link (satellite to phone)

Answer: Occupied bandwidth is always equal to $R_s \times (1 + \alpha)$ when RRC filters are used.

Hence

(i) B_{occ} = 10 k × 1.5 = 15 kHz (ii) B_{occ} = 50 k × 1.5 = 75 kHz.

c. The inbound link has clear air $(C/N)_o$ = 18.0 dB and the BPSK demodulator on the satellite has an implementation margin of 0.5 dB. What is the clear air BER in the baseband of the satellite receiver?

Answer: The bit error rate with BPSK modulation is given by $P_e = Q[\sqrt{(2\ C/N_{eff})}]$.

For C/N = 18.0 dB and an implementation margin of 0.5 dB, $(C/N)_{eff}$ = 17.5 dB or 56.23.

Hence BER = $Q[\sqrt{112.46}] = Q[10.60] \ll 10^{-16}$. There are no errors on this link in clear air.

d. What is the available fade margin (for $(C/N)_o$ on the uplink to the satellite) if the inbound link operating threshold is set at BER = 10^{-4}?

Answer: Overall C/N ratio for the uplink (inbound) is the same as $(C/N)_{up}$ because we have a baseband processor on the satellite. For $P_e = 10^{-4}$ with a BPSK link we require

$Q[\sqrt{(2\ C/N_{eff})}] = 10^{-4}$. Hence from the Q(z) table, $[\sqrt{(2\ C/N_{eff})}] = 3.70$,

C/N_{eff} = 6.85 or 8.4 dB and $(C/N)_{up}$ = 8.9 dB. The uplink fade margin is:

Fade margin = 18.0 – 8.9 = 9.1 dB.

e. The outbound link has clear air $(C/N)_o$ = 18.0 dB and the QPSK demodulator in the satellite phone has an implementation margin of 0.8 dB. What is the clear air BER?

Answer: The bit error rate with QPSK modulation is given by $P_e = Q[\sqrt{(C/N_{eff})}]$.

For C/N = 18.0 dB and an implementation margin of 0.8 dB, $(C/N)_{eff}$ = 17.2 dB or 52.48.

Hence BER = $Q[\sqrt{52.48}] = Q[7.24] \approx 2.2 \times 10^{-13}$. With a bit rate of 100 kbps, there are no errors on this link.

f. What is the available fade margin (for the overall $(C/N)_o$ on the downlink to the satphone) if the outbound link operating threshold is set at BER = 10^{-5} ?

Overall C/N ratio for the downlink (outbound) is the same as $(C/N)_{dn}$ because we have a baseband processor on the satellite. For $P_e = 10^{-5}$ with a baseband link we require

$Q[\sqrt{(C/N_{eff})}] = 10^{-5}$. Hence from the Q(z) table, $[\sqrt{(C/N_{eff})}] = 4.23$,

C/N_{eff} = 17.89 or 12.5 dB. Hence $(C/N)_{dn}$ = 13.3 dB. The fade margin is

Fade margin = 18.0 – 13.3 = 4.7 dB.

9. A Ka band satellite broadcasts digital television signals over the United States. The nominal bit rate of the signal is 28 Mbps. The digital signal can convey up to ten pre-recorded NTSC video signals. QPSK modulation is used, and error mitigation techniques are employed that provide an effective coding gain of 6 dB. [Coding gain of 6 dB means that when the $(C/N)_o$ value of the received signal is X dB, the BER corresponds to C/N = (X + 6) dB.]

The QPSK demodulator in the receiver has an implementation margin of 1.6 dB. The transmitters and receivers use ideal RRC filters with $\alpha = 0.25$.

a. What is the occupied bandwidth of the RF TV signal?

Answer: The signal is transmitted at 28 Mbps (this rate includes error coding) using QPSK modulation. The symbol rate is $R_s = 28 / 2 = 14$ Msps. Hence the occupied bandwidth is

$$B_{occ} = R_s \times (1 + \alpha) = 14 \times 1.25 = 17.5 \text{ MHz.}$$

b. What is the symbol rate of the transmitted QPSK signal, and the noise bandwidth of the earth terminal receiver?

Answer: The signal is transmitted at 28 Mbps (this rate includes error coding) using QPSK modulation. The symbol rate is $R_s = 28 / 2 = 14$ Msps. The noise bandwidth of any digital signal when RRC filters are used is equal to the symbol rate. Hence $B_N = 14$ MHz.

c. The minimum permitted BER after error mitigation in the receiver is 10^{-6}. What is the minimum permitted $(C/N)_o$ for the digital TV receiver?

Answer: The bit error rate for QPSK signals is $P_e = Q[\sqrt{(C/N_{eff})}]$.

For BER = 10^{-6} we require $Q(z) = 10^{-6}$, $z = \sqrt{(C/N_{eff})} = 4.76$. Hence $C/N_{eff} = 22.26$ or 13.5 dB. With 1.6 dB implementation margin and 6 dB coding gain, the minimum overall C/N ratio is

$$C/N = 13.5 + 1.6 - 6.0 = 9.1 \text{ dB.}$$

d. The Ka-band link suffers rain attenuation that reduces $(C/N)_o$ in the receiver by 7 dB for 0.1% of the year. If the BER is 10^{-6} under the 0.1% year conditions, what is the clear air

$(C/N)_o$ value?

Answer: Clear air C/N = 9.1 + 7 = 16.1 dB.

$(C/N)_{eff}$ = 16.1 – 1.6 + 6.0 = 20.5 dB or 112.2.

The bit error rate is given by $P_e = Q[\sqrt{(C/N_{eff})}] = Q(10.59) \ll 10^{-16}$. There are no errors on this link in clear air conditions.

e. A new coding algorithm is developed that provides a coding gain of 7 dB with a bit rate that increases to 30 Mbps. Assuming that the RRC filters in the system can be changed to match the new symbol rate, does implementation of the new coding algorithm improve the system performance? If so, what is the new $(C/N)_o$ margin?

Answer: Increasing the bit rate to 30 MHz gives a new symbol rate R_s = 15 Msps and requires a receiver noise bandwidth of 15 MHz. Noise power in the receiver increases by a factor 10 log (15/14) = 0.3 dB, and C/N is therefore reduced by 0.3 dB form 16.1 dB to 15.9 dB. The new coding gain is 7.0 dB, which exceeds the drop in C/N ratio by 0.7 dB. Hence the effective C/N ratio on the link improves by 0.7 dB and system performance improves. There are no errors in clear air, but for the 0.1% time condition when rain attenuation causes $(C/N)_o$ to fall by 7 dB, the new C/N value in rain is 15.9 – 7.0 = 8.9 dB.

$(C/N)_{eff}$ = 8.9 + 7 – 1.6 = 14.4 dB, BER = $Q[\sqrt{(C/N_{eff})}] = Q(\sqrt{26.91}) = Q(5.19)$

BER = 10^{-7}. This is a worthwhile improvement on the previous value of 10^{-6}.

$(C/N)_o$ margin is the difference between the minimum permitted value of $(C/N)_o$ and the clear air value. Hence $(C/N)_o$ margin = 16.1 – (13.5 + 1.6 – 7.0) = 8.0 dB.

10. This problem is about multiple access techniques in the inbound link of a VSAT network. This set of questions compares the operation of a Ku band satellite transponder in FDMA, in TDMA, and in FDMA-RA. There are three parts to the problem.

Part 1

100 VSAT stations in a star network share one 54 MHz transponder using FDMA. Each VSAT station has a solid state transmitter with an output power of 1 watt and an EIRP of 41 dBW from a 1.1 m diameter antenna. The transmitted data signals have a bit rate of 128 kbps and are transmitted using QPSK modulation and half rate FEC, giving a symbol rate of 128

ksps. At the hub station, the overall C/N ratio for each signal received from a VSAT station is 16 dB in clear air.

The $(C/N)_{up}$ ratio for one channel in the satellite transponder is 19.0 dB, and the $(C/N)_{dn}$ ratio for one channel in the hub receiver is 19.0 dB. The threshold C/N ratio in any hub station receiver for BER = 10^{-6} is 9.0 dB. This includes the receiver implementation margin of 0.5 dB.

The stations share the transponder using FDMA, with 51 kHz guard bands between the edges of the RF signals. The RRC filters used in the VSAT transmitters and the hub station receivers have a roll off factor $\alpha = 0.4$. To minimize intermodulation between signals, the transponder is operated with 3 dB output back-off.

a. Calculate the RF bandwidth occupied by each VSAT transmission.

Answer: The VSAT transmission rate is 128 kbps and modulation is QPSK, with half rate forward error correction encoding.. Symbol rate is 128 ksps, and RRC filters with $\alpha = 0.4$ are used. Hence the occupied bandwidth of the VSAT transmitted signal is

$$B_{occ} = R_s \times (1 + \alpha) = 1.4 \times 128 \text{ k} = 179.2 \text{ kHz.}$$

b. Calculate the maximum number of VSAT stations that can be included in the network if the transponder is bandwidth limited.

Answer: The transponder has a bandwidth of 54 MHz. If all this bandwidth is occupied by VSAT signals, with 51 kHz guard bands, each signal requires 179.2 + 51 = 230.2 kHz and the maximum possible number of VSAT channels in one transponder is given by

$$N = 54 \text{ MHz} / 230.2 \text{ kHz} = 236 \text{ (.6)}$$

c. Calculate the clear air C/N ratio for a received signal at the hub station, and the link margin, if the number of VSAT stations in the network is increased to the number you calculated in (b) above. Remember that the power available from the transponder is fixed. Adding more stations to the network lowers the power per channel at the transponder output.

Answer: The uplink $(C/N)_{up}$ ratio for any VSAT signal in the satellite transponder is 19.0 dB, independent of the number of signals transmitted to the transponder. Each uplink signal is operating in SCPC-FDMA mode. The satellite must share transponder output power between

234 signals. With 100 signals, $(C/N)_{dn}$ in the hub receivers was 19.0 dB. With 234 signals in the transponder, $(C/N)_{dn}$ is reduced by 10 log (100 / 234) or -3.7 dB. Hence $(C/N)_{dn}$ = 15.3 dB. Overall $(C/N)_o$ in the hub station receiver in clear air conditions is

$$(C/N)_o = 1 / [1 / (C/N)_{up} + 1 / (C/N_{dn}] = 23.75 \text{ or } 13.8 \text{ dB.}$$

The threshold for $(C/N)_o$ in the hub receiver is 9.0 dB. There are two link margins, one for the uplink and one for the downlink.

The limiting condition is overall C/N ratio at the hub station receiver = 9.0 dB.

For the uplink, $(C/N)_{up}$ is given by

$$(C/N)_o = 1 / [1 / (C/N)_{up} + 1 / (C/N_{dn}] = 9.0 \text{ dB} = 7.94$$

With linear transponder operation (backoff = 3 dB), $(C/N)_o$ falls in proportion to the reduction in $(C/N)_{up}$. Hence the uplink margin is 13.8 - 9.0 = 4.8 dB.

For the downlink, $(C/N)_{dn}$ is given by

$$(C/N)_o = 1 / [1 / (C/N)_{up} + 1 / (C/N_{dn}] = 9.0 \text{ dB} = 7.94$$

$(C/N)_{up}$ = 19.0 dB because we assume the uplink operates in clear air.

Hence $1 / [1 / 79.43 + 1 / (C/N)_{dn}] = 7.94$ and $(C/N)_{dn} = 8.82$ or 9.5 dB

Hence the downlink margin is 13.8 - 9.5 = 4.3 dB.

Part 2

The VSAT network described in Part1 is modified to be operate with TDMA on the VSAT uplinks instead of FDMA. There are 100 VSAT stations in the network.

The TDMA frame has a duration of 2 ms and is made up of 100 bursts from the 100 VSAT stations. There is a preamble of 100 symbols at the start of each VSAT station burst, and each burst is separated from the next burst by a guard time of 1.0 μs.

a. There are 100 VSAT station RF bursts in each frame of 2.0 ms, and 100 guard times of 1.0 μs. What is the duration of each station's burst?

Answer: The available time for VSAT transmissions in the 2 ms frame is

$$T_{VSATs} = 2 \text{ ms} - 100 \ \mu\text{s} = 1900 \ \mu\text{s}$$

100 VSAT stations share the frame, so each burst lasts for 1900 / 100 = 19 μs.

b. Each VSAT station must deliver 128 kbps of data, in the form of 128 k symbols, every second. How many data symbols are there in each RF burst, and what is the total number of symbols per burst after accounting for the 100 symbol preamble at the beginning of each burst? Hence find the burst rate for the VSAT transmissions in symbols per second.

Answer: There are 500 TDMA frames each second. The VSAT stations must deliver 128 kb each second, which requires 128,000 / 500 = 256 data bits per burst. There are 100 preamble symbols in each burst, corresponding to 200 preamble bits, giving a total of 456 bits/burst, or 228 symbols. Hence the symbol rate for each VSAT is 228 symbols in 19 μs = 12.0 Msps.

c. If all the VSAT stations, and the hub receiver, have RRC filters with roll off factor $\alpha = 0.4$, what is the RF bandwidth occupied in the transponder?

If the symbol rate of transmissions were increased until all 54 MHz bandwidth of the transponder were filled, what is the maximum number of VSAT stations in the network?

Answer: Each VSAT station transmits bursts at a symbol rate $R_s = 12.0$ Msps. Bandwidth occupied in the satellite transponder is $R_s \times (1 + \alpha) = 1.4 \times 12\text{ M} = 16.8$ MHz.

The transponder has a bandwidth of 54 MHz so we could increase the symbol rate to 54/1.4 = 38.57 Msps if we wanted to fill the bandwidth completely. This would allow $100 \times 38.57 / 16.8 = 229$ stations in the TDMA network.

d. The transponder can be operated with 1 dB output back-off when TDMA is used, and the implementation margin of the hub receiver is 1.5 dB . The EIRP of the VSAT stations must be increased because the noise bandwidth of the hub receiver has increased.

By comparing the symbol rate with 100 FDMA VSAT stations in Q#1 with the TDMA symbol rate for 100 VSAT stations in part (b) above, estimate the decibel increase in EIRP required from each VSAT transmitter.

Comment on the feasibility of transmitting this power level from a VSAT station.

Answer: Let's assume that we want to achieve the same clear air performance with the TDMA network that was available when the networks used FDMA, in Part 1.

The FDMA system has $(C/N)_{up} = 19.0$ dB with a 128 kbps signal at 128 ksps. The RRC filter noise bandwidth for this signal is 128 kHz. If we increase the noise bandwidth to

38.57 MHz for the TDMA signal, the transmit EIRP of the VSAT must increase by a factor of 38.57 / 128 = 431.1. Either we must increase VSAT transmit power to 431 W, or increase antenna diameter to $\sqrt{431.1} \times 1.1 = 22.84$ m, or some combination that gives the same EIRP. None of these combinations would classify as a VSAT station and all are clearly impractical.

On the downlink to the hub station, when operated in FDMA, the satellite achieved $(C/N)_{dn}$ = 19.0 dB with 100 signals at 128 ksps sharing the transponder power. This is equivalent to one signal at 12.8 Mbps. We have a single 38.67 Msps TDMA signal transmitted through the satellite, so the receiver noise bandwidth must be 38.57 MHz, giving a reduction in $(C/N)_{dn}$ of 4.8 dB. Backoff at the transponder output is reduced by 2 dB, from 3 dB to 1 dB, so the actual reduction in $(C/N)_{dn}$ is 2.8 dB, from 19.0 dB to 16.2 dB. Overall $(C/N)_o$ in the hub station in clear air is then

$$(C/N)_o = 1 / [1 / (C/N)_{up} + 1 / (C/N)_{dn}] = 27.34 \text{ or } 14.4 \text{ dB.}$$

The system is clearly impracticable because of the high VSAT transmitter EIRP required to operate the network in TDMA. VSAT networks operate their inbound uplinks in SCPC-FDMA, or occasionally, given sufficient link margin, MF-TDMA grouping a few VSAT stations into a small TDMA frame.

Part 3

The FDMA system described in Part1 is used with random access to serve a very large number of VSAT stations. All the parameters of Part1 are the same, except that each station has a small amount of data to send at varying intervals of time. The average message data rate for each VSAT station is 5.0 kbps and the maximum permitted channel loading is 12%.

a. How many VSAT stations can share each RF frequency?

Answer: The VSAT inbound channels have a bit rate of 128 kbps. At 12% loading the transmission rate averages 0.12 × 128k = 15.36 kbps. Each station must transmit an average of 5 kbps, so three stations can share one RF channel.

b. What is the maximum number of VSAT stations in the network when the number of RF channels is the value you calculated in Part 1 (c)?

Answer: There were a maximum of 234 VSAT stations in the network in part 1 c. With random access, this number increases to $3 \times 234 = 702$ stations.

11. This problem examines the use of a Ka-band satellite to provide connection to the Internet from a small two-way terminal. The problem is in three parts. The first part establishes the design of the communications links and terminals. The second part examines the capacity of the satellite. The third part looks at changes that must be made to support portable terminals.

Part 1. Communication Links

Description of the Satellite Communication System

A Ka-band GEO satellite is located at longitude 100° W. Star networks can be built with a single hub station, two transponders on the GEO satellite, and a number of earth stations, identified here as VSATs. The major parameters of the system components are given below. You may not need all of these parameters to answer the questions, and additional parameters are given in the individual questions.

The Ka-band satellite serves the United States. Coverage of the 48 contiguous states is achieved by a regional beam, but the satellite also carries an advanced antenna system with satellite switched spot beams that allow data packets to be transmitted to small earth stations with a high EIRP. This allows high speed data transmission in the outbound link.

The system is designed primarily to support Internet access via satellite, with highly asymmetrical links. Requests for access to the Internet are made by users at a low data rate through the satellite's region beam. Replies from the Internet can be received at a high data rate using the satellite's spot beam.

System Values

Uplink frequency for transponder #1	28.2 GHz
Downlink frequency for transponder #1	21.7 GHz
Uplink frequency for transponder #2	28.1 GHz
Downlink frequency for transponder #2	21.6 GHz
Range to satellite (all stations)	38,000 km

Satellite Transponders

Saturated output power	30 W
Transponder bandwidth	54 MHz
Transponder input noise temperature	500 K
Antenna gain, on axis, regional beam	33 dB
Antenna gain, on axis, switched spot beam	48 dB

VSAT Station Parameters

Transmitter output power	1.0 W
Transmit frequency	28.2 GHz
Receive frequency	21.7 GHz
Antenna diameter	0.5 m
Aperture efficiency	65 %
Receiver system noise temperature (clear air)	250 K
Receiver system noise bandwidth	TBD

Hub Station Parameters

Maximum transmit power	100 W
Transmit frequency	28.1 GHz
Receive frequency	21.6 GHz
Receiver system noise temperature (clear air)	250 K
Antenna diameter	4.0 m
Aperture efficiency	65 %
Receiver system noise bandwidth	TBD

Atmospheric Losses and Miscellaneous Losses

In clear air at 28 GHz	2.0 dB
In clear air at 21 GHz	2.0 dB

Constants: Boltzmann’s constant, k, = 1.38×10^{-23} J/K = -228.6 dBW/K/Hz

Part 1 Problems: C/N ratios in clear air conditions

Make all calculations for the worst case of a VSAT station that is located on the – 3dB contour of the satellite antenna beam (regional or spot), and for a hub station on the –2 dB contour of the regional beam. The spot beam is used only for transmissions at 21GHz from the satellite to the customers' earth stations. All other links use the satellite's regional beam.

a. Calculate the free space path loss for a 38,000 km path at 28.2 GHz and 21.7 GHz.

Answer: At $f = 28.2$ GHz, $\lambda = 0.01064$ m

$$L_{p28} = 20 \log (4 \pi R / \lambda) = 213.0 \text{ dB}$$

Scaling to 21.7 GHz, $L_{p21} = 213.04 – 2.28 = 210.8$ dB

The same path loss values will be used for the 28.1 GHz and 21.6 GHz links.

b. Calculate the gains of the hub and VSAT antennas at frequencies of 28.2 GHz and 21.7 GHz.

Answer: The hub station antenna has a diameter of 4.0 m and an aperture efficiency of 65%. At 28.2 GHz the hub station antenna gain is

$$G_{28H} = \eta \times (\pi D / \lambda)^2 = 0.65 \times (\pi \times 4.0 / 0.01064) = 906{,}671 \text{ or } 59.57 \text{ dB} \approx 59.6 \text{ dB.}$$

Scaling to 21.7 GHz, $G_{21H} = 59.57 - 2.28 \approx 57.3$ dB. We will use the same antenna gains for links at 28.1 GHz and 21.6 GHz.

The VSAT station has an antenna diameter of 0.5 m and an aperture efficiency of 65%. Scaling the gain of the hub station antenna gives, for the VSAT antenna

$$G_{28V} = 59.57 \text{ dB} - 20 \log (4.0 / 0.5) = 59.57 - 18.06 = 41.51 \approx 41.5 \text{ dB}$$

$$G_{21V} = 57.29 \text{ dB} - 20 \log (4.0 / 0.5) = 59.29 - 18.06 = 39.23 \approx 39.2 \text{ dB}$$

c. Calculate the inbound overall C/N in the hub station receiver in a noise bandwidth of 128 kHz when the VSAT has a transmitter output power of 1 watt and accesses the regional beam on the satellite. Make the overall C/N calculation for a single QPSK signal which is transmitted by transponder #1 at an output power of 1 watt.

Answer: VSAT stations transmit to the satellite in SCPC-FDMA mode. The VSAT EIRP at 28.1 GHz is 1 watt + 41.5 dB = 41.5 dBW. Path loss to the satellite is $L_{p28} = 213.0$ dB. The uplink budget follows:

EIRP	41.5 dBW
G_r Regional beam, on axis	33.0 dB
Path loss at 28.2 GHz	-213.0 dB
Losses 3 dB off axis + 2 dB atmospheric	-5.0 dB
Receiver power P_{rxp}	-143.5 dBW

The satellite transponder input noise temperature is 500 K = 27 dBK. Channel noise bandwidth for the VSAT signal is 128 kHz. Hence $N_{xp} = -228.6 + 27.0 + 51.1 = -150.5$ dBW

Hence uplink (transponder) $(C/N)_{up}$ ratio is -143.5 + 150.5 = 7.0 dB.

The downlink $(C/N)_{dn}$ ratio in the hub station receiver is calculated for a trial value of 1 W transponder output power. This is to establish C/N ratios that can later be modified in the final system design. For a satellite transmit power of 1 W and a hub station on the 2 dB contour of the satellite regional beam footprint, the downlink budget at 21.7 GHz is

EIRP	33.0 dBW
G_r Hub station at 21.7 GHz	57.3 dB
Path loss at 21.7 GHz	-210.8 dB
Losses 2 dB off axis + 2 dB atmospheric	-4.0 dB
Receiver power P_{rxp}	-124.5 dBW

The hub station receiver system noise temperature is 250 K = 24 dBK. Receiver noise bandwidth for the hub station 128 kHz.

Hence N_{xp} = -228.6 + 24.0 + 51.1 = -153.5 dBW and $(C/N)_{dn}$ = 29.0 dB.

Overall $(C/N)_o$ for the inbound link is

$$(C/N)_o = 1 / [\, 1 / (C/N)_{up} + 1 / (C/N)_{dn} \,] = 4.98 \approx 7.0 \text{ dB.}$$

d. Calculate the outbound overall C/N in transponder #2 with a hub station transmit power of 1 watt. Make your calculation in a receiver noise bandwidth of 1 MHz, for a single QPSK signal, with the output power of transponder #2 set at 1 watt and the spot beam of the satellite transmitting to the customers' terminals.

Estimate the beamwidth of the spot beam from the satellite. Using a map of the United States, estimate the minimum number of spot beam positions required to serve the entire US.

Answer: The hub station transmits to transponder #2 on the satellite in SCPC-FDMA mode. The EIRP of the hub station at 28.1 GHz is 1 watt + 59.6 dB = 59.6 dBW. Path loss to the satellite is L_{p28} = 213.0 dB.

The uplink budget follows:

EIRP	59.6 dBW
G_r Regional beam, on axis	33.0 dB
Path loss at 28.1 GHz	-213.0 dB
Losses 2 dB off axis + 2 dB atmospheric	-4.0 dB
Receiver power P_{rxp}	-124.4 dBW

The satellite transponder input noise temperature is 500 K = 27 dBK. Channel noise bandwidth for the trial hub station signal is 1.0 MHz.

Hence $N_{xp} = -228.6 + 27.0 + 60.0 = -141.6$ dBW. Uplink (transponder) $(C/N)_{up}$

$(C/N)_{up} = -124.4 + 141.6 = 17.2$ dB.

The downlink $(C/N)_{dn}$ ratio in the VSAT station receiver is calculated for a trial value of 1 W transponder output power. This is to establish C/N ratios that can later be modified in the final system design. For a satellite transmit power of 1 W and a VSAT on the 3 dB contour of the satellite spot beam footprint, the downlink budget at 21.6 GHz is

EIRP	48.0 dBW
G_r VSAT station at 21.7 GHz	39.2 dB
Path loss at 21.7 GHz	-210.8 dB
Losses 3 dB off axis + 2 dB atmospheric	-5.0 dB
Receiver power P_{rxp}	-128.6 dBW

The VSAT receiver system noise temperature in clear air is 250 K = 24 dBK. Channel noise bandwidth for the signal is 1.0 MHz.

Hence $N_{xp} = -228.6 + 24.0 + 60.0 = -144.6$ dBW and $(C/N)_{dn} = 16.0$ dB.

Overall $(C/N)_o$ for the outbound link is

$(C/N)_o = 1 / [1 / (C/N)_{up} + 1 / (C/N_{dn}] = 22.63 = 13.5$ dB.

The spot beam has a beamwidth of 48 dB. Hence the beamwidth is approximately

$\theta_{3\text{ dB}} = [33{,}000 / 63095]^{1/2} = 0.72^{o}$.

If the United States is assumed to subtend a rectangle of 6^{o} E-W by 3^{o} N-S, when viewed from GEO orbit, it takes roughly 32 beams to fill this area. Similar results can be found using a smaller number of beams to fill the area on a map. However, the distribution of spot beams in a practical system must take account of population densities and provide more channels to highly populated regions than sparsely populated areas.

Part 2 System performance

Connection to the Internet is achieved by the following procedure.

The customer sends a connection request, in the form of a data packet, to the hub station via the satellite and its regional beam. The hub station decodes the request and notes the location of the station. The connection between the Internet and the hub is established through an Internet

Service Provider (ISP) and the public switched telephone network (PSTN). A response from the ISP is sent back to the customer using the satellite's spot beam. Since the packet from the customer contain the VSAT station location, the hub station can send instructions to the satellite to point the spot beam in the correct direction when transmitting packets to the customer. Note that with a linear transponder (bent pipe) on the satellite, the beam pointing instructions must be sent the satellite at the same time as the data packet.

The links between the ISP and the customer in this system are highly asymmetric. The customer can send only short requests at a low data rate. The ISP can dump data to the customer at a high data rate, mainly because of the high EIRP of the satellite's spot beam transmissions. This mode of operation suits applications where the customer is browsing the Internet for information, or is requesting large files or video frames from the Internet. It works less well for sending files from the customer to the Internet – as is done with e-mail, for example. In this problem you are asked to design a VSAT network based on your results from Part 1.

Ka band links are subject to high attenuation in rain. The outbound link is required to achieve a 99.9% availability for a typical VSAT station for which slant path attenuation exceeds 7 dB at 21.7 GHz and 12 dB at 28.2 GHz, for 0.1 % of an average year. The inbound link is required to achieve a 99.7% availability for a typical VSAT station for which slant path attenuation exceeds 4 dB at 21.7 GHz and 7 dB at 28.2 GHz, for 0.3 % of an average year.

The link is declared unavailable if the BER exceeds 10^{-6} in the data stream supplied to the customer, or output by the hub station.

Begin your analysis by assuming that 20 active VSAT stations share the output power of transponder #1 equally at all times using QPSK-SCPC-FDMA. Half rate FEC coding is used in the inbound and the outbound link and provides a coding gain of 5 dB at a BER of 10^{-6} in the recovered data stream. The implementation margin of the QPSK demodulators in the hub receiver is 0.5 dB, and in the VSAT receiver implementation margin is 0.8 dB. Assume that there are always 20 active VSAT stations receiving data from the outbound link in packet form, using TDM and a single QPSK carrier. Assume linear operation of the transponders, but include the effect of increased sky noise when rain is present on the uplink.

Transponder #1 (inbound, SCPC-FDMA) is operated with 2 dB output back-off.
Transponder #2 (outbound, TDM) is operated with 1 dB back off.

Part 2 Problems

a. Determine the clear air overall C/N required on the inbound uplink and downlink for one VSAT transmission to meet the 99.7% availability criterion, and the corresponding clear air C/N in the hub station receiver with

(i) rain in the inbound uplink

(ii) rain in the inbound downlink. Remember to include the effect of increased sky noise.

Answer: (i) Inbound link analysis with rain attenuation on the uplink.

The 99.7% availability requirement translates to a slant path attenuation that exceeds 4 dB at 21.7 GHz on the downlink to the hub station and 7 dB at 28.2 GHz on the uplink to the satellite. Both of these links use the regional beam of the satellite. The minimum permitted BER on any link is 10^{-6}, corresponding to an effective overall $(C/N)_o$ ratio of 13.6 dB for QPSK modulation. The implementation margin of the hub receiver is 0.5 dB, and of the VSAT receiver it is 0.8 dB. There is 5 dB coding gain from the use of half rate forward error correction coding. Hence the minimum overall $(C/N)_o$ ratio in the hub station receiver is

$$(C/N)_o \text{ minimum} = 13.6 - 5.0 + 0.5 = 9.1 \text{ dB}$$

When rain occurs in the uplink, $(C/N)_o$ in the hub station receiver falls in direct proportion to rain attenuation on the uplink path. For 7 dB uplink rain attenuation we require

$$(C/N)_o = 9.1 + 7.0 = 16.1 \text{ dB in clear air.}$$

The value of $(C/N)_{up}$ in the trial calculation in Part 1 was 7.0 dB with 1 W transmitted by the VSAT station. $(C/N)_{dn}$ was 29.0 dB with 1 watt per channel transmitted by the satellite. With 20 VSAT signals and 2 dB backoff at the transponder output, the transponder transmits 30 W – 2 dB = 12.8 dBW. This power is shared between 20 signals, so P_t per channel is 12.8 – 13.0 = -0.2 dBW. Hence in clear air conditions, $(C/N)_{dn}$ = 28.8 dB.

With these operating (C/N) values, $(C/N)_o$ = 7.0 dB in clear air.

To achieve $(C/N)_o$ = 16.1 dB in clear, air, we must reduce the receiver noise bandwidth by 9.1 dB, a factor of 8.13, to 128 kHz / 8.13 = 15.75 kHz. With QPSK modulation, the symbol rate of the VSAT transmission is 15.75 ksps. Because we have half rate FEC encoding in the links, the data rate is equal to QPSK symbol rate, and the bit rate is 15.75 kbps.

(ii) Inbound link analysis with rain attenuation on the downlink

The limiting condition for the downlink is $(C/N)_o = 16.1$ dB with 4 dB rain attenuation on the downlink. Sky noise temperature will increase due to the rain in the path. For a medium temperature of 290 K

$$T_{sky\ rain} = 290\ (1 - 0.4) = 174\ K$$

In clear air, the atmospheric attenuation at 21.7 GHz is given as 2.0 dB. (Atmospheric attenuation is really a variable that depends on water vapor content of the atmosphere, i.e. humidity at the receiving site. A value of 2 dB attenuation corresponds to a low angle slant path and high humidity.)

The clear sky noise temperature is

$$T_{sky\ clear\ air} = 290\ (1 - 0.631) = 107\ K$$

The receiver LNA contribution is $250 - 107 = 143$ K, giving $T_{s\ rain} = 174 + 143 = 317$ K. The increase in system noise power is therefore

$$\Delta N = 10 \log (317 / 250) = 1.0\ dB$$

giving a reduction in $(C/N)_{dn}$ of $4.0 + 1.0 = 5.0$ dB.

Based on a receiver noise bandwidth of 128 kHz, the clear air downlink C/N ratio was $(C/N)_{dn\ ca} = 28.8$ dB, so in this bandwidth $(C/N)_{dn\ rain} = 28.8$ dB - 5.0 dB = 23.8 dB. However, the poor uplink performance in rain required the bandwidth to be reduced to 15.75 kHz, giving $(C/N)_{up} = 16.1$ and $(C/N)_{dn} = 23.8 + 9.1 = 32.9$ dB in clear air.

In clear air conditions the overall $(C/N)_o$ ratio in the hub receiver for a 15.75 ksps transmission from a VSAT station with 4.0 dB rain attenuation on the downlink is

$$(C/N)_o = 1 / [\ 1 / (C/N)_{up} + 1 / (C/N)_{dn}\ ] = 16.0\ dB.$$

This is well above the minimum permitted value of 9.1 dB, showing that the uplink from the VSAT station is the limiting path.

b. Using the results you obtained in Part 1, and Part 2 question (a), determine the maximum data rate for the VSAT request packets to meet the 99.7% availability criterion with access to the transponder through the satellite's regional beam, with 20 active VSATs at any time.

Answer: The inbound uplink from the VSAT station to the satellite is the limiting factor in the inbound link, because of the low uplink C/N ratio in the transponder. In Part 2 (a), the uplink $(C/N)_{up}$ was found to be 16.1 dB in clear air to meet the 99.7% availability criterion, forcing a reduction in channel noise bandwidth to 15.75 kHz.. The symbol rate on the inbound link is 15.75 ksps, giving an inbound data bit rate of 15.75 kbps. This is the bit rate at which requests can be sent to the hub station, and on to the ISP.

c. Determine the clear air overall C/N in the VSAT station receiver for an outbound data rate of 1 Mbps using QPSK-TDM to meet the 99.9% availability criterion, for

(iii) rain in the outbound uplink

(iv) rain in the outbound downlink. Remember to include the effect of increased sky noise.

Answer: (i) Outbound link analysis with rain attenuation on the uplink.

The 99.9% availability requirement translates to a slant path attenuation that exceeds 7 dB at 21.7 GHz on the downlink to the VSAT station and 12 dB at 28.2 GHz on the uplink to the satellite from the hub station. The outbound uplink uses the regional beam of the satellite and the outbound downlink uses the spot beam. The minimum permitted BER on any link is 10^{-6}, corresponding to an effective overall $(C/N)_o$ ratio of 13.6 dB for QPSK modulation. The implementation margin of the VSAT receiver it is 0.8 dB. There is 5 dB coding gain from the use of half rate forward error correction coding. Hence the minimum overall $(C/N)_o$ ratio in the hub station receiver is

$(C/N)_o$ minimum = 13.6 – 5.0 + 0.8 = 9.4 dB

When rain occurs in the uplink, $(C/N)_o$ in the VSAT station receiver falls in direct proportion to rain attenuation on the up link path. For 12 dB uplink rain attenuation we require

$(C/N)_o$ = 9.4 + 12.0 = 21.4 dB in clear air.

The value of $(C/N)_{up}$ in the trial calculation in Part 1 was 17.2 dB with 1 W per channel transmitted by the hub station in a channel noise bandwidth of 1 MHz. $(C/N)_{dn}$ was 16.0 dB with 1 watt per channel transmitted by the satellite.

The 20 signals destined to the VSAT stations are transmitted as a TDM bit stream at 1 Msps. We should increase the hub station transmit power to 20W now that there are 20 signals to be sent by TDM, giving $(C/N)_{up}$ = 30.2 dB in clear air in 1 MHz receiver noise bandwidth.

Transponder #2 has 1 dB backoff at the transponder output, and transmits 30 W – 1 dB = 13.8 dBW. Hence in clear air conditions, $(C/N)_{dn}$ = 16.0 + 13.8 = 29.8 dB.

With these operating (C/N) values, $(C/N)_o$ = 27.0 dB in clear air. There is now a margin above the minimum permitted overall C/N ratio that can be used to increase the bit rate of the TDM signal.

(ii) Outbound link analysis with rain attenuation on the downlink

The limiting condition for the downlink is $(C/N)_o$ = 21.4 dB with 7 dB rain attenuation on the downlink. Sky noise temperature will increase due to the rain in the path. For a medium temperature of 290 K

$$T_{\text{sky rain}} = 290\,(1 - 0.2) = 232\text{ K}$$

In clear air, the clear sky noise temperature is

$$T_{\text{sky clear air}} = 290\,(1 - 0.631) = 107\text{ K}$$

The receiver LNA contribution is 250 – 107 = 143 K, giving $T_{\text{s rain}} = 232 + 143 = 375$ K. The increase in system noise power is therefore

$$\Delta N = 10 \log (375 / 250) = 1.8\text{ dB}$$

Hence $(C/N)_{dn}$ falls by 8.8 dB from its clear air value of 39.8 dB to 21.0 dB. Overall $(C/N)_o$ is now 20.5 dB with 7 dB rain attenuation on the downlink. The requirement for 99.9% availability is met, since $(C/N)_o$ exceeds the minimum value of 9.4 dB by a margin of more than 10 dB.

d. Using the results you obtained in Part 1, determine the maximum data rate that can be supplied to each VSAT station with 20 active stations in the network at the same time, for the 99.9% availability criterion. Note that for the small percentages of time used here, you may assume that rain never occurs simultaneously in both the uplink and downlink.

Answer: The data rate at which the hub station can transmit is 1.0 Mbps, based on the design criteria used in part (c) above. The bit stream is a TDM sequence of packets delivered to 20 VSAT stations, so each station has a data rate R_b = 50 kbps. The bit rate can be increased because there is excess (C/N) ratio on the outbound link when we meet the 99.9% availability criterion.

e. If your results from parts (b) and (d) above show that either transponder #1 or #2 is not bandwidth limited, it is possible to optimize the system to transmit at higher bit rates. Redesign the VSAT and hub stations to increase the bit rates in either the inbound link, the outbound link, or both links, within the limits that the VSAT antenna diameter cannot exceed 1m, and the transmit power cannot exceed 2 watts. The hub station antenna diameter cannot exceed 5m and the transmit power cannot exceed 200 watts. You might also consider whether the number of simultaneous users can be increased. The satellite is leased and cannot be changed, except that the gain of the transponders can be adjusted to suit the earth stations used in the network.

Answer: The transponders have a bandwidth of 54 MHz and are carrying very small bandwidth signals in the current design. If we increase transmit power at the hub station to 100 W and at the VSAT station to 2 W, and also increase the VSAT antenna diameter to 1 m, we can achieve significant improvements in performance. The EIRP of the VSAT station is increased by 9 dB, and EIRP of the hub station is increased by 20 dB. We need to repeat the link analysis in rain under the new conditions.

Inbound links. In part (a) we found that the minimum overall $(C/N)_o$ ratio in the hub station receiver is

$(C/N)_o$ minimum = 13.6 – 5.0 + 0.5 = 9.1 dB

When rain occurs in the uplink, $(C/N)_o$ in the hub station receiver falls in direct proportion to rain attenuation on the uplink path. For 7 dB uplink rain attenuation we require

$(C/N)_o$ = 9.1 + 7.0 = 16.1 dB in clear air.

The value of $(C/N)_{up}$ in the trial calculation in Part 1 was 7.0 dB with 1 W transmitted by the VSAT station. We can increase VSAT EIRP by 9 dB, giving $(C/N)_{up}$ = 16.0 dB with 7 dB of uplink rain attenuation. In clear air conditions, $(C/N)_{dn}$ = 29.0 dB, giving $(C/N)_o$ = 15.78 dB ≈ 15.8 dB. To achieve $(C/N)_o$ = 16.1 dB we must reduce the receiver noise bandwidth by 0.32 dB, a factor of 1.076, to 128 kHz / 1.076 = 119 kHz. The clear air uplink $(C/N)_{up}$ ratio is 16.3 dB in 119 kHz noise bandwidth. With QPSK modulation, the symbol rate of the VSAT transmission is 119 ksps and the bit rate is 119 kbps.

The limiting condition for the downlink is $(C/N)_o$ = 16.1 dB with 4 dB rain attenuation on the downlink. Taking account of sky noise temperature increase, we found that a reduction in $(C/N)_{dn}$ of 5.0 dB occurs when there is 4 dB rain attenuation on the downlink, giving $(C/N)_{dn\ rain}$ = 29.0 dB - 5.0 dB = 24.0 dB in a receiver noise bandwidth of 128 kHz. Reducing the receiver noise bandwidth to 119 kHz increases $(C/N)_{dn}$ to 24.3 dB. Uplink performance in rain required the bandwidth to be reduced to 119 kHz, giving $(C/N)_{up}$ = 16.3 dB in clear air.

Overall $(C/N)_o$ ratio in the hub receiver for a 119 ksps transmission from a VSAT station with 4.0 dB rain attenuation on the downlink is

$$(C/N)_o = 1 / [1 / (C/N)_{up} + 1 / (C/N)_{dn}] = 15.7\text{dB}.$$

This is well above the minimum permitted value of 9.1 dB, showing that the uplink from the VSAT station is still the limiting path. However, we are now able to access the hub station from the VSAT at 119 kbps, a major improvement over the original bit rate of 15.75 kbps.

Outbound links. In the calculations in part (c), a hub transmit power of 1 W was used. Increasing the hub station transmit power to 100 W will improve outbound performance a great deal. We need to analyze the outbound link with 100 W hub transmit power, 12 dB uplink rain attenuation and 7 dB downlink attenuation, using a VSAT station with a 1 m antenna and 6 dB additional gain.

The clear air uplink $(C/N)_{up}$ with hub station P_t = 20 W was 30.2 dB in a noise bandwidth of 1 MHz. Increasing P_t to 100 W makes $(C/N)_{up}$ = 37.2 dB. $(C/N)_{dn}$ was 29.8 dB in a noise bandwidth of 1 MHz in clear air. Increasing the VSAT antenna diameter to 1 m improves $(C/N)_{dn}$ to 35.8 dB. Thus overall $(C/N)_o$ in clear air is 28.8 dB. With 12 dB uplink rain attenuation, $(C/N)_o$ falls to 16.8 dB, which is 7.7 dB above the minimum permitted value of 9.1 dB.

When there is 7 dB rain attenuation on the downlink, $(C/N)_{dn}$ falls by 8.8 dB to 21.0 dB. $(C/N)_{up}$ is 37.2 dB in clear air giving $(C/N)_o$ = 19.9 dB, which is 10.8 dB above the minimum permitted value of 9.1 dB.

We can expand the receiver noise bandwidth in the VSAT terminals, to increase the outbound bit rate, or we can add more VSATs to the network. Since the outbound bit rate was rather low, at 50 kbps per VSAT station, let's increase the TDM outbound bit rate by 7.7 dB to 5.88 Mbps. This gives a symbol rate of 5.88 Msps and a receiver noise bandwidth of 5.88 MHz. Each VSAT now receives a signal at a bit rate of 294 kbps from the hub station. Alternatively, we could increase the number of VSATs to 50, giving each station a bit rate of 118 kbps on the outbound link. Many combinations of bit rate and number of VSATs are possible within the availability criteria.

If we increase the number of active VSATs to 50, the power in transponder #1 will be divided 50 ways, instead of 20 ways, giving P_t = -0.2 - 4.0 = -4.2 dBW. This reduces $(C/N)_{dn}$ in the hub station in clear air by 4.0 dB to 25.0 dB. With 4 dB of rain attenuation on the downlink, this is reduced to $(C/N)_{dn\ rain} = 20.0$ dB. With the upgraded VSAT station ($D = 1$ m, $P_t = 2$ W) the uplink $(C/N)_{up}$ ratio in clear air is 16.0 dB, so overall $(C/N)_o$ is 14.5 dB, well above the limiting value of 9.1 dB. Hence uplink rain attenuation is still the limiting condition for the inbound links and we can maintain the inbound bit rate of 119 kbps.

Performance Summary:

Number of simultaneous active VSAT stations in network :	50
Outbound data rate from hub to VSAT	228 kbps
Inbound data rate from VSAT to hub	119 kbps
Bandwidth occupied in Transponder #1 ($\alpha = 0.25$, ideal RRC filters)	7.35 MHz
Bandwidth occupied in Transponder #2 ($\alpha = 0.25$, ideal RRC filters)	7.35 MHz
($\alpha = 0.25$, ideal RRC filters and 50 kHz guard bands)	9.937 MHz
Power required from transponder #1	18.9W
Power required from transponder #2	23.8 W

Part 3 Portable terminals

The one advantage of radio systems over wired communications links is portability. This question asks you to design a portable Ka-band terminal which can be used to connect to the Internet (provided the customer has a clear view of the southern sky). The critical element in a portable communications link is the antenna. A large antenna provides a high data rate, but is cumbersome and must be pointed accurately at Ka-band frequencies. A small antenna is easier to set up, but cannot provide a high data rate. Let's assume that the dimension of the antenna are limited to the dimensions of a typical laptop computer – 0.25 m × 0.2 m – with an aperture efficiency of 25 %, and that some method is provided that helps the customer point the antenna beam towards the satellite so that there is no more than 1 dB loss of gain due to antenna mispointing.

Because the portable terminals cannot achieve the same C/N ratios as the fixed terminals, separate transponders will be needed to service the portables. For convenience, we will call these transponders #3 (inbound) and #4 (outbound) and use the same frequencies as transponders #1 and #2. The ability of the system to operate during rain fades on the outbound link is relaxed with an availability of 99.7% required in each direction.

a. Calculate the gain and the beamwidth of the portable antenna at frequencies of 28.2GHz and 21.7 GHz.

Answer: The aperture are of the antenna is 0.25 m × 0.2 m = 0.05 m^2 . Aperture efficiency is 25% so transmit gain at 28.2 GHz is

$$G_t = \eta_A 4\pi A / \lambda^2 = 0.25 \times 4\pi \times 0.05 / (0.01064)^2 = 1387 = 31.42 \text{ dB}$$

Scaling to 21.7 GHz

$$G_r = 31.42 - 2.28 = 29.14 \text{ dB}$$

b. Using your results from Part 1, find the inbound and outbound overall C/N ratios in the hub station and portable receivers using the conditions in Part 1 in clear air conditions. Don't forget to allow an extra 1 dB of loss to account for antenna mispointing.

Answer: The results from Part 1 (a) for the inbound link, using a noise bandwidth of 128 kHz for the uplink and 1 MHz for the downlink, with 1 watt of transmit power at the earth station and at the satellite, and a single channel, were

Uplink (transponder) $(C/N)_{up}$ ratio = 7.0 dB

Downlink (hub receiver) $(C/N)_{dn}$ = 29.0 dB

For the outbound link, using the same bandwidths, the results were

Uplink $(C/N)_{up}$ = 17.2 dB

Downlink $(C/N)_{dn}$ = 16.0 dB

The VSAT station antenna gains in Part 1 were

G_{28V} = 41.51 dB, G_{21V} = 39.23 dB

Antenna gain has been reduced by 10.1 dB and an additional loss of 1 dB is present because of antenna mispointing. Hence, inbound $(C/N)_{up}$ and outbound $(C/N)_{dn}$ will be lower by 10.1 dB. Using the part 1 results given above:

Inbound link: Uplink (transponder) $(C/N)_{up}$ ratio = 7.0 - 10.1 = -3.1 dB

Downlink (hub receiver) $(C/N)_{dn}$ = 29.0 dB

Overall C/N = -3.1 dB

Outbound link: Uplink $(C/N)_{up}$ = 17.2 dB

Downlink $(C/N)_{dn}$ = 16.0 – 10.1 = 5.9 dB

Overall C/N = 5.7 dB

c. Assume that ten active stations share each transponder. Determine the maximum data rates that customers can achieve on the inbound and the outbound links with 99.7% availability of the inbound and outbound links.

Answer: **Inbound link.** The 99.7% availability criterion requires minimum C/N at the hub station of 9.1 dB in clear air, with the addition of 7 dB uplink rain attenuation and 4 dB downlink rain attenuation.

With ten active stations, 30 W transponder output power and 2 dB output back off, $(C/N)_{dn}$ is 3 dB higher than in Part 1. So $(C/N)_{dn}$ = 32.0 dB. To achieve $(C/N)_o$ = 9.1 + 7 .0 = 16.1dB with 7 dB of uplink rain attenuation we require $(C/N)_{up}$ = 9.08 ≈ 9.1 dB. Since the calculated $(C/N)_{up}$ is –3.1 dB in 128 kHz noise bandwidth we must reduce the uplink noise bandwidth by 19.2 dB or a factor of 83.17 to 1.54 kHz. Symbol rate on the QPSK uplink is 1.54 ksps and we use half rate FEC encoding, the data bit rate is 1.54 kbps. Rain on the downlink causes little change in the high value of $(C/N)_{dn}$ and can be ignored. The very low bit rate for the inbound channel is unsatisfactory.

Outbound Link. The downlink to the portable terminal will be the limiting link. From Part 1, or 30 W of transponder transmit power with 1 dB output back off and a noise bandwidth of 1 MHz

Downlink $(C/N)_{dn}$ = 16.0 – 10.1 = 5.9dB

In Part 2 we showed that with 4 dB of rain attenuation on the downlink, $(C/N)_{dn}$ fell by 5.0 dB.

Uplink C/N will be very high with 10 active terminals, and its impact on overall C/N can be ignored and we will use $(C/N)_o$ = $(C/N)_{dn}$. Therefore we require

$(C/N)_{dn}$ = 9.4 + 5.0 = 14.4 dB

on the downlink to achieve 99.7% availability. We would need to reduce the downlink noise bandwidth by 8.5 dB or a factor of 7.08 to 141.2 kHz.

The limiting case will be when the uplink from the hub station suffers 7 dB rain attenuation. Both the uplink and downlink C/N ratios will fall by 7 dB, which is a worse case than attenuation on the downlink. Hence overall $(C/N)_o$ will fall by 7 dB, to –1.1 dB, which will require a bandwidth reduction of 15.5 dB, or a factor of 35.48 to 28.18 kHz. Thus the outbound link can operate at 28.18 kps, giving a data rate of 28.18 kbps.

d. Transponders #3 and #4 can be switched into baseband processing mode. In this mode, the incoming QPSK signal is demodulated to baseband, the data bits are recovered and then remodulated onto a carrier for transmission as a new QPSK signal. This allows the transponder to transmit at its rated output power at all times despite uplink attenuation. The bit error rate for the link is then the sum of the BERs on the uplink and the downlink. Rework your solution to part (c) above using baseband processors for both inbound and outbound links and determine the new data rates for the inbound and outbound links.

Answer: Baseband processing does not alter uplink C/N ratios. It prevents downlink C/N ratios from failing during uplink rain attenuation events. Thus the use of a baseband processing transponder (#1) in the inbound link improves only the downlink $(C/N)_{dn}$ ratio, which is already very high. It does not change the uplink C/N which is the limiting factor in the link.

On the outbound link to the portable terminal, we can remove the effect of uplink attenuation from the downlink. The limiting case is now 5.0 dB drop in $(C/N)_{dn}$ when 4 dB of rain attenuation occurs on the downlink. The reduction in bandwidth required to meet the 99.7% availability requirement is 13.5 dB or a factor of 22,39. Hence the outbound link noise bandwidth is 44.66 kHz, the symbol rate is 44.66 ksps and the date rate is 44.66 kbps.

e. Draw a block diagram of transponder #3 when used in its baseband processing mode. Your block diagram should include all the filters, amplifiers, mixers, oscillators, modulators and demodulators, and all other important blocks. Label each filter and amplifier with a center frequency and bandwidth, and indicate the gain of each amplifier. Label all oscillators with their frequencies. (Attach the block diagram as the last page of your answer packet.)

Answer: Block diagrams are not included in the solutions manual.

f. Comment on the performance of the fixed and portable Ka-band Internet link system. If the transponders on the GEO satellite cost $1.5 M per year each to lease, and the service provider's costs to support the customer base that shares these transponders are $ 0.5M per year, what would you expect to have to charge the customer for access to the Internet when using the fixed terminal and the portable terminal? You can establish a charging structure made up of a monthly fee plus a per minute access charge. Assume that you can achieve a continuous level of activity of 20 fixed or 10 portable terminals for 12 hours per day.

Each user can be assumed to connect to the Internet for 15 minutes once each day, but is active (in the sense of data transfer over the satellite) for 1 minute per day. How do the data rates and the charges you propose for the portable Internet access service compare to typical charges for cable modem service?

Answer: The capacity of the Ka band Internet access system is rather low. We can support 50 active VSAT terminals (1 m diameter antenna, 2 W transmitter) in the fixed network with inbound and outbound data rates of 118 kbps. This is comparable to DSL rates, The portable terminals have even lower data rates. The best that can be achieved with linear transponders is an outbound bit rate of 28.18 kbps and an inbound data rate of 1.54 kbps. Inbound transmissions would have to be kept to very short messages to keep access times reasonable. The outbound data rate is comparable to data rates available with some cellular telephone systems, but the inbound rate is much lower. The portable terminal would be attractive only where there is no access to cellular telephone data service.

The cost of operating the Internet access system is \$3.5 M per year, and each terminal needs one minute of data transfer time per effective day (12 hours). That allows 720 terminals to share each active channel. The fixed network can support $20 \times 720 = 14{,}400$ users, giving an annual cost per user of \$3.5 M / 14,400 = \$2430 per year. This can be divided up between monthly charges and user fees - for example, \$100 per month user fee plus 8.5 cents per minute. These figures are higher than most DSL providers were charging in 2001.

The network can support 7200 portable terminals, giving an annual cost per terminal of \$4860. User fees would have to be much higher, at least \$200 per month, with 17 cents per minute access fee. Many other charging packages can be developed - extensive market research would be needed before such a system could be marketed. The very low data rate on the inbound link is a severe limitation in the portable terminal. The uplink fade margin of 4 dB could be reduced a little in order to improve access data rate, but the small antenna size, low antenna efficiency, and low transmit power remain major limitations.