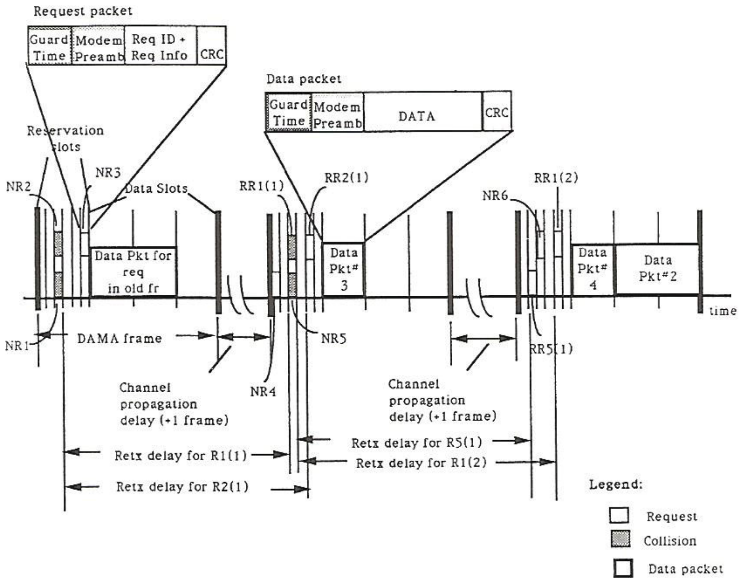

Fig. 7.12 *Illustration of DAMA with slotted ALOHA access*

scenario uses slotted ALOHA for access [34–36] (as shown in Fig. 7.12), so that the reservation overhead required is independent of the actual number of terminals supported. Although Fig. 7.12 shows a system based on a TDMA-like frame, an interleaved format may also be used to minimise framing latency effects. Note that, in principle, it is also possible to use other slotted contention mechanisms (such as the tree CRA) for the reservation messages. It is observed that, since contention access is characterised by a relatively low capacity, the allocation of channel time for reservations could become significant unless the ratio of request message to data message length is quite large.

Typical achievable capacities for VSAT traffic parameters are in the range of 0·4 to 0·6, depending on the length distribution of message traffic to be supported. Slotted ALOHA access generally leads to more effective coverage of a range of VSAT traffic profiles than the TDMA access case discussed above. As for all DAMA protocols, this protocol is characterised by a high minimum delay of ~ 0·6 s, offset to some extent by low delay variance. As for the TDMA access case discussed above, the throughput and delay variance advantages of DAMA are at the expense of higher implementation complexity and poorer robustness. Nevertheless, since DAMA with slotted ALOHA access provides good overall performance and can handle mixed interactive/file-transfer traffic, it is an important candidate for many VSAT applications.

7.2.3.3 *Unslotted locally synchronous reservation* Traditionally, controlled access has been associated with time slotted channels because of the need to identify and allocate channel time segments to stations on demand. In this subsection, a recently proposed alternative approach [37] is described which does not require

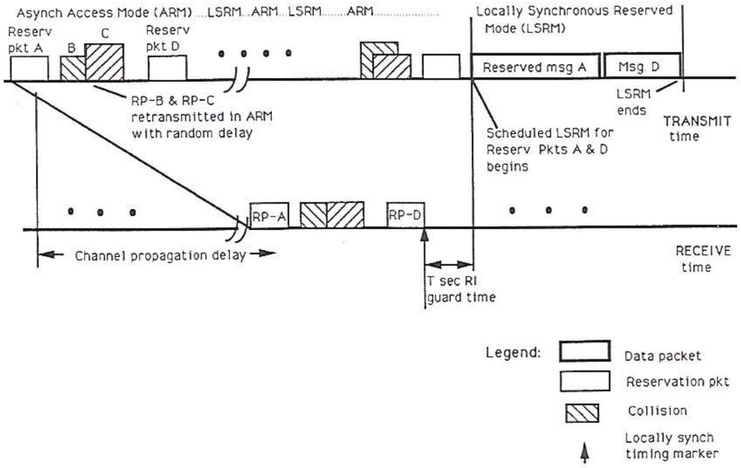

Fig. 7.13 *Illustration of channel events in locally synchronous reservation with ALOHA access*

TDMA-like timing, and is classified as 'locally synchronous' or 'self-synchronising'. Protocols of this type were conceived as semi-compatible upgrades of unslotted random access protocols such as ALOHA, SREJ–ALOHA or time-of-arrival CRA, for use in environments with a high proportion of long messages or mixed interactive/file-transfer traffic.

The principle in locally synchronous reservation systems is to provide initial access for request packets in an unslotted mode such as ALOHA. When a specified number of successful requests ($K > 1$) have been received, the channel switches to the locally synchronous reserved message transmission mode. As in the time-of-arrival CRA, scheduled transmissions are locally synchronised using channel event based timing. An example of the operation of such a protocol using ALOHA access is shown in Fig. 7.13. For typical ratios of data packet to reservation packet length, achievable capacity is of the order of 0·6–0·7 with ALOHA access and 0·8–0·9 with time-of-arrival CRA access (applicable to fixed length packet formats only). Since partitioning of channel time is dynamically achieved in these protocols, they tend to have superior delay-throughput characteristics when compared with conventional TDMA based systems. Of course, the irreducible reservation latency delay is also a characteristic of these protocols, as indicated in Fig. 7.2.

7.2.3.4 *Hybrid reservation/random access* The demand assignment approaches described above are suitable for traffic scenarios with a relatively high proportion of long messages. However, for traffic profiles with a mix of short interactive and long transaction/batch messages, the use of pure DAMA results is obviously inefficient for the short messages, and is associated with a high latency delay. On the other hand, random access systems, which are well suited to interactive traffic, are generally quite inefficient for mixed traffic environments. These considerations motivate hybrid reservation/random access schemes which combine the low delay advantages of random access with the high throughput properties of reservation schemes.

Several approaches have been proposed for this purpose [38–41]. The simplest strategy is to transmit short messages in the reservation slots directly, without reservation delays, and to transmit a reservation message (which could be 'piggy-backed' with short data packets) only if additional capacity is required. One could also establish procedures in which there is no explicit reservation of data slots, but where successful random access in a frame results in an implicit reservation of the same slot in future frames. These protocols offer the possibility of high DAMA throughput ($>0{\cdot}5$) along with low access delay for interactive messages, potentially leading to throughput-delay characteristics which transition gracefully from the low-d/low-S random access curves to the high-d/high-S reservation curves in Fig. 7.2. However, optimisation of performance (while avoiding subtle instability and deadlock conditions) over a range of traffic profiles may be difficult to achieve in practice.

7.3 Performance comparison of candidate VSAT protocols

In this section, a more detailed quantitative performance comparison of candidate VSAT multiaccess protocols is presented, chosen from those discussed in Section 7.2. Specifically, based on a variety of implementation and performance factors, unslotted ALOHA, SREJ–ALOHA, slotted ALOHA and DAMA with slotted ALOHA access have been chosen for the detailed comparison. Note that all the techniques considered in this section are 'mature' and have been validated by a variety of independent analytical and simulation studies. Although analytical tools for performance evaluation are available for each of the above four access methods, direct event simulation is used for the results presented here. This makes it possible to obtain delay distributions, which are important for data network design, as well as to incorporate realistic traffic models which must generally be approximated in the analytical models. Detailed discussion of the simulation models used can be found in Reference 42.

7.3.1 *VSAT traffic models*

Remote stations which support interactive data applications typically generate short, variable length messages with average data rate orders of magnitude lower than the multiaccess (terminal to hub) channel speed. Roughly speaking, the remote station traffic model is described by two attributes: (i) the average rate at which new messages are generated, and (ii) parameters specifying the length distribution. Note that (i) and (ii) together can be combined to determine the average data rate per station in bits per second. In Fig. 7.14, approximate regions in the average data rate versus average message length plane that are occupied by some common VSAT applications are shown. It is observed that the important interactive data scenario is in the region near the origin, corresponding to low average data rate and short messages. Note that although, in Fig. 7.14, the length distribution has been approximated by a single parameter which is the average value, in general, an accurate evaluation requires exact determination of message length distribution for a particular application. It is often reasonable to

Section 7.3 and Figs. 7.14–20 are from: RAYCHAUDHURI, D., and JOSEPH, K.: 'Channel access protocols for VSAT networks: a comparative evaluation', IEEE Communications Magazine, *Special series on VSAT, May 1988, pp. 34–44*

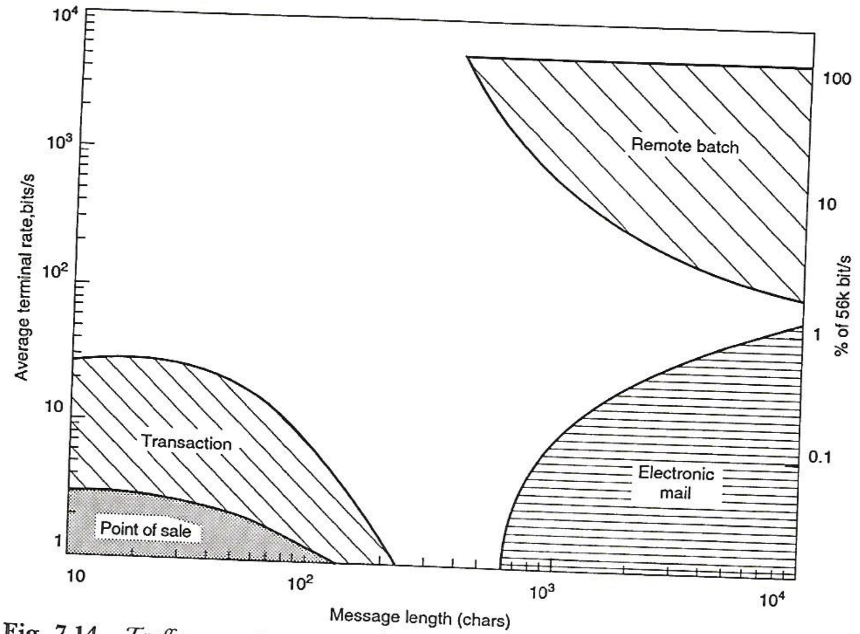

Fig. 7.14 *Traffic source parameter regions for potential VSAT applications*
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assume the distribution to be a truncated exponential with specified average and maximum length (typically 256 characters, based on present data communication practice). Since the exponential distribution tends to produce pessimistic results compared with other alternatives, it is a reasonably good choice when the distribution is completely unknown. It should be noted that there are many subtleties to the station traffic model involving the detailed nature of the arrival process (which is, in general, not a Poisson source) that need to be considered in the evaluation. Typically, each remote station is connected to a cluster controller that supports several interactive data terminals, which do not contribute traffic to the VSAT while they are waiting for a reply from the host computer. Detailed models for the general case, with $M \geq 1$ terminals per VSAT and buffering at the VSAT, have been considered [43]. For simplicity, the results here are limited to the frequently used source traffic model with a single interactive terminal ($M = 1$) per VSAT and exponential interarrival time between messages from each station.

The parameters used in this performance comparison correspond to a typical interactive transaction application from the parameter region identified in Fig. 7.14, and are summarised for convenient reference in Table 7.3.

7.3.2 *Channel and protocol parameters*

The channel parameters (summarised in Table 7.4) used in these numerical examples are based on typical 56 kbit/s VSAT transmission speed, and are believed to reflect typical modem capabilities. Parameters for each of the four

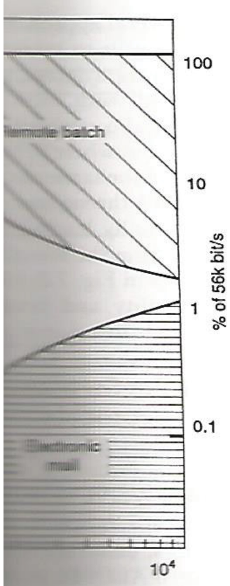

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Table 7.3 *Summary of traffic source parameters used in performance comparison* © IEEE 1988

Interactive terminals per VSAT	= 1
New message rate per terminal (unblocked mode)	= 250 msg/h = 0·07 msg/s
New message rate per terminal (blocked mode)	= 0
New message length distribution	– truncated exponential
Average new message length	= 100 chars (800 bits)
Maximum new message length	= 256 chars (2048 bits)

protocols under consideration have been selected according to established design principles, and are given in Table 7.5. Note that, as discussed earlier, the key retransmission delay parameter is chosen for minimum stable delay, and is optimised at each level of load, N. For ALOHA, the retransmission delay is the only significant parameter of the protocol. However, for slotted ALOHA and SREJ–ALOHA, the choice of appropriate packet sizes is also important. For slotted ALOHA, the convenient approach is adopted of selecting a message packet size (i.e. slot size less guard time and all overheads) equal to the maximum possible message length. For the present example, referring to the traffic model in Table 7.3, this is assumed equal to 256 characters, as might be the case in many practical systems. For SREJ–ALOHA, subpacket size is an extremely important choice: in general, optimum subpacket size depends upon the acquisition and addressing overhead, but is also a load dependent quantity. Fortunately, it can be shown that, for the present set of parameters, there is a fairly robust choice of subpacket size (50 characters for an average message length of 100 characters, as given in Table 7.5), which is close to optimum at moderate to heavy channel load. For DAMA/TDMA, several parameters such as the fraction of time allocated to reservation traffic, the average retransmission delay for colliding reservation messages and the message and reservation slot sizes need to be specified. The design procedure used here is based on optimally allocating a fraction of channel capacity to the reservation channel, noting that total delay is the sum of reservation access delay and message assignment delay. As discussed above for the ALOHA protocols, the retransmission delay for the slotted ALOHA reservation subchannel is selected for minimum stable delay. As for the slotted ALOHA case, the DAMA/TDMA system is based on a message slot size equal to the maximum

Table 7.4 *Summary of channel parameters used in performance comparison* © IEEE 1988

Channel data rate	= 56 kbit/s
Channel symbol rate (rate 1/2 coded)	= 112 kbit/s
Minimum E_b/N_0 required	= 8·0 dB
Modem acquisition preamble	= 32 bits (4 characters)
One way propagation delay	= 0·27 s
Minimum ACK delay (2 hops)	= 0·54 s

Table 7.5 *Summary of protocol parameters used in performance comparison* © IEEE 1988

General

Link level overhead per packet or subpacket (L2) = 7 chars
Network level overhead per message (L3) = 8 chars
Minimum ALOHA mode retransmission delay = 0·67 s
Retransmission delay optimised for delay at each traffic load, under constraint of stable operation.

ALOHA

Single variable length packet per message
ALOHA packet: data length + L2 + L3 + preamble

SREJ–ALOHA

Multiple fixed length subpackets per message
Subpacket size optimised for each average message length, L
SREJ subpacket: fixed data length + L2 + preamble
Subpacket size: *S* = 40 char for L = 50 char
50 100
60 150

Slotted ALOHA

Single fixed length packet per message
Slotted ALOHA packet: data length + filler data + L2 + L3 + preamble
= 275 chars (fixed)
Time slot size: packet length + guard time (4 chars) = 279 chars

DAMA/TDMA (slotted ALOHA reservation)

Reservation packet length 26 chars (including preamble)
Reservation slot length: reservation packet length + guard time = 30 chars
DAMA message packet: data length + filler data + L2 + L3 + preamble
= 275 chars (fixed)
DAMA message slot size: message packet length + guard time (4 chars) = 279 chars
Assignment delay = 0·67 s
Fractional allocation of message and reservation slots optimised for minimum delay.
Message and reservation slots interleaved

message length of 256 characters. In general, DAMA efficiency can be improved by using shorter message slots, but this is at the expense of some increase in implementation complexity.

7.3.3 *Numerical results*

Fig. 7.15 shows the familiar throughput-delay characteristics of the four protocols under consideration. Note that throughput shown is the useful data throughput, after accounting for overheads such as acquisition preamble in ALOHA, guard time, acquisition time and wasted slot time (due to variable message length) in slotted ALOHA, subpacket overhead in SREJ-ALOHA and reservation channel

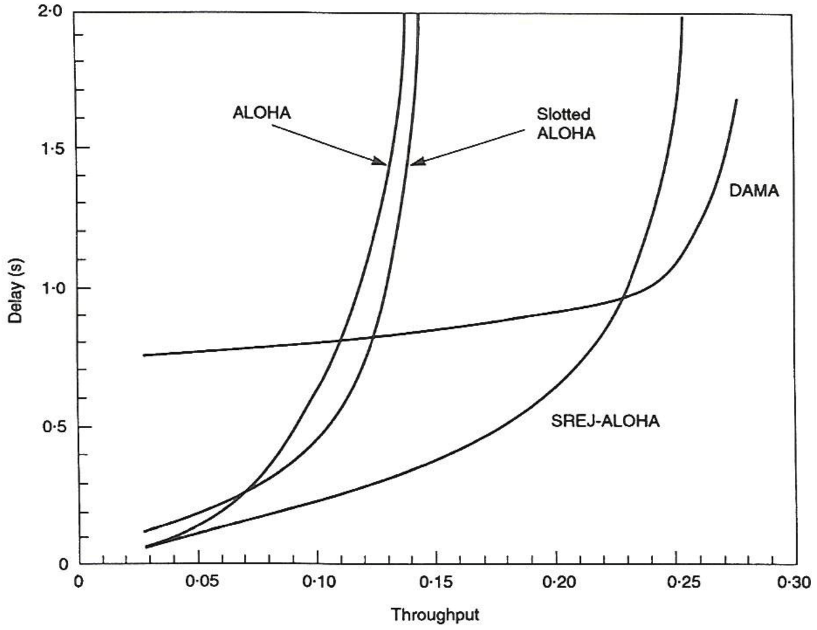


Fig. 7.15 *Delay-throughput characteristics for candidate multiaccess protocols* © IEEE 1988

overhead and wasted message slot time in DAMA/TDMA. The delay values include the effect of slot synchronisation latency delays for the slotted protocols. It is observed from the figure, that, for this message model, slotted ALOHA performs only slightly better than ALOHA, while both are considerably outperformed by SREJ–ALOHA. Obviously, the relative performance is strongly dependent on message length, an effect which should be investigated at a later point. Fig. 7.15 also shows that the maximum throughput achieved by the DAMA approach is higher than that of the random access protocols, but is achieved with a high irreducible delay of about 0·75 s.

As discussed earlier, a more useful characterisation, as in Fig. 7.16, is provided by plotting curves of average delay and peak (95th percentile) delay as a function of the number of VSAT stations supported on the same channel, *N*. Since interactive network design specifications must include average as well as peak delay constraints, such a set of curves is a prerequisite for determining the 'capacity', i.e. the number of remote stations (VSATs) supported on a channel while satisfying the performance requirements, *N**. The operating value of *N** is determined by the tighter of the average and peak delay constraints. From Fig. 7.16, it can be observed that peak delay for ALOHA tends to rise rather rapidly, while DAMA is characterised by high average delay and low delay variance. Slotted ALOHA and SREJ–ALOHA provide better peak delay properties than ALOHA, but are also characterised by rapidly rising peak delay as the channel becomes overloaded. In Table 7.6, a comparison is presented of protocol capaci-

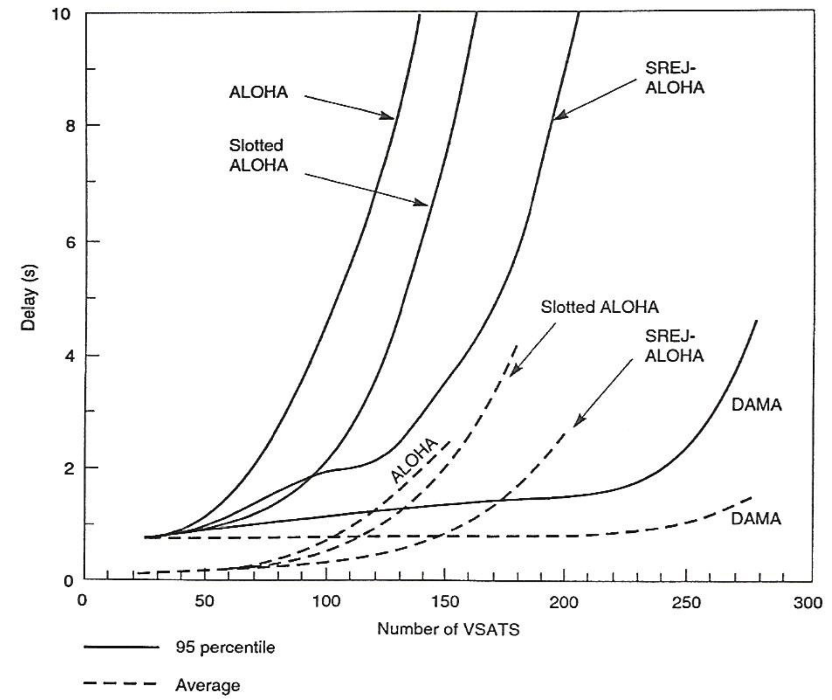


Fig. 7.16 *Average and peak delay versus number of VSATs for candidate multiaccess protocols.* © IEEE 1988

ties with delay constraints of (0·75 s average, 2·5 s peak) and (1 s average, 3 s peak). Observe that the 0·75 s average delay case is not achievable with DAMA, but when the average delay requirement is relaxed to 1 s, DAMA supports many more terminals than the contention access techniques. Comparing the ALOHA

Table 7.6 *Channel capacities for candidate protocols under alternative delay constraints* © IEEE 1988

Multiaccess protocol	Channel capacity (number of VSATS supported, N^*)	
	Delay constraints: 0·75 s average 2·5 s peak (95%)	Delay constraints: 1·0 s average 3·0 s peak (95%)
ALOHA	75	80
Slotted ALOHA	105	110
SREJ–ALOHA	130	140
DAMA/TDMA	*	230

* Objective not achievable

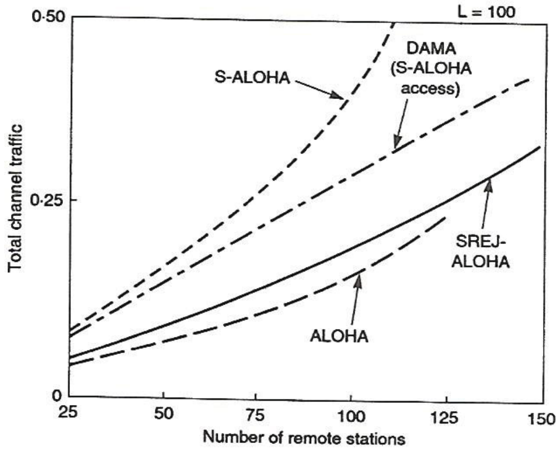


Fig. 7.17 *Variation of total traffic with number of VSATs for the different protocols* © IEEE 1988

protocols, it is observed from the table that, at both performance levels, SREJ–ALOHA supports about 25% and 75% more stations than slotted ALOHA and ALOHA, respectively.

Curves of total channel traffic (G) versus the number of remote stations per channel (N) are given in Fig. 7.17. These curves are of some ancillary importance because they relate to the 'power efficiency' of a protocol, which needs to be considered in power limited situations that frequently characterise VSAT networks. From the figures, observe that, at any value of N, ALOHA has the lowest total channel traffic (and hence the best power efficiency), followed by SREJ-ALOHA, DAMA and slotted ALOHA, in that order. Note also that random access systems display a rapid increase in G after reaching their respective congestion points, due to a non-linear increase in retransmission traffic.

Further characterisation of the protocols in terms of delay distributions at specified load levels is given in Fig. 7.18. In the figure, delay distributions are plotted for ALOHA, slotted ALOHA, SREJ–ALOHA and DAMA, designed to operate at an N^* corresponding to an average delay of 1 s (as determined from curves in Fig. 7.16). Observe that, as expected, DAMA demonstrates relatively low delay variance, while ALOHA is characterised by very high delay variance, mainly due to repeated collisions experienced by long messages. Slotted ALOHA and SREJ–ALOHA display moderate delay variance, although substantially greater than that of DAMA. SREJ–ALOHA appears to have lower 'tails' of the delay distribution than the other contention access techniques. A second detailed characterisation of interest is the plot of average delay versus message length shown in Fig. 7.19. Observe that DAMA and slotted ALOHA, for which the slot size has been chosen to equal the maximum message length, have delays which are independent of the actual length. In contrast, ALOHA and SREJ–ALOHA accommodate variable length transmissions, so that longer messages tend to have a higher collision probability (and hence delay) than short messages. In ALOHA, the delay penality experienced by long messages can be rather significant, par-

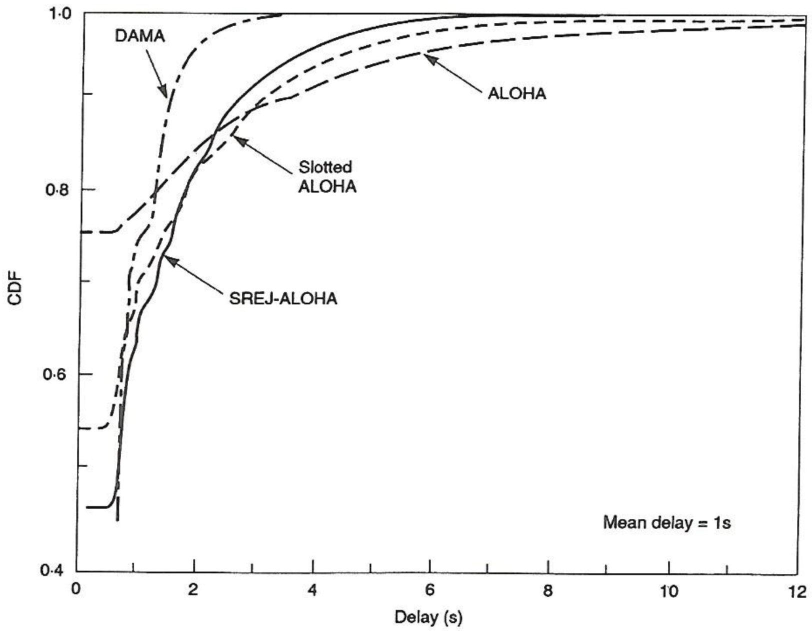
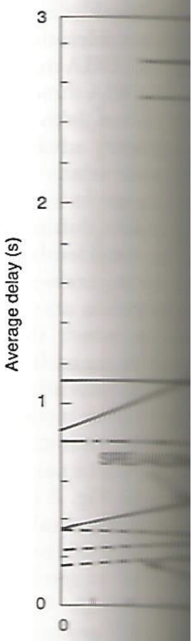


Fig. 7.18 *Delay distributions for candidate protocols at channel load corresponding to an average delay of 1·0 s.* © IEEE 1988

ticularly at high channel load. However, the SREJ mechanism in selective reject ALOHA overcomes this problem to a large extent, so that the curves show only a modest increase in delay with message length.

The above results in Figs. 7.15–7.19 were based on a specific VSAT traffic source model, with an average of 250 messages/hour and truncated exponential messages with maximum 256 characters and average 100 characters. In order to study the sensitivity of protocol performance with respect to average message length, Table 7.7 is introduced which shows the number of VSATs supported per channel (based on a 1·0 s average delay criterion), for average message length equal to 50, 100 and 150 characters respectively (truncated exponential distribution assumed). The results show that, as expected, slotted ALOHA and DAMA have capacities which are insensitive to the message length, while both ALOHA and SREJ–ALOHA exhibit decreasing capacity as message length increases. In general, it is found that SREJ–ALOHA has the highest capacity for short to medium length, while for message lengths of 150 characters or higher, slotted ALOHA is the preferred protocol. Overall, Figs. 7.15–7.19 provide a detailed comparison of the candidate VSAT protocols considered. In general, contention techniques are characterised by curves of delay versus number of VSATs which start at the origin (i.e. low delay at low throughput), whereas DAMA systems exhibit significant latency (irreducible) delay. This may indicate the need to use random access for applications requiring very low access delay, even before



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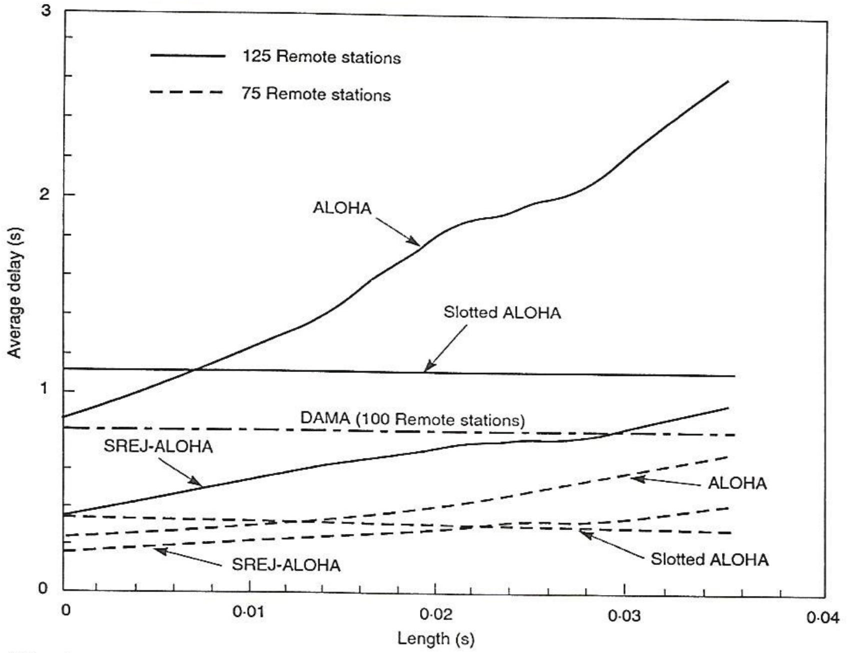

Fig. 7.19 *Variation of average delay with message length for the candidate protocols* © IEEE 1988

considering implementation complexity factors. When selecting between random access protocols, it has been shown that, for practical parameter ranges, SREJ–ALOHA is superior to both ALOHA and slotted ALOHA (which is definitely more complex in terms of implementation). For short message environments, ALOHA may also be used, especially because it offers significant implementation advantages. Slotted ALOHA is generally outperformed by SREJ–ALOHA, but can be used in environments with a large fraction of long fixed size messages. It has also been observed that SREJ–ALOHA and slotted ALOHA offer approximately equivalent delay distribution effects, while ALOHA is generally charac-

Table 7.7 *Variation of channel capacity (with average delay constraint equal to 1·0 s) with average message length.* © IEEE 1988

Message length (characters)	Channel capacity (number of VSATS supported, N^*)			
	ALOHA	Slotted ALOHA	SREJ–ALOHA	DAMA/TDMA
50	180	130	205	250
100	100	130	160	250
150	75	130	115	250

terised by long delay tails. Depending on the application, the 'peak' delay performance such as those shown in Fig. 7.16 is also an important consideration for network design. In applications requiring very low peak delays, ALOHA may not be a suitable protocol, and either SREJ–ALOHA or slotted ALOHA should be used. For scenarios in which relatively high (> 0·75 s) average access delay is permissible, DAMA with slotted ALOHA access may provide capacity advantages. In addition, suitably designed DAMA protocols tend to provide relatively low ratios of peak delay to average delay, which may be an advantage in some applications. However, the implementation complexity, which involves slotting, framing, service queue management and control signalling, is considerably greater than for any of the contention access techniques. Thus, the requirement for low cost VSAT equipment is likely to motivate the use of contention access for first generation VSAT systems, except in traffic scenarios for which the capacity penalty would be extremely severe. Moreover, as discussed in the earlier section, there are various approaches to semi-compatible upgrades of contention protocol equipment for future traffic scenarios which require a reservation mode.

To complete the discussion, an attempt will be made to provide a qualitative comparison between multiaccess protocols over the range of traffic source parameters shown in the terminal-rate/message-length diagram shown in Fig. 7.14. The results presented so far apply to the interactive (transaction or point-of-sale) environment shown near the origin of Fig. 7.14. Widening the scope of comparison to the entire region shown in the Figure, it would be useful to specify optimum regions for the various alternative VSAT protocols. Accordingly, Fig. 7.20 provides a qualitative assessment of optimum regions for the VSAT protocols discussed. An attempt has been made to incorporate the issue of satellite power as well as bandwidth, without entering into the details, which are discussed in Chapter 9. Specifically, Fig. 7.20*a* shows the optimum protocol regions* for a moderately power limited example, as might be encountered in a system with small antenna size (1·2 m), high ratio of hub outbound traffic to inbound traffic and/or high availability requirements. Fig. 7.20*b* shows a similar plot for a moderately bandwidth limited system, which may occur in a situation with larger antennas (1·8 m or greater), powerful forward error corrected modems, balanced outbound and inbound traffic and/or low availability requirements.

Observe from the two Figures that, in general, ALOHA-type protocols are optimum for scenarios with short messages and low average data rate per remote station, in agreement with conventional wisdom. DAMA is recommended for higher message lengths, but for low to medium station traffic volume, while TDMA is the choice for systems with high station traffic volume, independent of message length. Note that there is considerable overlap between optimum regions for the power limited scenario since bandwidth use is relatively non-critical. On the other hand, for the bandwidth limited case, there is little overlap between the optimum regions for each of the protocols, and this can be attributed to the greater importance of the multiaccess efficiency in determining system capacity.

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*Note also that TDMA, which is a useful protocol for medium to high volume stations, is now included. Also the three ALOHA protocols have been lumped together, with the understanding that the choice between these will depend upon the message length regime of interest along with implementation factors.

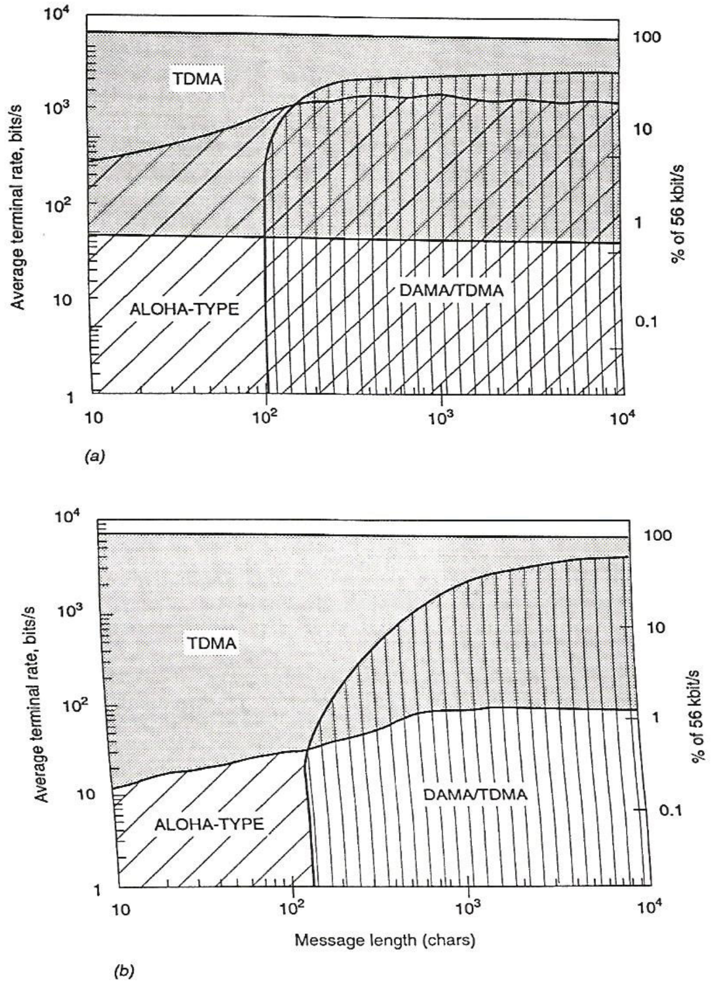

Fig. 7.20 *Optimum protocol regions for typical Ku-band satellite scenarios* © IEEE 1988

a moderately power limited case
b moderately bandwidth limited case

7.4 Conclusions

A review of established and new approaches to satellite multiaccess for VSAT applications has been presented. A variety of contention and reservation based protocols for use on both slotted and unslotted channels has been described and compared in terms of key attributes such as throughput, delay, stability, robustness, operational convenience and implementation complexity. After the survey, detailed performance results for four candidate 'first generation' VSAT protocols were presented (ALOHA, selective reject ALOHA, slotted ALOHA and DAMA with slotted ALOHA access) applied to an example transaction application. It has been shown that, among the random class systems considered, SREJ–ALOHA generally outperforms both ALOHA and slotted ALOHA. DAMA is shown to achieve a higher capacity and lower delay variance than the random access alternatives, but this is at the expense of a 0·75 s irreducible delay, poor robustness and higher implementation complexity. In view of the relatively low impact of VSAT to hub space segment cost on overall system economics, it is expected that delay, implementation complexity and robustness will be primary considerations in VSAT access protocol selection, with capacity (within reasonable ranges) being an important, but secondary issue.

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hardware recognition of an 8 or 16 bit address. Since there is no contention on the outbound channel, it is considered to provide reliable transmission. In this scenario, the data link layer needs to do no extra work to provide reliability; the physical layer has already done it. On this basis, some vendors' data link protocols do not provide confirmation of data link frames received on the outbound channel. If the inbound channel is also operated in a non-contention mode, such as fixed TDMA, it may be considered to provide reliable transmission and the inbound data link protocol will not provide confirmation of reception. If the inbound channel operates in a contention mode such as ALOHA, SREJ-ALOHA, slotted ALOHA, or DAMA [4], then the data link layer will usually provide confirmation of reception. (The design could still leave this for a higher layer to perform, but then it would be subject to longer timeouts before recovery as described above.)

If a vendor has sufficient routing requirements, a network routing layer and a network routing protocol may be defined. This could support routing between a switch and multiple interface units at the hub, among multiple switches at the hub, or even to support a two-hop network in which an inbound packet is routed back out to another VSAT.

Each vendor has defined a layer which performs network addressing and guarantees delivery of all customer information in sequence, without duplicates and without losses.

Although the above discussion describes three possible layers above the physical layer, in practice vendors usually have two layers. The data link layer provides reliable transmission so that every frame arrives error-free at its data link destination and a network/transport layer provides network addressing and ensures that every PDU is accepted at its network destination for delivery to the customer equipment. Such a two-layer design generally supports the multiplexing of many network connections into one data link connection. A vendor might design a product to provide a one-to-one correspondence between network connections and data link connections; in this case the two layers might be collapsed into one layer, probably called a data link layer, which would provide all the services described above and utilise one protocol.

8.4 Protocol software

The software design for a processor used in a remote VSAT or in the hub unit aims to fulfil the requirements of a VSAT network as described above. Two important considerations are the real-time nature of the activity and the layered structure of the protocols.

Communications systems are inherently real-time in that they function as a controlling element in a time-critical environment [5]. They need to respond to multiple events which occur in an asynchronous manner and frequently at the same time. The VSAT unit may need to receive a frame on the outbound channel while it is transmitting a frame on the inbound channel and while there may be full duplex communications occurring at one or more customer ports. It can accomplish the processing of these simultaneous events in a pseudo-parallel manner by having a process to handle each type of event and sharing the processor among the processes in some co-ordinated fashion.

10.15 Monitoring loss of burst reception

Burst transmissions are used in many VSAT systems to transmit data from the VSAT to the hub. The burst must be short to maintain system throughput but a significant training sequence is required to aid the hub demodulator in capturing the burst. The loss of burst synchronisation also reduces throughput as many attempts may be necessary to convey the message. As the training sequence must be kept short to maintain system throughput, major design effort is required to provide hub demodulators which can reliably acquire with a short training sequence.

The loss of burst synchronisation may be detected either by the hub demodulator sensing signal presence but not receiving error free data, or by allowing the VSAT to transmit in the burst how many attempts have been required to obtain signal acknowledgment from the hub. The latter method clearly has some advantage as the policing system is able to identify which VSAT is experiencing synchronisation problems and can log the fault accordingly. If a particular VSAT shows consistent difficulties in obtaining burst synchronisation, the problem could be detected, investigated, and a service visit scheduled as appropriate prior to complete failure of the unit.

10.16 Monitoring of hub reception at the VSAT

A major system integrity safeguard is based on the principle that a VSAT terminal should only be allowed to transmit if it correctly receives a signal from the hub. This ensures the VSAT receiver must be functioning correctly when the VSAT transmits; thus the VSAT is able to receive a signal to terminate transmission if the hub so requests. This provides the hub with the necessary control over VSAT transmissions and also prevents a VSAT with a depointed antenna from repeatedly transmitting in an attempt to establish contact with the hub. This latter situation does not necessarily threaten the network integrity, but if the antenna is depointed in such a manner as to point at another satellite, the repeated transmissions may cause interference to other satellite systems.

The VSAT terminal may establish correct reception from the hub by monitoring and checking the transmission for data errors. The VSAT transmit enable is thus only activated when continuous error free reception is achieved.

10.17 Monitoring of interference

The presence of unexpected signals, which represent interference, can be detected by a spectrum analyser used to scan the appropriate satellite transponders. The use of predefined spectral masks allows for the detection of distorted signals or signals which occur significantly off the expected centre frequency. An example of distortion might be where a VSAT high power amplifier was saturating and causing spectral spreading. This could be detected as a significant rise in the noise floor either side of the main carrier.

If the VSAT network shares the transponder with other users it may be of interest to assess the presence of intermodulation products. This may be of is shared amongst individual terminals. In the outbound direction a single 512 kbit/s carrier contains individually addressed messages to each remote port card, in sequential or time division multiplex (TDM) mode.

A network may have several inbound links, each with a transmission rate of 128 kbit/s and shared by tens or possibly hundreds of VSATs transmitting in sequence, in a TDMA format. The inbound TDMA frame is 45 ms long and contains 720 bytes. Approximately 30 bytes per frame are used for system messages, such as requests for service, and acknowledgments to outbound messages. The remainder of the frame is divided into 'slots', each slot comprising 8 bytes.

Each application has a dedicated interface port at each remote site and at the hub station, and this relationship of applications and access ports is defined as a session. The session is allocated an appropriate number of slots as determined by a sizing procedure to establish the required data rate capacity.

The ISBN has three different modes of accessing the TDMA frame depending upon the nature of each application.

16.4.1.1 *ALOHA mode* Many kinds of data transactions involve small messages occurring at random, and often long intervals, and any attempt to predict them or preassign capacity would result in considerable waste of transmission time. Statistically, it is much more practicable to predict the total capacity requirement of a large network comprising some hundreds of terminals.

ALOHA access allows each PES to transmit a message to the hub as soon as it arrives from the user port. The PES awaits an acknowledgment from the hub, which if not forthcoming causes the PES to retransmit after a randomly determined interval (1–4 s). Hence, a failure of the message to arrive at the hub for any reason, whether high error rate or collision with a simultaneous burst, causes a retransmission, giving effectively perfect overall error free performance.

Each application session has its own allocation of slots in the inbound TDMA frame, so that contention for capacity is amongst members of the session only. This ensures that there is no interdependence or interference between applications, and each can be dimensioned in terms of capacity and response time according to specific user requirements. ALOHA mode gives the fastest overall response time, but the finite probability of collision means that there will be occasional instances of increased delay.

16.4.1.2 *Stream mode* In stream mode a number of slots in the frame are assigned to a particular PES port for the duration of a transaction. It is most suitable for transactions comprising messages of long or indefinite duration. The set-up time for the mode is 1–2 s, but once established there is no further set-up delay.

The TDMA frame structure includes a superframe of 8 frames (360 ms). In order to improve transmission efficiency, stream bursts can be transmitted once, twice or four times each superframe, enabling longer bursts and reducing the proportion of overhead bytes per burst.

16.4.1.3 *Transaction reservation* Transaction reservation is the second type of non-contention access method, and is most suitable for messages which are large but of a limited duration (a few seconds). In this mode the remote data port card requests the hub for capacity to transfer a specific volume of data, typically some thousands of bytes, at a predefined data rate. The hub identifies a sequence of

Fig. 16.2

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16.4.2 *Tel*

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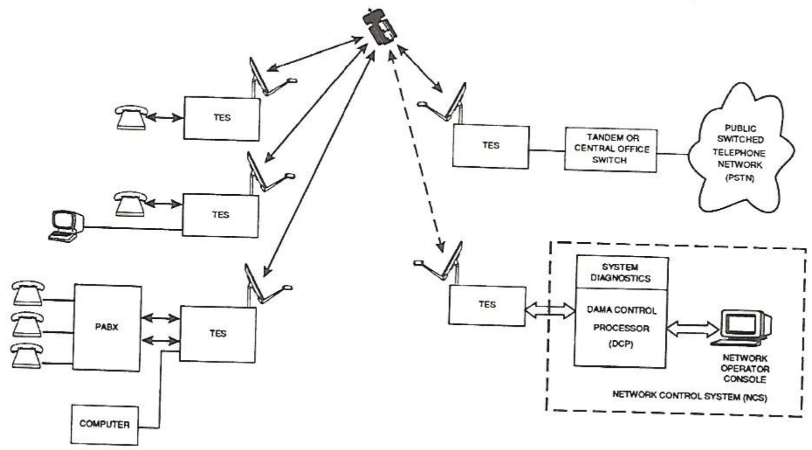


Fig. 16.2 *Telephony Earth Station network concept*

frames with available capacity, and responds with a command to generate bursts in those frames. The last burst of the sequence includes a 'piggyback' request for further capacity if required. Of the three access methods, in practice transaction reservation carries the highest volume of traffic.

Recognising the need for minimising the antenna size, a new family of PES products has been introduced, utilising rectangular-format antennas as small as 1·0 m. The smaller antennas are appropriate for applications such a point of sale, where ease of antenna location on many small retail outlets is critically important, and where the volume of data through each terminal is small.

Another version of PES is available for data broadcast applications, enabling the VSAT terminals to be equipped with receive-only sub-systems.

16.4.2 *Telephony Earth Station (TES)*

Telephony Earth Station is a mesh-configured system, i.e. communication is directly between remote terminals without intervention of a hub station in the transmission link, as shown in Fig. 16.2. This architecture allows the minimum satellite delay, appropriate for a voice network, although antenna sizes are generally higher than those of PES which operate only to a large hub station.

Although TES is optimised for switched telephony, it also supports continuous data circuits at rates up to 19·2 kbit/s asynchronous, and 64 kbit/s synchronous. Voice coding rates can be selected from either 32 kbit/s adaptive differential pulse code modulation (ADPCM), as defined by CCITT, or proprietary residual excited linear predictive (RELP) codes operating at 16 kbit/s or 9·6 kbit/s. Carriers are voice activated in order to gain a satellite power saving for the 60% of the time that each speaker in a conversation is silent. During the 'carrier-off' period, the receiver reinserts background noise at the correct level, to avoid the cut-off effect of voice carrier deactivation.

A selection of forward error correction algorithms is available so that individual voice and data channels can be optimised in the satellite for the correct use of carrier power and bandwidth. There is automatic transmit level compensation, so that carriers working to large receive antennas are lower than those operating to small antennas. These techniques enable satellite power to be minimised, on a call-by-call basis.

Calls can be set up or terminated at either a telephone instrument, or by various types of telephone exchange. A Microvax 3100 comprising the network control system (NCS) is installed at one of the VSAT terminals to manage and implement call set-up, routing and clear down, and to record call statistics for use for billing etc. The NCS has two dedicated channels for requests, operating in TDMA/ALOHA mode, used by any station wishing to establish or clear down a call. The NCS has a separate broadcast-mode TDM channel through which it responds to requests, and instructs transmission channels to be created or cleared down. Once a circuit between two sites has been created and the two satellite channels established and tested, the NCS drops out of the transaction until either party requests a clear down.

TES is based on a modular architecture. The indoor unit comprises a chassis supporting up to four channel cards, but there is no fixed limit on the number of chassis which may be configured at any site. The 70 MHz IF allows connection to standard RF terminals, and TES supports a range of antenna sizes and RF bands to accommodate any domestic, regional or international satellite coverage beam.

Each channel card has five functions, and can be selected to operate for voice traffic, data traffic, dedicated remote control and monitoring, TDMA/ALOHA request channel, or TDM/broadcast control channel. A channel card selected for traffic mode can also operate the control and monitoring function when traffic is not being passed.

16.4.3 *inTELEconference*

Hughes has developed its basic VSAT technology to produce a specialised multipoint video conference system known as inTELEconference, in response to demands from industry. inTELEconference is an intelligent, reservation-based satellite network that allows a pool of small aperture earth stations to share space segment to support a mixture of low-speed digital video and audio conferencing sessions. Individual subnetworks are created, in which up to 16 terminals can operate at any time, with either one or two pictures being transmitted simultaneously with the audio.

Audio is mixed so that all sites can hear the others at all times. Four modes of operation are available (*a*) broadcast (to any number of sites), (*b*) two-way interactive, (*c*) multipoint, and (*d*) two-way with multipoint. There are several ways of selecting the site or sites currently transmitting a picture, the process known as 'baton passing'.

The system is a mesh configuration, i.e. terminals communicate directly not via a hub station, and typically employs 2·4 m antennas. A data rate of 384 kbit/s is supported as used by several high-quality video conference codecs.

Two kinds of access methods are used. Compressed video signals are carried in a 384 kbit/s TDM channel, which includes capacity for audio and control signals. The stations not transmitting video access a TDMA channel operating at 192 kbit/s, which can support up to eight compressed audio channels plus control information.

inTELEconference is fully supported by a dedicated network management system which provides status monitoring of user sites, reservation control, and system configuration and diagnostic facilities.

16.5 System performance

Digital communications system performance tends to be measured in terms of a bit error rate, the bits received in error measured as a proportion of the total. It may be assumed that in a digital message all bits 'count', and that an error passed to the application will cause a corruption of function or of information. End-user applications are usually designed with a degree of tolerance, and will often use an error detection technique involving a parity check (or check sum) for each block of data. If the error rate is too high, greater than about 1 error in 10^6 bits, normal levels of user tolerance break down and the link is effectively out of service.

It is the function of the demodulator in the satellite receive chain to convert the analogue transmitted signal back to a digital bit stream. The demodulator has to detect transitions in phase of the modulated carrier in the presence of received noise, caused by various thermal and interference effects but all contributing to a phase error or uncertainty at the transition between each bit and the next. The proportion of noise in the received signal is expressed in a carrier to noise ratio (C/N), and the probability of an error increases as the C/N ratio is reduced. Curve (*a*) of Fig. 16.3 shows the relationship between E_b/N_0 and error rate for two-phase (180° phase transition) phase shift keying (PSK) modulation. The C/N is expressed as E_b/N_0, the ratio of energy per information bit and the noise spectral density. This enables account to be taken of the type of modulation and the forward error correction (FEC) coding.

A low BER is achieved at the cost of a high E_b/N_0, which is counter to the need to minimise the power level of the transmitted signal. Signal power uses a valuable resource, i.e. the capacity of the satellite transponder and the transmit-level capability of the earth station power amplifier. This is especially true in small antenna systems which have low receive sensitivity and a low transmit power level.

It is possible to reduce the E_b/N_0 requirement for a given BER by repeating information in an expanded bandwidth and recovering the additional information in a coherent manner which reinforces the wanted signal in the presence of random noise. This is the function of wideband frequency modulation in analogue systems and in digital systems is achieved by forward error correction. In this technique additional data is sent interleaved with the message signal which, when recovered, enables errors to be detected and corrected. Half-rate FEC, in which the ratio of information bits to total transmitted bits is 1:2, typically allows a reduction of signal level of 1/3 or 1/4 of its uncoded level. The encoding process is relatively straightforward, but the decoding alogorithm involves considerable ingenuity in design and low-cost high-speed implementation using integrated circuit technology. Fig. 16.3 shows the BER versus E_b/N_0 relationship for 1/2 rate coding (curve *b*) and 3/4 rate coding (curve *c*). The codes are a proprietary convolutional type using sequential decoding.

For VSAT applications using ALOHA access, the retransmission procedure designed to overcome packet collisions also applies for losses of data caused by

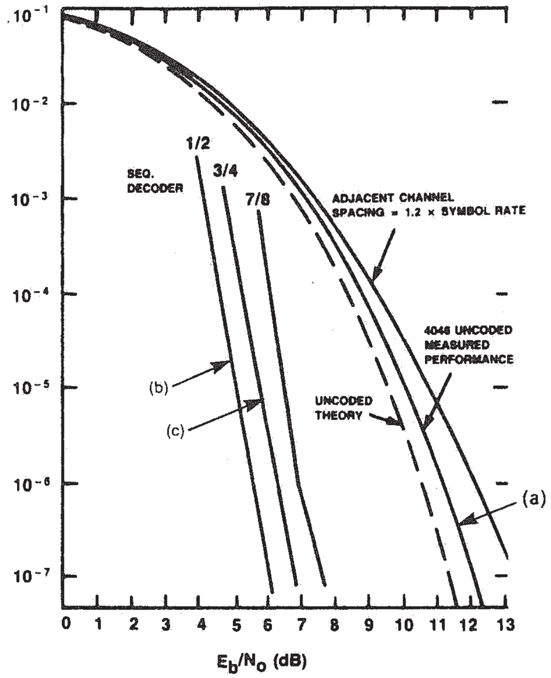


Fig. 16.3 *Relationship between bit error rate and* E_b/N_0

atmospheric attenuation or other causes. The effect of burst retransmission is to add a delay of about 1 to 3 s.

Stream services tend to be provided without a retransmission protocol, and the link design must give a satisfactory error rate for around 99·9% of the time. This performance can be achieved by selection of link parameters, including antenna diameter, uplink radio power, the satellite receive sensitivity and transmit power.

Availability is a function of a number of factors, of which the most critical involve equipment reliability. The hub station normally has full duplication or redundancy of all functions in the baseband and radio frequency sections. Any failure can quickly be detected and rectified under the supervision of operations staff.

VSATs are not designed with redundancy, since there are relatively few elements. The approach taken is to design the VSAT to have a high mean time between failure (over two years), and to design it with a sophisticated alarm, monitoring and control facility linking directly back to the hub station. The VSAT is modular, so that if a fault does occur a locally based maintenance technician can replace the identified module and return the unit to service.

specific application will depend on the quantity of VSATs in the network, traffic density and the acceptable response time.

17.4 Adaptive assignment/time division multiple access (AA/TDMA)

17.4.1 *General*

The primary applications for VSAT networks are at point of sale (POS) and banking/financial locations for credit card verification, as well as other financial transactions and for data communications between computers. These applications can be separated into two different categories – interactive and batch. And there are some differences in the traffic volume and transmission delay requirements between these two categories.

In interactive applications, with inquiry/response traffic, a short response time is a very important requirement for the end user. With this type of application, the traffic is usually light and occurs in bursts, and therefore the throughput of the satellite channel tends to be less critical.

In the other type of application, which is used to transfer batch data such as file transfer or facsimile data, the throughput of the satellite is far more important than the response time as the data volume is usually higher.

To make these VSAT networks economical, the satellite channels must be shared among many users, and a multiple access scheme, that allows several earth stations to share a single satellite channel, must be adopted.

In order to satisfy all these requirements, a proprietary AA/TDMA scheme has been developed which not only offers users a short response time for interactive type traffic but also provides high satellite throughput for batch type traffic.

17.4.2 *Random access TDMA*

In random access TDMA (RA/TDMA) schemes, also known as 'slotted ALOHA', each VSAT transmits its data packet as a burst signal within a TDMA slot as soon as a slot is available. The burst signals are therefore transmitted randomly from the remote VSATs, and when data collides it is lost and has to be retransmitted.

This scheme offers a shorter transmission delay than any other scheme, provided the channel loading is light and the risk of collision is subsequently low. It is therefore ideally suitable for lightly loaded interactive transaction traffic data which requires a minimum transmission delay.

However, as the traffic density increases so does the probability of collision and the need for retransmission which makes the operational network unreliable. Theoretically, the maximum channel throughput is limited to approximately 37% of the total channel capacity available because of the increased risk of collision. Strict flow control is therefore very important in any random access scheme.

17.4.3 *Demand access TDMA*

Demand access TDMA (DA/TDMA) schemes offer a high satellite channel throughput, with a small sacrifice in the transmission delay. In a DA/TDMA

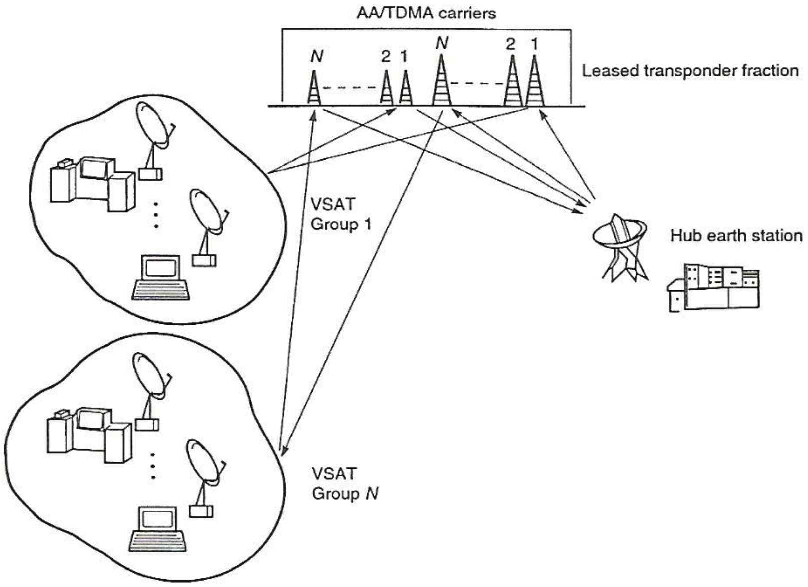


Fig. 17.5 *Inbound and outbound data channels*

scheme the VSAT, on receipt of data from the user's DTE, requests a channel from the control processor at the hub station. The channel is assigned by the hub station, and the data is transmitted in the assigned TDMA slot.

With this scheme there is no risk of collision and the channel throughput can be optimised. However, the transmission delay is longer than in the RA/TDMA scheme, because of the time required for channel reservation and assignment which is approximately three times the satellite round-trip delay.

17.4.4 *AA/TDMA*

The proprietary AA/TDMA scheme, used in the NEXTAR system, is used for both interactive and batch data traffic and operates in a very similar manner to the RA/TDMA and DA/TDMA schemes described above.

17.4.4.1 *Inbound and outbound data channels* The outbound and inbound traffic flows are handled in an asymmetrical fashion, with the outbound and inbound satellite channels, from different user groups, shown in Fig. 17.5.

The outbound channels, from the hub station to the VSATs, are operated in a continuous TDM mode and the data packets, from the VSATs to the hub station, are transmitted in a burst TDMA mode adopting the frame format and data format shown in Fig. 17.6.

Data packets, sent from the hub to one or more VSAT, share the same outbound carrier. Each data packet is transmitted successively in a packet multiplex manner, on a 'first-in, first-out' basis and has an address field containing the address information for the destination. Each VSAT receives all the data

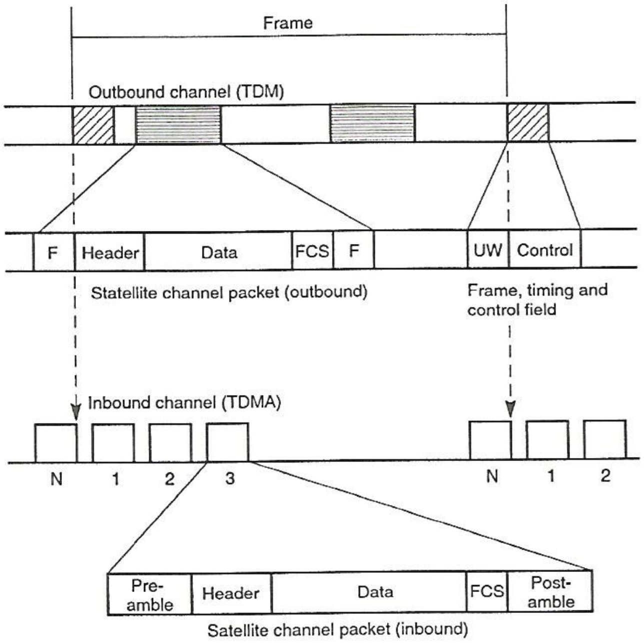


Fig. 17.6 *AA/TDMA frame format and packet format*

packets transmitted from the hub station, but only accepts the data packet whose address matches its own address; all other data packets are discarded.

Frame timing and control sequences are periodically inserted in the outbound data and contain a unique word (UW) and a control field. The UW is used to synchronise the timing of the TDMA frame from the VSATs, so the inbound data bursts transmitted in the same slot from many different VSATs will all arrive at the satellite at the same time.

The inbound data packets, transmitted in a burst TDMA format, consist of a preamble, a header, a data portion, a frame check sequence (FCS) and a post-amble. The preamble is used for the carrier recovery and clock recovery of the hub station PSK demodulators. The header contains an address field to identify the VSAT, and various other control information.

Since the length of the data field is fixed, dummy filler bits are inserted after the user data when the length of the user message is shorter than the field length. If, on the other hand, the user message is longer than the field length, the user message is segmented and transmitted in multiple satellite packets. The FCS is used to detect transmission errors and the post-amble is attached for the convolutional error correction circuit in the receiver.

The frame length is set at an optimum value, taking the satellite round-trip delay time and equipment processing time into consideration. The slot length can be changed to the most suitable length required which means that an average or most probable length user message can be transmitted in a single satellite packet.

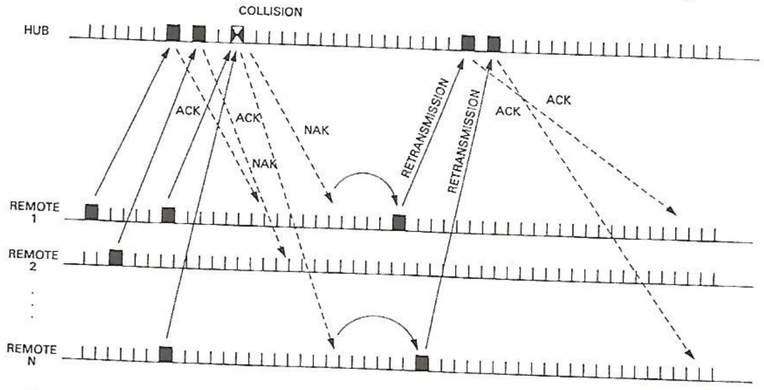


Fig. 17.7 *Random access method transmission*

17.4.4.2 *Random access and reservation* In the AA/TDMA scheme, user data can either be transmitted in a random access or reservation mode and the mode is automatically selected by the length of the user's data message.

For short inbound user messages that can be sent in a single packet, the random access method is used with each VSAT transmitting its data packet in a TDMA slot, as shown in Fig. 17.7, as soon as it is ready for transmission. The hub station returns an acknowledgment in the frame timing and control sequence of the outbound channel, if the packet has been received successfully.

As other VSATs may be transmitting their bursts in the same TDMA slot, collisions can sometimes occur and the data will be lost. The VSAT, which transmitted the lost data, will know that it has been lost because it will not receive an acknowledgment from the hub station. It will then retransmit the data after a randomly selected time interval, to minimise the risk of a second collision, and await acknowledgment from the hub station.

If the packet reaches the hub station at the first attempt, the maximum transmission delay, for a single hop satellite link, will be approximately 270 ms plus the processing time. Even if a collision occurs on the first transmission, most packets will successfully reach the hub at the second attempt. In this case, with one retransmission, the transmission delay time will be approximately 1 s plus the processing time.

For long inbound user data messages, that are longer than the pre-determined value and cannot be accommodated in a single satellite packet, the user message is transmitted using the reservation access method, as shown in Fig. 17.8.In the reservation access method the VSAT transmits the first parts of its data packet in a TDMA slot, together with a request for the required number of additional slots, using the same procedures as used in the random access method.

The satellite access controller (SAC), in the hub station, will then assign the required number of slots and advise the location of the reserved time slots in the frame timing and control sequence in the outbound channel. If the first transmission from the VSAT is lost due to collision with another VSAT transmission, there will be no acknowledgment from the hub station and it will retransmit the

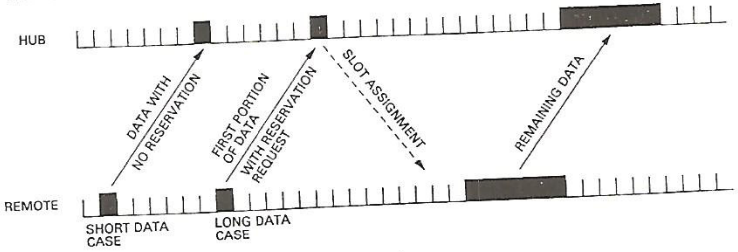


Fig. 17.8 *Reservation access method transmission*

data after a randomly selected time interval to minimise the risk of a second collision.

Once the first transmission has been received and additional time slots assigned, all the VSATs will be informed, in the frame timing and control sequence, that these slots have been reserved and cannot be used for packet data transmission. The VSAT that made the initial request for additional time slots is then free to complete its transmissions without risk of further collision.

The unique feature of the AA/TDMA system is that it allows co-existence of interactive transaction type data and lengthy batch type data. The baseband processor (BBP), at the VSAT, determines the length of the incoming user message and decides, on a message by message basis, which transmission method is to be used: random access method, if the message length is less than the pre-determined value, and reservation access method, when it is longer.

In addition, the maximum number of time slots in a frame that can be reserved is limited to a pre-determined number so that there are always a certain number of time slots available for the random access method of operation. No slot is pre-assigned for the random or reservation access method of operation; the slots are only made available for reservation access when a request is received from, and assigned to, a VSAT. So that if there are no reservation requests, all the slots are available for random access transmission by the VSATs.

Computer simulations have been made to check the delay-time/throughput characteristics of the AA/TDMA system for mixed mode of transmission and the results are shown in Fig. 17.9. From these results it can be seen that, for a mix of short and long messages, a total throughput of 40% was achieved with very little increase in the transmission delay time.

17.4.4.3 *Protocol conversion* As the NEXTAR data network is intended to replace existing terrestrial data networks and interconnect directly with the user's existing data terminal equipment (DTE) there must be no change in the existing protocols used by the DTE. In order to achieve this without degrading the transmission and at the same time compensating for the satellite delay time, protocol conversion within the NEXTAR system is necessary.

In the AA/TDMA system, the protocol conversion is performed by the SAC at the hub station, and by the BBP at the VSAT. Figure 17.10 shows the network architecture of the AA/TDMA VSAT network with the physical and data link levels of the user protocols converted to the satellite protocol.

The SACs, at the hub station, are connected to the front end processor or host computer whilst the BBPs, at the VSATs, are connected to the user's DTEs. The

able 18.1 *Typical link budget for regional satellites*

	Hub to VSAT		VSAT to HUB	
	4/6 GHz	11/14 GHz	4/6 GHz	11/14 GHz
IRP earth station	51 dBW	55.2 dBW	37.9 dBW	42.1 dBW
ree space loss	200 dB	207.7 dB	200 dB	207.7 dB
atellite G/T	− 2.5 dBK	1.0 dBK	− 2.5 dBK	1.0 dBK
$/K_t$ uplink	77.1 dBHz	77.1 dBHz	64.0 dBHz	64.0 dBHz
atellite EIRP	17 dBW	17 dBW	3.9 dBW	3.9 dBW
Free space loss	197 dB	205.4 dB	197 dB	205.4 dB
Earth station G/T	14.5 dBK	23.2 dBK	24.5 dBK	29 dBK
C/K_t down	63.1 dBHz	63.2 dBHz	60 dBHz	55.9 dBHz
E_b/N_0 at receiver	10 dBHz	10 dBHz	18 dBHz	15.9 dBHz

18.2 Operation of the Fastar SCPC DAMA network

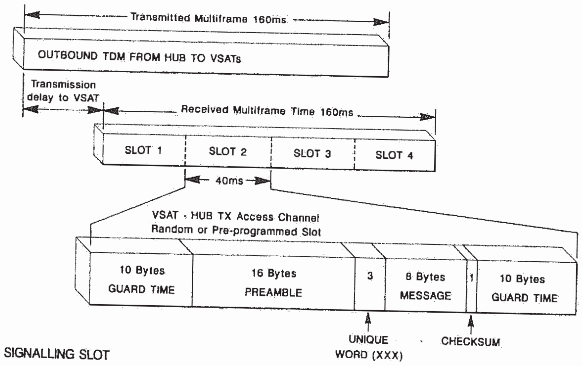
18.2.1 *System architecture*

The basic Fastar SCPC DAMA network (Figs. 18.1 and 18.3) comprises 20 × 9·6 kbit/s timeslots, plus overhead and framing, to make a 204·8 kbit/s outbound channel. Signalling through the system is achieved by use of one of the inbound SCPC channels (access channel) and time division slot 1 (control channel) on the outbound TDM frame. In a standard network the inbound channels consist of one access channel and 19 SCPC (message) channels, whilst the TDM outbound channel contains one signalling timeslot and 19 message timeslots for the TDM DAMA channels.

18.2.2 *Channel assignment*

The assignment of a bi-directional channel from VSAT to hub (Fig. 18.3) is achieved in the following manner: the VSAT detects data present at either its voice or data interface and inhibits real-time transfer until a channel has been assigned. The VSAT then uses the access channel at frequency f_1, requesting either connection to another VSAT via the hub or connection to a hub direct line. The hub, accordingly, informs both the VSAT originating the transmission and the VSAT receiving the transmission which frequency channel and timeslot respectively to use. The hub also informs both the originating and receiving VSAT of the timeslot and frequency channel respectively that will be used for the reverse link. The hub contains a 20 channel cross point switch which allows VSAT to hub line connections to be made.

Termination of a call is the exact opposite of request for transmission: on receiving an end of message signal from the data port the originating VSAT terminates the transmission and signals to the hub, via the access channel, that the working channel is no longer required. The hub acknowledges this request via the control channel (timeslot T1) and both transmitting and receiving VSAT cease data transmission.



GUARD TIME at start of slot	10 Bytes	8.3ms
PREAMBLE	16 Bytes	13.3ms
UNIQUE WORD	3 Bytes	1 part in 10^7 misdetection probability
MESSAGE	8 Bytes	
CHECKSUM	1 Byte	summed over 8 message Bytes
GUARD TIME at end of slot	10 Bytes	8.3ms

Fig. 18.5 *VSAT–Hub random or slotted access channel*

18.2.3 *Access channel*

The access channel (Fig. 18.5) provides all the signalling information from VSAT to hub. Within the Fastar SCPC DAMA system all VSATs use a pre-assigned channel (typically channel 1) to communicate signalling to the hub. Every request to open and close a channel from VSAT to hub is sent on this particular channel. The protocol of the access channel is shown in Fig. 18.5. The access channel utilises a slotted random access system (slotted ALOHA). The synchronisation occurs via the incoming TDM frame using the transmitted multiframe as a start marker with a known transmission delay to the VSAT included. This transmission delay can be adjusted to compensate for VSATs operating in vastly different geographical locations. Using the multiframe timeslot of 160 ms, the access channel is further sub-divided into 40 ms slots. Each of these slots is further sub-divided into guard time, preamble time, unique word, message and checksum. The guard time at the beginning and end to the access message prevents the corruption of data due to the overlap of ALOHA slots caused by timing errors due to geographical location. The 16 byte preamble is sufficient to allow the hub burst demodulator to lock onto the signal and recover the message. The transmission from VSAT to hub via the access channel does not use forward error correction.

As the network increases in size or the activity on the network expands, the incidence of collisions on 'request for access messages' will increase. This is resolved by action at both hub and VSAT. Once a collision is detected, the contending VSATs retransmit after individually pseudo-randomly determined delays. The likelihood of a subsequent collision is considerably reduced. On entry

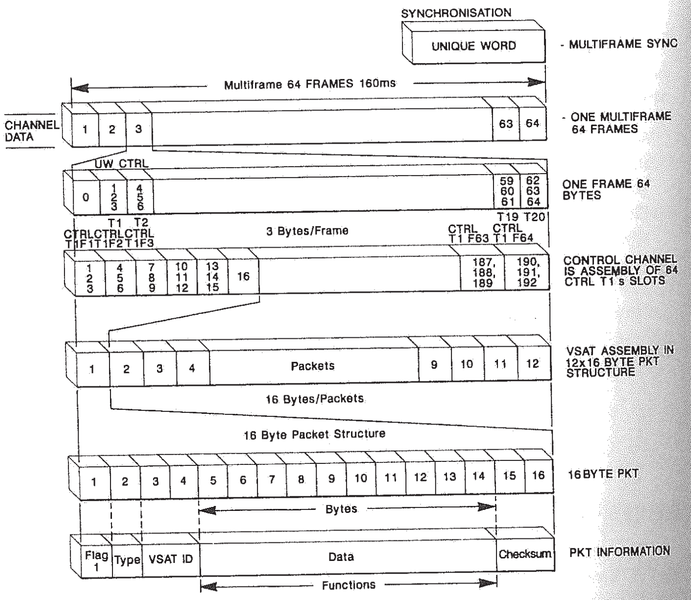


Fig. 18.6 *Control channel (hub to VSAT signalling)*

into the system the number of previous attempts is logged at the hub. In the case of large numbers of VSATs indicating delays on entry, the hub will send out a multiplier function to increase the randomisation.

The VSAT can send the following types of messages to the hub via the access channel:

(*a*) Request a channel
(*b*) Clear a channel
(*c*) VSAT data } specialised data messages
(*d*) Hub data }
(*e*) Forced clear

These allow calls to be originated, channels cleared for end of transmission confirmation and for priority override by forcing a specified channel clear.

18.2.4 *Control channel*

The control channel shown in Fig. 18.6 is the signalling channel used by the hub to respond to VSAT requests on the access channel or to pass overall network data to all VSATs, i.e. a bulletin board feature. The control channel is derived from timeslot T1 on the received TDM frame at the VSAT. This TDM frame is based on the standard IBS frame structure in Fig. 18.7. The 3 bytes of timeslot 1 in each frame are demultiplexed to form the packet structure shown; each multiframe provides 12 packets, each packet containing 16 bytes.

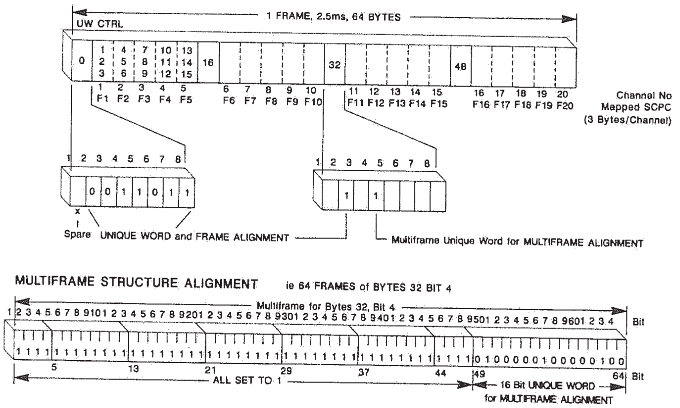


Fig. 18.7 *IBS frame structure*

Frame structure

1 Frame = 60 bytes of information + 4 bytes framing, 2·5 ms, Information rate = 204·8 kbit/s

1 multiframe = 64 frames, 160 ms

The control channel has a defined packet structure to allow simple responses to VSAT:

(*a*) *Bulletin board*: An overall message transmitted to all VSATs with system information present, e.g. loading, randomisation, interval charge rate
(*b*) *Bulletin board 2 and 3*: These show status of the network by indicating if channels are busy or clear
(*c*) *Acknowledge channel*: Used to send back, 'clear' to transmit, to VSAT, channel number to use
(*d*) *Allocation*: To inform receiving VSAT to await transmission on a particular channel
(*e*) *Timing correction*: Used by hub operator to send auto-timing correction when VSAT is first switched on for delay equalisation on access channel caused by geographical location

These standard messages are used by the hub to respond to VSAT requests for channel allocation and perform the housekeeping and policing functions required by the system.

18.2.5 *Sizing of the VSAT network*

The number of VSATs that can be supported by a system of a particular size (i.e. number of channels) can be determined by using the Erlang criteria (depicted in Fig. 18.4), originated for telecommunication use. The main assumption for these

Chapter 22

Link budgets for VSAT systems

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22.1 Introduction

The link budget assesses the quality of a satellite link. It compares the received signal power available via the uplink station, satellite and downlink station with the combination of noise and interference which arises in the link. A basic satellite link is illustrated in Fig. 22.1 which shows an uplink earth station, a satellite and a downlink station. In practice, especially in VSAT systems, there are a large number of small earth stations and usually a single large earth station, sometimes also known as a hub earth station. The need for a large earth station will become apparent from consideration of link budgets. The difference between the power of the wanted signal and the sum of interference and noise power in the same bandwidth for a satellite link is often small. A satellite communications link budget shows that the link is often severely power limited. Signalling techniques must be used that can provide an acceptable level of service in this situation.

22.2 Link budget principles

22.2.1 *The satellite*

In this discussion the satellite is assumed to carry a conventional repeating or transparent type of transponder. This type of transponder receives the signal transmitted, amplifies it, frequency converts it and finally boosts the signal with a high power amplifier for the return link to earth. Much discussion is currently being given to a different type of transponder called a regenerative transponder wherein the signal received from the ground is demodulated then re-modulated and transmitted to earth on a different carrier frequency. Even though these transponders offer better performance they need to be tailored to the signal being used. Currently, there is a high degree of risk associated with the prediction of the future parameters of a satellite communications system at the design stage of the satellite which will precede its operational stage by a number of years. For this reason most satellite transponders today are of the repeater type. These are versatile but offer inferior performance in comparison with the regenerative type, as the noise received with the uplink signal is amplified and retransmitted as though it were part of the wanted signal.

22.2.2 *The uplink*

22.2.2.1 *The signal* The satellite uplink comprises a transmitting uplink station,

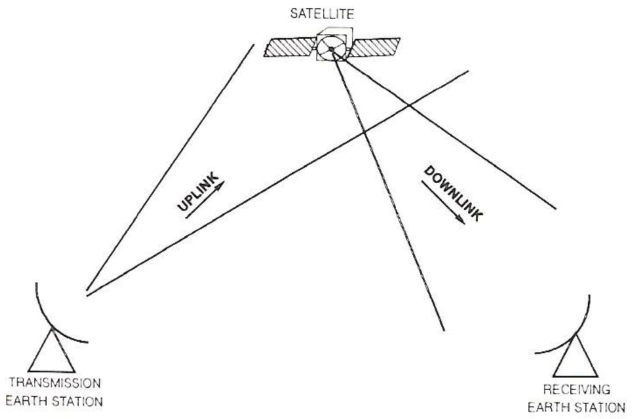

Fig. 22.1 *Basic satellite link*

and a satellite transponder which receives the signal. The essential elements of the uplink are shown in Fig. 22.1. The signal from the high power amplifier (HPA) in the uplink station is fed to the antenna system and is beamed towards the satellite. The antenna concentrates the microwave power in a directional and near parallel beam. By focusing the signal power in this way the flux density in the direction of the satellite is significantly increased but low in other directions. It is often convenient to express the focused power in terms of the equivalent radiated power from an isotropic radiator. In this way the power from a focused 100 W source may be expressed as equivalent to, for example, a 10 MW isotropic source. This equivalent power is referred to as the equivalent isotropic radiated power (EIRP), and is calculated by multiplying the signal power by the focusing gain of the antenna, in this case 100 000 or 50 dBi relative to isotropic. A Ku-band system with 50 dBi gain can be realised using an antenna of 3 m diameter. The beam from the uplink station is not perfectly parallel and is subject to an inverse square law loss caused by spreading of the signal beam with increasing distance from the transmitter. This spreading loss is frequency independent. The signal level received at a distance from the transmitter is characterised by its power flux density (PFD) measured in watts per square metre (W/m^2 or dBW/m^2). Fig. 22.2 gives the PFD at the satellite. The receiver in the satellite 'collects' the signal by concentrating incident wavefronts to the focus of the receive antenna and thence into the waveguide feed. An antenna thus has an effective collection area, or effective aperture, which is related to its physical size, by the efficiency of operation, η, at the selected frequency. The gain of an antenna G_R is expressed as the ratio of its aperture A relative to that of an isotropic antenna A_i as shown in Fig. 22.3.

The uplink signal transmitted to the satellite transponder is called the 'wanted signal' and the satellite transponder is called the 'wanted satellite'. There will, however, be a number of other satellite transponders either co-located or in the vicinity of the wanted one, each of which will be receiving its own signals. These unwanted signals may enter the receiver of the wanted satellite transponder causing interference to the wanted signal path. Fig. 22.4 illustrates this situation

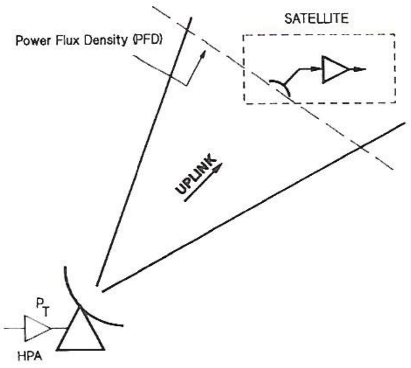

Fig. 22.2 *Power flux density at satellite*

PFD = $(P_T G_T / 4\pi d_u^2)$ Wm^{-2}
d_u = distance from earth station to satellite (in metres)
P_T (in watts)
G_T (in dBi)

for a single interfering earth station on the uplink. Protection is obtained by control of the ratio of transmit powers, the modulation method, the frequency and polarisation of operation and the extent to which the interferer is pointing to the satellite combined with the satellite antenna gain in the direction of the unwanted signal's originating ground station (see Fig. 22.4). Maximum benefit should be obtained from the transmit earth station directivity as the satellite may

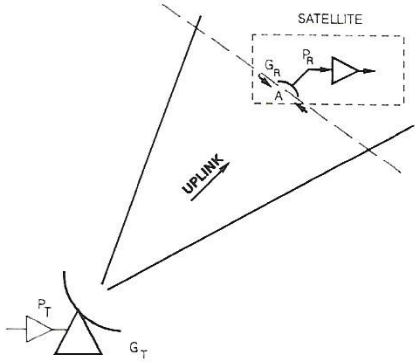

Fig. 22.3 *Received power at satellite*

P_R = PFD × $A\eta$
$A = (\lambda^2/\eta 4\pi)\, G_R$
λ = wavelength
η = efficiency
$A_i = \lambda^2/4\pi$
$A = A_i G_R$

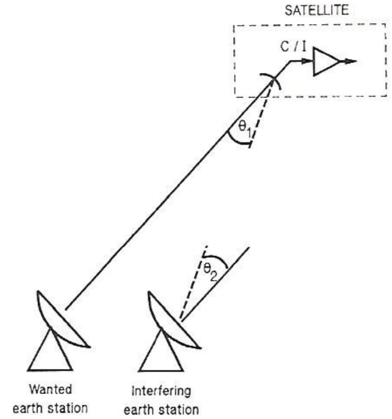

Fig. 22.4 *Carrier-to-interference ratio*

$$
\begin{aligned}
(C/I) &= (P_R/P_I) \\
P_I &= PFD_I \times A_i \times G_R(\theta_1) \\
PFD_I &= (P_{TI}G_{TI}(\theta_2)/4\pi d_{uI}^2) \\
(C/I) &= \text{carrier-to-interference ratio} \\
d_{uI} &= \text{distance from interfering earth station to satellite}
\end{aligned}
$$

have been designed to receive signals from a large geographical area, often including the unwanted interfering earth station. In contemporary satellite systems, total signal interference can be higher than the transponder thermal noise.

22.2.2.2 *Noise* Noise is an unwanted phenomenon which limits the performance of the satellite communications link. Of the several different types of noise it is usually thermal noise which ultimately determines link quality and capacity although oscillator phase noise can play a part, especially in VSAT systems where the user is usually seeking the lowest possible cost system and where low data rate signals are carried. Thermal noise has a flat power spectrum with frequency. Noise power density in the frequency band of interest, B (measured in Hz), is expressed as the product of noise temperature, T (measured in degrees Kelvin), and Boltzmann's constant, k (which has units of Joules per degree Kelvin). The noise temperature is the equivalent physical temperature of a matched resistor which would give the same noise power as the communications link presents to the receiver.

On the uplink the satellite transponder is looking at part or all of the earth's surface, which has a physical and noise temperature of about 300 K. For this reason there is little benefit from a system viewpoint in trying to make the noise temperature of the satellite receiver significantly lower than this. In many cases, satellite receivers operate with a noise temperature of about 1200 K, of which 300 K is due to the 'hot' earth. Fig. 22.5 illustrates the derivation of the uplink noise power including contributions from the earth and the satellite receiver. An alternative representation is by noise figure where the equivalent noise temperature

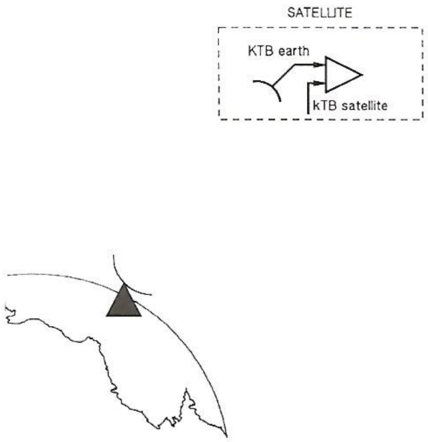

Fig. 22.5 *Derivation of uplink noise*

$$
\begin{aligned}
N &= kT_S B \\
&= k(T_{earth} + T_{satellite})B
\end{aligned}
$$

of the receiver is related to its noise figure F by;

$$T = T_0(F - 1)$$

where $T_0 = 290\,\mathrm{K}$, F = noise figure expressed as algebraic ratio (F is normally expressed in dB terms where the noise figure is $10\log_{10}F$).

22.2.2.3 *Signal to noise plus interference ratio* The wanted signal, sometimes called the carrier signal, can be compared with the noise signal and any interference present in the satellite receiver. Fig. 22.6 shows the ratio of these elements

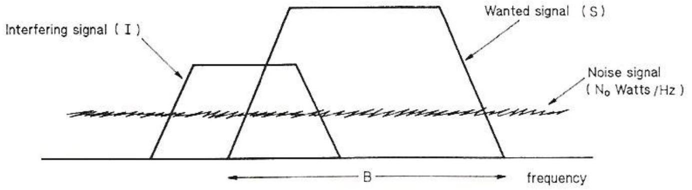

Fig. 22.6 *Signal to noise plus interference*

Wanted signal power = S watts in bandwidth B Hz
Unwanted interfering signal power = I watts
= I' watts in bandwidth B Hz
(given by overlap)
Unwanted noise power = $N = N_0 B$ in bandwidth B Hz
Ratio of wanted signal to unwanted components = $S/(N + I')$ as algebraic ratio
= $10\log_{10}(S/(N + I'))$ dB
where N_0 = power spectral density measured in watts/Hz

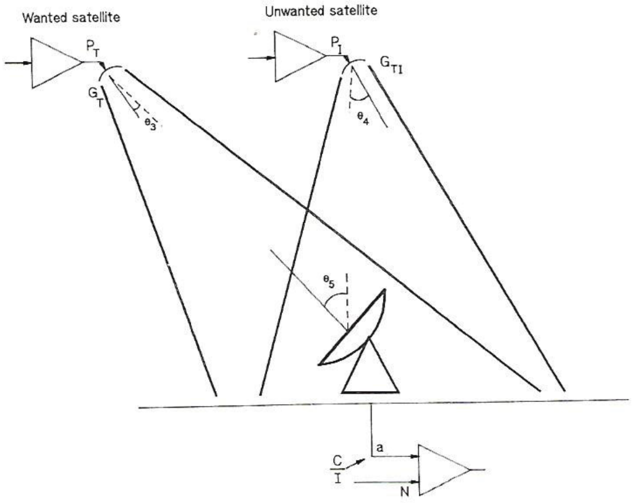

Fig. 22.7 *Composite view of downlink*

$$(C/I) = (P_R/P_I)$$
$$P_R = PFD_W \times A \times G_R(\theta) = (P_T G_T(\theta_3) \times A \times G_R(\theta)/4\pi d_w^2)$$
$$P_I = PFD_I \times A \times G_R(\theta_5) = (P_I G_{TI}(\theta_4) \times A \times G_R(\theta_5)/4\pi d_u^2)$$
d_w = range to wanted satellite from receive earth station
d_u = range to unwanted satellite from receive earth station
N = kT_sB, T_s = system noise temp
$$T = aT_{ant} + T_0\,(1 - a) + T_R$$
T_{ant} = antenna noise
a = feed line loss (fractional)
T_R = receiver noise temperature
$$C/(N + 1) = ((C/N)^{-1} + (C/I)^{-1})$$

expressed both as a linear ratio and also in the more normal logarithmic ratio in decibels.

22.2.3 *The downlink*

The downlink can be considered in exactly the same way as the uplink, in terms of wanted signal, interfering signals and noise power. Fig. 22.7 provides a composite view of the downlink. The satellite usually transmits to a wide geographic area: consequently, the satellite antenna cannot be pointing directly at all the earth stations to which it is transmitting. There is a resulting angular difference between the boresight of the satellite antenna and the direction of the receiving earth station given by θ_3 in Fig. 22.7. Each earth station receiving signals from the satellite will have its own angular offset from the satellite transmit boresight which could introduce losses of up to 5 dB from the maximum signal power available. The locus of points of equal loss is known as a contour which could be expressed as equivalent EIRP, received flux density at the ground or available carrier to noise ratio, C/N, for a standard receiver. Fig. 22.8 shows maximum downlink EIRP contours for Eutelsat 2 (reproduced by permission of Eutelsat). The satellite transponder could contain one or more signals at varying powers. The total receive power must be calculated to obtain the drive level of the non-linear satellite transponder. The total output power can then be deduced from the known transfer characteristic of the transponder system, and from this the wanted signal power can then be calculated.

The access planning for transponders takes account of the loading of the channel with signals. It may be appropriate, where a single signal is being transmitted by the transponder, to operate the transponder at saturation. In many circumstances it is common to operate a transponder below saturation, known as a 'backed off' mode of operation. This places the transponder in a more linear mode and is suitable for handling multiple signals without excessive intermodulation. Some basic observations may be made for this scenario.

Modulation methods which preserve a constant carrier signal envelope are ideal for multiple carrier operation because the operating point of the transponder can be accurately maintained. A corollary is that modulation methods with strong carrier amplitude variations (band-limited phase shift keying (PSK), for example) need special consideration because these variations can be transferred from one carrier to another within the same transponder owing to the amplitude-modulation/phase-modulation characteristics of the amplifier (AM/PM conversion).

Because the wanted signal is affected by the total signal (including noise) power in the transponder the output power of the wanted signal can depend on the other signals, especially so if the wanted signal is relatively weak. This can lead to a phenomenon known as small signal suppression [1], where small signals have a lower relative power than might be expected from a linear channel. This effect can be serious in a two-way VSAT system where the signals from the small VSAT earth station to the large hub station can be much smaller than the other signals in the satellite transponder.

An earth station receiver with a reasonable elevation angle, views a cold sky with minimal interference emanating from the earth via the receiving antenna sidelobes. In these circumstances it is worthwhile using a front-end amplifier with a low noise temperature as a significant benefit to the system performance can be realised. In current Ku-band VSAT systems earth station receiver noise figures of between 1 dB and 2 dB are common. The equivalent noise temperature range for an amplifier of this type is 75 K to 170 K. A further 50 K may be typically expected in the system due to sky noise, background atmospheric attenuation and earth radiation received via the antenna sidelobes.

22.2.4 *The overall link*

The signal to noise ratio for the overall link is calculated by combining the separate uplink and downlink contributions as shown in Fig. 22.9. A typical link budget for a 64 kbit/s link from a large hub to a 1·8 m VSAT receiver is given in Table 22.1. Each line in Table 22.1 is an imporant element of the link budget

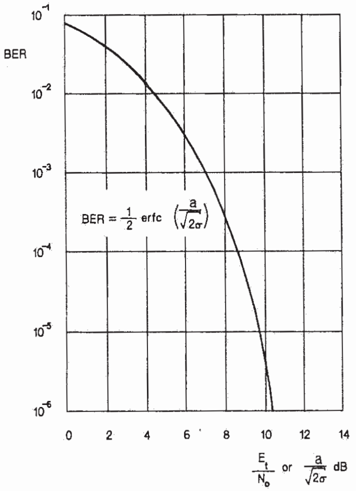

Fig. 22.11 *Binary PSK BER*

the errors caused by noise in the demodulator can be removed by means of error control. Error control can be accomplished either with error detection combined with a technique for requesting the retransmission of the bits or block in error or with a forward error correction (FEC) technique which enables the receiver to both detect and correct errors without needing to inform the transmitter. In a satellite link where the propagation delay makes the retransmission technique difficult and inefficient, the FEC method is preferred. This is especially the case in a VSAT system where there could be several hundreds of earth stations receiving the same signal.

Forward error correction relies on inserting extra data bits into the data channel in such a way that should some bits become corrupted, a receiver may both detect and correct for the induced errors.

The reduction in *BER* using this technique more than offsets the increase of information capacity and thus gives a net gain. An efficient algorithm for estimating the correct sequence by real-time processing in the decoder is known as the Viterbi algorithm, which provides a method for calculating the most likely transmitted sequence.

In the steady state for a particular type of code (known as rate 1/2, constraint length 7) a reduction of some 5 dB in E_b/N_0 may be achieved while maintaining a given bit error rate of say 1 error in 10^8 data bits. Chapters 11 to 14 of Reference 1 give a useful introduction to FEC.

22.2.7 *Availability*

Table 22.2 *Atmosphere attenuation as a function of elevation angle and time (Western Europe)*

Elevation angle (deg)	Attenuation (dB) at 12·1 GHz not exceeding a time of	
	99%	99·9%
5	6·8	14·0
10	4·7	9·7
15	3·2	7·4
20	2·5	6·4
25	2·1	5·8
30	1·8	5·3
35	1·7	5·1
40	1·6	4·9
45	1·5	4·8

In the frequency bands used by VSATs the signal strength can be reduced by the presence of water vapour and oxygen in the atmosphere. Furthermore, water droplets arising from heavy rain can be particularly damaging to the link as they can absorb, scatter, reflect and de-polarise the incident signal. Such effects manifest themselves on both the uplink and downlink as fades in signal strength. The higher frequency band of the two available for a particular uplink/downlink combination is almost always selected for the uplink because the higher band of the two will be more adversely affected by the atmosphere, and usually there is more power available on the ground than in space to mitigate its effects. Excess attenuation due to rainfall is given in Reference 2:

$$\alpha \;=\; a(f)R^{b(f)} \times \text{slant path through raincell}$$

where
α is in dB/km
$a(f)$ = frequency dependent multiplier
R = rainfall rate (mm/h) for a particular climatic zone
$b(f)$ = frequency dependent exponent

Taking account of rainfall rate and the percentage of the year (or the worst month) for which it occurs in a given geographic region, as well as the path length through the average rain cell, it is possible to arrive at the excess attenuation which can be expected for a particular link, which can be used directly in the link budget.

Obviously similar tables for other scenarios can be constructed from available data. The overall impact of the effect of the atmosphere and heavy rainfall within the atmosphere is to put an upper limit (less than 100%) on the percentage of time for which a satellite link can be expected to operate. The limit depends not only on the link conditions (geography, rainfall rate and so on) but the margin designed into the link. Such a margin is expensive to provide; over-sizing the earth station, retaining some satellite power to overcome fading, is costly and striving for very high availability usually suffers from a case of the law of diminishing returns. Attenuation values relating to availabilities of 99% and 99·9% are indicated in Table 22.2.

Table 22.3 *One way VSAT link. Case description: 512 kbit/s to 90 cm VSAT*

Uplink 14 GHz earth station	
EIRP	65·1 dBW
Uplink path loss	207·0 dB
Atmospheric loss (clear sky)	0·2 dB
Excess attenuation (rainfall)	0·0 dB
PFD for saturation	− 76·4 dBW/m^2
nput back off (IBO)	20·7 dB
PFD at satellite	− 97·1 dBW/m^2
Satellite G/T	1·0 dB/K
Uplink C/N_0	87·5 dBHz
Downlink 12·5 GHz	
Saturated satellite EIRP (− 2 dB contour)	43·0 dBW
Output back off (OBO)	14·9 dB
Satellite EIRP at − 2 dB contour	28·1 dBW
Downlink path loss	205·4 dB
Atmospheric loss (clear sky)	0·2 dB
Excess attenuation (rainfall)	4·0 dB
Receiver antenna gain	45·0 dB
Receiver G/T	19·5 dB/K
Downlink C/N_0	66·6 dBHz
Uplink and downlink	
Overall C/N_0	66·6 dBHz
Encoded information rate	57·1 dBHz
User information rate 1024 kbit/s	57·1 dBHz
C/N measured in encoded signal bandwidth	9·5 dB
mplementation margin	1·5 dB
E_t/N_0	5·0 dB
E_b/N_0	8·0 dB
Bit error rate	1 in 10^6

22.3 Link budgets for VSAT systems

22.3.1 *One-way systems*

One-way systems are broadcast systems which do not have a return path, at least not via the satellite. A typical link budget for a 512 kbit/s link using 2 phase PSK, and a satellite similar to those used by Eutelsat is given in Table 22.3.

22.3.2 *Two-way systems*

Two-way systems allow a return channel to be established to the hub station. The llocation strategy or access method for return channels is a subject in its own ight and has been considered elsewhere in this book. Table 22.4 illustrates the link budget which might apply to the outbound link given in Section 22.3.1 and a return link at 64 kbit/s.

Table 22.4 *Two way VSAT link. Case description: 512 kbit/s to 1·8 m VSAT outbound; 64 kbit/s to 9·0 m hub inbound*

Uplink 14 GHz		
	OUT	IN
Earth station	65·1	45·0 dBW
Uplink path loss	207·0	207·0 dB
Atmospheric loss (clear sky)	0·2	0·2 dB
Excess attenuation (rainfall)	0·0	4·0 dB
PFD for saturation	− 76·4	− 76·4 dBW/m^2
Input back off (IBO)	20·7	44·8 dB
PFD at satellite	− 97·1	− 121·2 dBW/m^2
Satellite G/T	1·0	1·0 dB/K
Uplink C/N_0	87·5	63·4 dBHz
Downlink 12·5 GHz		
Saturated satellite EIRP (− 2 dB contour)	43·0	43·0 dBW
Output back off (OBO)	14·9	39·0 dB
Satellite EIRP at − 2 dB contour	28·1	4·0 dBW
Downlink path loss	205·4	205·4 dB
Atmospheric loss (clear sky)	0·2	0·2 dB
Excess attenuation (rainfall)	4·0	0·0 dB
Receiver G/T	19·5	32·1 dB/K
Downlink C/N_0	66·0	61·0 dBHz
Uplink and downlink		
Overall C/N_0	6·6	57·6 dBHz
Encoded information rate	60·1	51·1 dBHz
User information rate	57·1	48·1 dB
C/N measured in encoded signal bandwidth	9·5	9·5 dB
Implementation margin	1·5	1·5 dB
E_t/N_0	5·0	5·0 dB
E_b/N_0	8·0	8·0 dB
Error rate	1 in 10^6	1 in 10^6

22.4 Conclusions

This chapter has attempted to explain the mechanics of performing a link budget. As mentioned in Section 22.1, the difference between the level of the wanted signal and that of the sum of noise and interference can be very small on a satellite link.

The chapter has not reviewed the trade-offs which can be made in the link budget but it will be apparent to readers that this is a natural extension of the material given here. Often a satellite link designer faces a *fait accompli* in terms of the satellite to be used and its parameters. In such cases, the trade-off is restricted to those parameters controlled by the earth stations or ground segment. These would be transmit power, receiver sensitivity, G/T, signal bandwidth and factors such as *BER* required, modulation and degree of forward error correction. Even these parameters may be constrained by the particular characteristics of a satellite service offering, e.g. the Intelsat Business Service (IBS) or the Eutelsat Satellite MultiServices (SMS). For VSAT systems, however, most satellite operators leave these parameters open for the user to specify.

A satellite link designer who has the freedom to specify the satellite could add a number of additional parameters to the trade-off. Such parameters would be satellite receive G/T, input power flux density to cause saturation in the transponder power amplifier, transponder bandwidth, as well as the satellite antenna gain and coverage area for the receive antenna and transmit antenna on the satellite.

Whatever the complexity of the trade-off, the link designer is always striving to maintain a positive margin for the particular channel in the most economic manner. In a VSAT system where the number of terminals can be large, the system economics favour a higher relative performance in the hub station and the satellite in order to allow simpler and lower performance terminals.

22.5 References

1 BHARGAVA, V.K. *et al.*: 'Digital communications by satellite' (Wiley Interscience, 1981)
2 CCIR Report 564–4