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CHAPTER 2

THE CHANNEL MODEL

The multi-access packet switching techniques introduced in the last chapter may be applied to wire communications as well as radio communications (both satellite and ground radio) [HAYE 72]. For example, a multi-drop line can be used in either the multi-access or broadcast mode; also, a loop system can be used as a multi-access broadcast system. However, as we mentioned before, we are interested in the use of radio packet communication for large populations of users over wide areas. With this in mind, we discuss below some advantages of radio communications over conventional wire communications. Since this research is motivated by the ongoing research and development of the ARPANET Satellite System [ABRA 72, BUTT 74], the use of a satellite channel will be assumed in all the numerical examples in this dissertation. In the next section, we shall examine some satellite channel characteristics and cost trends. Finally, in the last section, abstract models for the channel and channel users will be given.

2.1 Advantages of Satellite and Radio Packet Communications

Consider the use of packet communication in a computer-communication network environment to support large populations of (bursty) users over wide areas. We can identify the following advantages of satellite and ground radio channels over conventional wire communications:

(1) Elimination of complex topological design and routing problems

Topological design and routing problems are very complex in large networks [FRAN 72B, GERL 73]. Existing implementations suitable for a (say) 50 node network may become totally inappropriate for a 500 node network required to perform the same functions [FRAN 73]. On the other hand, ground radio and satellite channels used in the multi-access broadcast mode provide a completely connected network topology, since every user may access any other user covered by the broadcast.

(2) Wide geographical areas

Wire communications become expensive over long distances (e.g., transcontinental, transoceanic). Even on a local level, the communication cost for an interactive user on an alphanumeric console over distances of over 100 miles may easily exceed the cost of computation [ABRA 70]. On the other hand, satellite and radio communications are relatively distance-independent.

(3) Mobility of users

Since radio is a multi-access broadcast medium, it is possible for users to move around freely. This consideration will soon become important in the development of personal terminals in future telecommunication systems [MART 71, ROBE 72A].

(4) Large population of active and inactive users

In wire communications, the system overhead usually increases directly with the number of users (e.g., polling schemes). The maximum number of users is often bounded by some hardware limitation (e.g., the fan-in of a communications processor). In radio communication, since each user is merely represented by an ID number, the number of active users is bounded only by the channel capacity and there is no limitation to the number of inactive (but potentially active) users.

(5) Flexibility in system design

A radio packet communication system can become operational with two or three users. The size of the user population can be increased up to the channel capacity. More users can be accommodated by increasing the radio channel bandwidth. In other words, the communication system can be made bigger or smaller without major changes in the basic system design and operational schemes.

(6) Statistical load averaging

In wire communications, the use of adaptive routing techniques [FULT 72] in a store-and-forward packet switched network, for example, enables communication links to be better utilized than in a circuit switched network. However, at any instant, there may still be unused channel capacity in some parts while congestion exists in other parts of the network. The application of packet switching techniques to a single high-speed satellite or radio channel permits the total demand of all user input sources to be statistically averaged at the channel. Note also that each user transmits data at the (high-speed) channel rate.

(7) Multi-access broadcast capability

This capability in radio communication may be useful for certain multi-point to multi-point communication applications.

(8) Reliability

The norminal bit error rate of a satellite channel using forward error correction techniques is estimated to be $P_{be} = 1 \times 10^{-9}$ and better, compared to $P_{be} = 1 \times 10^{-5}$ for typical terrestrial links [CACC 74].

2.2 Satellite Channel Characteristics and Cost Trends

In addition to their multi-access broadcast capability, satellite channels have other characteristics which distinguish them from conventional communication channels and must be taken into consideration in any satellite communication system design.

The satellite

We quote the following information on the Anik satellites [GRAY 74]:

> "The satellites are about 6 feet in diameter and 11 feet high. At launch they weighed about 1250 lbs. and their orbiting weight is about 600 lbs. Each satellite's electronics system is powered normally by about 23,000 solar cells with sufficient on-board battery capability to provide power during eclipse periods when the satellite is in shadow....The life expectancy of the batteries is a minimum of seven years. Each spacecraft consists of an electronic communications system, literally a microwave receiving and transmitting station in space, and on-board propulsion systems to inject it into its synchronous orbit and correct for wobble or spin."

Round-trip delay (RTD)

A satellite in geosynchronous orbit is stationed approximately 36,000 kilometers above the equator. A signal transmitted by an earth station to the satellite transponder (at one frequency) is beamed back to earth (at another frequency) and can be received by all stations covered by the transponder beam. The round-trip propagation delay (RTD) is approximately a quarter of a second. Depending on a station's geographical location on earth, a difference of 15 milliseconds exists. Furthermore, the satellite drifts approximately 200 miles in range during the day, which produces an additional two milliseconds difference in RTD. Without loss of generality, we shall assume the maximum RTD value for all stations in our work.

Burst synchronization and channel slotting

Despite differences in the RTD values of earth stations, tests performed with an Experimental TDMA system over INTELSAT I (Early Bird) during August 1966, indicate that transmission bursts from different stations can be synchronized at the satellite transponder requiring guard times less than 200 nanoseconds [GABB 68]. In our case of a packet switched system, the satellite transponder time was assumed to be the global reference time (channel time) for all earth stations. The very small guard time required for burst (packet transmission) synchronization demonstrates the feasibility of channel slotting. Several slotting techniques have been examined by Rettberg [RETT 73A].

Automatic acknowledgment

To ensure data integrity in a communication channel, a very reliable method is the use of an error detecting block code in conjunction with positive acknowledgment of each message by its recipient. In a satellite channel, any signal relayed by the transponder is received by all earth stations including the sender(s). Channel collision (packet transmissions overlapping in time at the satellite) will be known to the sender as well as the addressed receiver of a collided packet. Thus, assuming that the satellite channel has a low (random noise) error rate, positive acknowledgments may not be necessary.

Data rates and small earth stations

An excellent introduction to the currently operational SPADE system (using an INTELSAT IV global-beam transponder) is available in [CACC 71]. We summarize here some relevant information on channel data rates and considerations for small earth station operation.

The SPADE system utilizes single-channel-per-voice-carrier transmissions. 7-bit PCM encoding is used for voice with the encoded output at 56 KBPS (8000 samples/sec.). The channel transmitted bit rate is 64 KBPS. Since 4-phase coherent PSK modulation is used, the transmitted symbol rate is 32,000 symbols per second using a bandwidth of 38 KHz. The SPADE channel unit can be operated in continuous or voice-activated mode depending on whether data or voice is transmitted.

The SPADE system with standard INTELSAT earth stations will achieve a maximum capacity of 800 voice channels (assuming voice activation). This capacity is simultaneously bandwidth and power limited. Hence, if smaller earth stations (i.e., stations with smaller antennas) are used, the capacity will be power limited and there will be a reduction in system capacity. One approach to minimize the power limited condition is to use error coding to provide a tradeoff of the excess available bandwidth to reduce the net per-channel required power.

Costs and other considerations

We emphasize again that we are primarily interested in systems involving fairly large populations of users. In such a packet switched satellite broadcast system, the cost of earth stations dominates the satellite bandwidth cost. A standard INTELSAT earth station with a 97-foot antenna costs between $3-3.5 million dollars! We note that if a node has enough traffic to justify the cost of a large satellite station, its traffic is probably high enough and consequently, sufficiently "smooth" to warrant its own satellite channel. On the other hand, an earth station for a domestic satellite system (such as Anik and future U. S. systems) can use a 30-foot antenna which costs from $150,000 upwards.* This figure is comparable to the costs of peripheral devices in present large computer installations. In a recent study [DUNN 74], even smaller earth stations

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*The above figures were quoted in an informal conversation with people in the General Electric Company Space Division.

(with antenna diameter between 10 to 15 feet) were suggested. The annual cost per station was estimated to be approximately $5,000 to $15,000.

We also note that there is an existing regulatory restriction on the use of an INTELSAT IV channel in the multi-access broadcast mode for several stations. Discussions are under way with various agencies to remove these regulatory barriers in either the INTELSAT system or one of the domestic systems [ABRA 73].

With domestic satellite systems, data rates are not limited to that of a single voice channel. For example, data rates ranging up to 60 MBPS will be available over the American Satellite Corporation system. Furthermore, specialized network configurations will be available to suit a user's customized requirements [CACC 74].

We quote the following remarks on projected satellite technology cost trends by Roberts [ROBE 74]:

> "Although terrestrial communications cost appears to limit the future price of computer-communication service, including packet-switching networks, the situation is rapidly changing with the introduction of domestic satellites....Applying the least-mean-square exponential fit to this data, the rate of technological improvement in the cost performance of satellites is found to be 40.7 percent per year, or a factor of ten every 6.7 years. This can only be treated as a crude estimate of the cost trend for satellite communication, but since it is quite in keeping with the general cost trend for electronics, it is a

quite credible growth rate....Satellites will play an important role in reducing the future cost of packet switching service...."

2.3 An Abstract Model

Consider packet switched satellite and radio systems using the slotted ALOHA random access technique. In order to evaluate the performance of these communication systems via model building and theoretical analysis or simulation, it is desirable to define abstract models which include only the salient properties and operational features. We define the following models for the multi-access broadcast channel and its users.

2.3.1 The Channel

We assume a bandwidth limited channel. Since users of this channel are in general geographically distributed, we assume a global reference time called channel time (see Section 1.3). Channel transmissions are assumed to be free of random noise errors so that a packet of data is received incorrectly if and only if it collided with another packet at the channel. We assume fixed size packets. Channel time is slotted such that all users synchronize their packet transmissions into channel slots. A channel slot length is exactly equal to the duration of a packet transmission. Any guard time required to separate packet transmissions in the channel is neglected. From now on, time will be expressed in channel slots. All rates will be normalized with respect to a channel time slot.

Channel Input

The channel input in a channel time slot is a random variable representing the total number of new packets transmitted by all users in that time slot. The channel input rate S is the average number of new packet transmissions per time slot (assuming stationary conditions).

Channel Traffic

The channel traffic in a channel time slot is a random variable representing the total number of packet transmissions (both new and previously collided packets) by all users in that time slot. The channel traffic rate G is the average number of packet transmissions per time slot (assuming stationary conditions).

Channel Throughput (Output)

The channel throughput (or output) in a channel slot is a random variable representing the number (0 or 1) of successful packet transmissions in that time slot. The channel throughput (output) rate S_{out} is the same as the probability of the channel traffic in a channel slot exactly equal to one (assuming stationary conditions). The maximum possible throughput rate of a channel is defined to be the channel capacity S_{max}.

Retransmission Delay (RD)

Whenever a packet has an unsuccessful transmission, it incurs a retransmission delay equal to the amount of time from the packet's collision at the channel until its subsequent retransmission attempt. Each retransmission delay can be regarded as the sum of a deterministic delay and a random delay. Random delays are needed since if packets which collided at the channel are retransmitted after the same deterministic delay, they will collide again for sure. (Of course, if there is only a small number of channel users, each user may use a separate deterministic RD and no random delay is necessary.)

For example, in a satellite system, the deterministic delay corresponds to a station's round-trip propagation delay (assumed to be the same for all earth stations). Random delays may be inserted independently by earth stations into the retransmission times of previously collided packets to minimize their probability of colliding again. In a terminal access radio communication network such as the ALOHA system, the retransmission delay corresponds to a terminal's positive acknowledgement time-out interval.

The retransmission delay is probably the most important design variable in the system. As we shall see, it determines the channel's throughput-delay performance, dynamic and stability behavior. As a result, it will be utilized for dynamic channel control. We shall assume the deterministic delay in RD to be R slots[*] and the random delay to be uniformly distributed over K slots. This will be referred to as uniform retransmission randomization.[**] Hence, RD has the probability density function shown in Fig. 2-1.

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[*] In a terminal access ground radio system, the round-trip propagation delay(corresponding to the deterministic delay) is in general a fraction of a time slot rather than equal to many slots.

[**] Another simple probability density function which can be utilized is the geometric distribution (geometric retransmission randomization). It turns out, as we show in Chapter 5 via simulations, that the channel performance is dependent primarily upon the average value of RD and quite insensitive to its exact distribution.

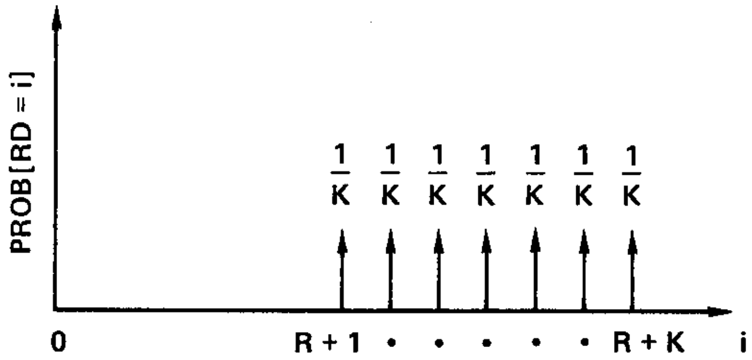

Figure 2-1. **Probability Density Function for a Retransmission Delay (RD).**

Packet Delay

The total delay a packet incurs is defined to be the amount of time from the packet's initial transmission until "successful transmission occurs." (Nodal processing delays will be neglected.) Conditioning on a successful packet transmission, let R' be the delay from the time the sender of the packet finishes transmitting the packet until successful transmission occurs. In a satellite channel, this amount of time is just one round-trip propagation delay (hence, $R' = R$). In a ground radio terminal access network, the meaning of R' is not so well defined; it can either be interpreted as the channel propagation time from the terminal to the central computer or as the delay until a positive acknowledgment is received from the central computer. Without loss of generality, we shall assume $R' = R$ throughout this dissertation. We show in Fig. 2-2 the total delay of a packet which has exactly one collision.

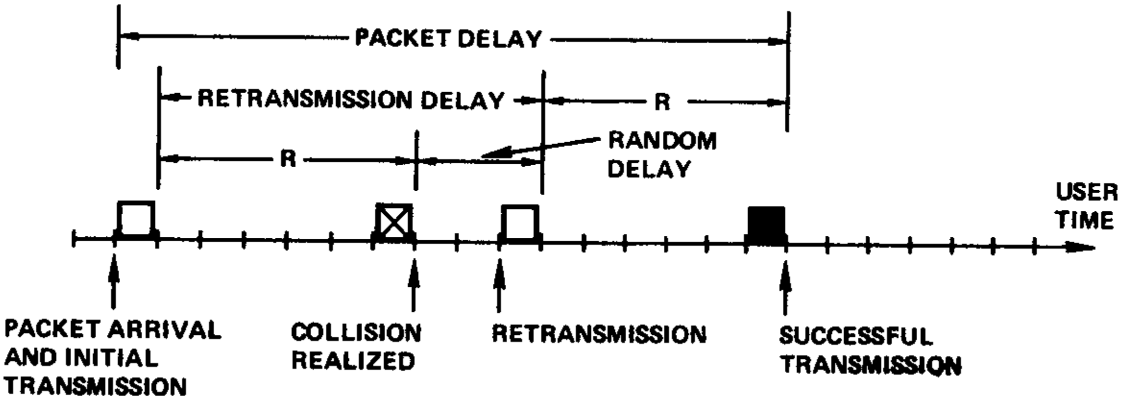

Figure 2-2. Delays Incurred by a Small User Packet

Numerical Constants

For purposes of numerical examples throughout this dissertation, we assume the following numerical constants based upon a satellite voice channel. A satellite channel is characterized by a very large channel propagation delay (compared to ground radio). These assumptions will be reflected in our numerical results and conclusions drawn from these results. However, the methodology and analytic tools developed in this dissertation will not be dependent upon these assumptions.

Unless stated otherwise, R will be taken to be 12 channel time slots and each time slot is 22.5 milliseconds long, giving 44.4 slots/second. The above figures are computed from the assumptions of a 50 KBPS satellite voice channel,* 1125 bits/packet (including

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*Actually, a SPADE voice channel has a transmitted bit rate of 64 KBPS in which case the assumption of 1440 bits/packet (probably including error correcting codes, guard time, etc.) will give rise to the same numerical constants.

overhead bits for address, parity check, etc.) and a round-trip propagation delay of 0.27 second.

Note that we have assumed a 50 KBPS channel because this happens to be a currently available satellite channel data rate. With the introduction of domestic satellite systems which will provide a wider range of data rates [CACC 74], a higher channel data rate may be considered (e.g., a 1.5 MBPS channel was included in the proposed Telenet packet switching network [TELE 73]). On the other hand, we may want to use a lower data rate for a ground radio system.

2.3.2 Channel Users

"Users" are defined to be entities which have the capability (e.g., antenna, transceiver, modem, logic, buffers, etc.) to transmit and receive packets of information over the channel as well as to accept input and deliver output to its "source." Examples of channel users may include a wide variety of devices such as hand-held personal terminals [ROBE 72A], teletype consoles, data concentrators and nodal switching units (see Fig. 1-1). The terminal control units of the ALOHA system [KUO 73] and the satellite IMPs of the ARPA network [BUTT 74] are some practical examples.

In this dissertation, we shall distinguish two abstract models of users: small users and large users.

Small users

A small user is one with buffer space for exactly one packet awaiting transmission. If and only if the buffer is empty, a packet arrival occurs with probability σ . (A packet arrival is said to occur only when a new packet is ready for transmission in the current time slot, i.e., after it has been entered by the source and processed by the user.) Thus, the user "think" time (i.e., the time between the successful transmission of a packet and the initial transmission of the next packet) is geometrically distributed with an average value of $\frac{1}{\sigma}$ slots. A small user can be in one of two states: blocked (buffer occupied) or thinking (buffer empty). An example of a small user in a ground radio system is a teletype console with keyboard lockout such that the human user cannot enter a new line of characters (a packet) before the previous packet is successfully transmitted.

A small user or terminal as characterized by our abstract model may or may not be "small" in a real system. If, instead of a 50 KBPS channel, we now consider a 2 MBPS channel with 20 kilobit packets and if the sum of the average user think time and packet delay is 2 seconds, the "small" user has a data rate of 10 KBPS!

Large users

Large users will be considered in Chapter 3 only. A large user is defined to be one with a large buffer capacity such that new packets generated by the source will never be blocked due to lack of buffer space. Unless stated otherwise, the stream of packet arrivals to a large user is assumed to be a Poisson process.

In a large user, several packets may be awaiting transmission at the same time. We assume that all new arrivals are scheduled for transmission immediately. A scheduling conflict occurs when more than one packet is scheduled to transmit in the current slot. The highest priority packet will transmit while the other packets are rescheduled independently (see below). Any priority rule will give rise to the same average packet delay (conservation law! [KLEI 64]). The following priority rule will be assumed for mathematical convenience.

Priority rule

We list in decreasing order of priority (depending on a packet's most recent history) for transmitting in the current slot:

(1) packets randomized into the current slot after a collision at the channel

(2) packets randomized into the current slot after a scheduling conflict

(3) new arrivals in the current slot

The first-come-first-served rule is used for packets in the same priority group. Ties are broken by random selection.

Rescheduling delay

A packet which is blocked due to a scheduling conflict is rescheduled in one of the next L slots, each such slot being chosen with probability $\frac{1}{L}$ (uniform rescheduling randomization). The average rescheduling delay is thus $(L + 1)/2$. We note that the uniform rescheduling randomization serves the same purpose as the uniform retransmission randomization. Our numerical results in this dissertation will be obtained using the same value for both L and K. We show below in Fig. 2-3 the total delay of a large user packet which has one channel collision and is rescheduled three times.

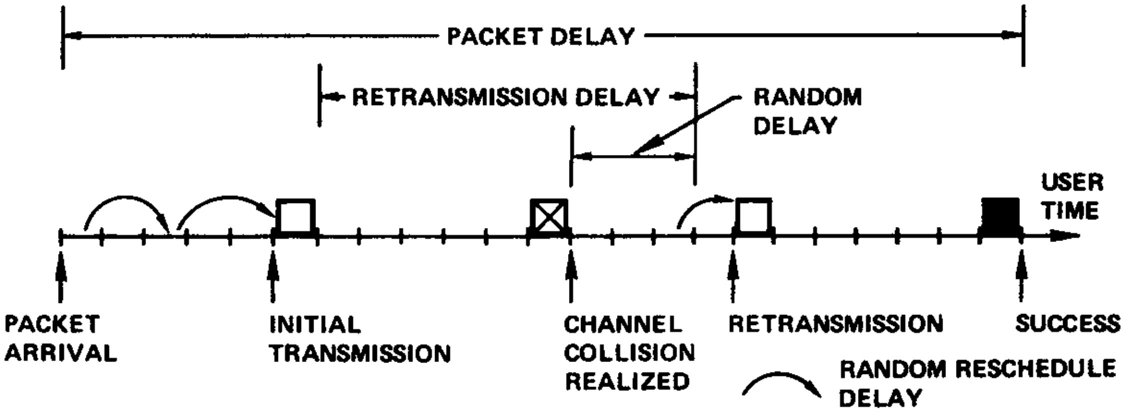

Figure 2-3. Delays Incurred by a Large User Packet.