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PACSIM:
Using Simulation in Designing a Communications Satellite

by

Russell Gottfried

September, 1992

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The Naval Postgraduate School is developing a small, experimental, low-orbit packet radio satellite for launch in 1995. It is the first for use by the amateur radio community to implement spread spectrum communications. To aid in designing the spacecraft's communications network, we have develped a packet-level, reusable, object-oriented simulation model, PACSIM, which:

-- fully emulates the activity of users in the network;
-- has the ability to provide information on these measures in several thousan different scenarios.

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Using Simulation in Designing a Communications Satellite

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ABSTRACT

The Naval Postgraduate School is developing a small, experimental, low-orbit packet radio satellite for launch in 1995. It is the first for use by the amateur radio community to implement spread spectrum communications. To aid in designing the spacecraft's communications network, we have developed an object-oriented, reusable, high resolution simulation model, PACSIM, which:

- fully emulates the activity of users in the network;
- has the ability to provide information on these measures in several thousand different scenarios.

We describe this satellite-user network and elucidate the strong interdependence of design factors. Simulation results are presented. Also, we critique the use of simulation as a decision aid for assessing the effect of design decisions such as data transfer rate, spacecraft memory allocation for store-forward and capture protocol among other factors.

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I. NETWORK DESCRIPTION

A. BACKGROUND

The Petite Amateur Navy Satellite (PANSAT) is a small, low-orbit spread spectrum communications satellite scheduled for launch in 1995. It is designed for use by amateur radio operators. The spacecraft's orbit is expected to be at an altitude between 450-800 kilometers, at an inclination of 93.5° and a maximum slant range of approximately 2000 km. Users on the ground will be provided with a view of the satellite between four and ten minutes in duration. The size of the user base is currently unknown. However, the fields of spread spectrum, packet radio and satellite communications are widely used among amateur radio operators and attention to this program has grown.

1. Summary of session

The spacecraft will normally be in receive mode until it arrives in the view of a user's ground station and acquires the pseudo-noise coded signal from it. This sequence is a 128 bit stream and is transmitted by the subscriber until acquisition is achieved. The receiver assesses if it is following the sequence in synchronization with the transmitted signal. If not, it "slides" and "looks" again to determine whether it matches.

The communications payload of PANSAT is designed for a central frequency of 437.25 Mhz (960 Khz bandwidth). Uplink and downlink will be done within this bandwidth, with information relayed in bit packets. These packets are stored and retrieved in the spacecraft control unit's (SCU) on-board processor. Data storage and retrieval are accomplished using the operators' callsigns as references. PANSAT is intended to have its own address for use by the ground control station. Commands for the satellite are envisioned only to request experiment data and provide telemetry and performance information to the control station.

B. HIGH-LEVEL DESCRIPTION

1. General

The system consists of uncoordinated users who contend for access to a single channel. As shown in Figure 1 these users, also called subscribers, are located at ground sites not necessarily covered by a single orbit of the spacecraft. Due to the periodicity of PANSAT's path, it will not be in a user's view during each orbit.

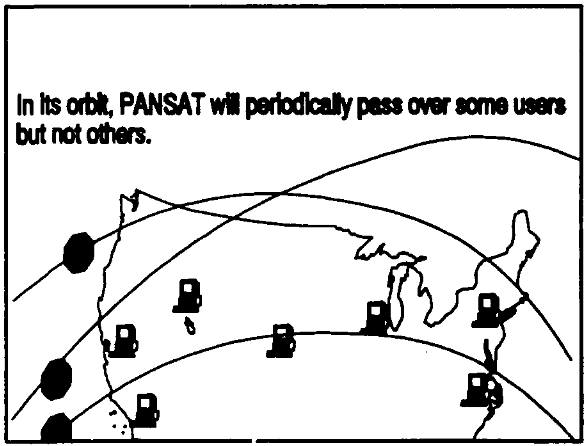


Figure 1 *User access is a function of PANSAT's orbit.*

As the spacecraft comes over the horizon, a subscriber will attempt communications windows due to the low orbit of the satellite. Users access the channel by locking-up, or synchronizing, with the satellite. When two or more subscribers simultaneously attempt to initiate a session with the spacecraft, there are two possible results: either there is a collision or one will capture the server. A collision results in unsuccessful attempts for both users and requires later scheduled synchronization transmission. Tagged to the end of the synchronization is a preamble identifying the user, followed by the data packet along with its routing instructions, called the header.

If the message arrives at the spacecraft, the SCU

- routes the message for the appropriate addressees ;
- forms a queue of messages stored for the addressee ;
- transmits, or downloads, the stored traffic after synchronizing with the recipient, .

The caller then requests a disconnect and the satellite returns to a ready state, awaiting a new attempt for synchronization.

2. Channel Access

As mentioned above, users are not coordinated by a master clock nor can they sense whether a channel is being accessed or in use. The only information provided is the starting time of the communications window. This window of time reflects the interval during which the spacecraft is in the view of a user. In other words, the low-earth orbit of the view of a user. In other words, the low-earth orbit of the satellite provides a limited horizon on the ground. As this horizon, or footprint, traverses the ground, it covers the position occupied by a user. The period from initial coverage in the footprint to termination is the communications window.

Due to the absence of overall network control, the occurrence of transmission delay and an array of other arbitrary factors, it is assumed that no two callers' synchronizing signals are initiated at the exact same time. However, a characteristic of this transmission-driven protocol is that the synchronization sequence -- the elements of which are called chips -- is sent iteratively until the SCU's receiver achieves a lock and is captured.

If another attempt occurs such that its sequence is within a phase difference not exceeding the duration of a single chip, the SCU's receiver will be unable to distinguish between the signals and a collision results (Pursely, 1987, p. 118). A collision causes a failed attempt and another is made after a delay. If there is sufficient offset between two synchronization streams, then one will be successful, depending upon which bit stream is more proximal to the pattern expected at the spacecraft's receiver. A caller is made aware of an unsuccessful synchronization if during the time following the signal, no acknowledgement or subsequent message transmission is received from the satellite.

3. Packet Flow

The message generated by the user is subject to bit error, associated with the bit error rate identified in the spacecraft designers' link budget analysis. Occurrences of bit error, which are not independent events, may signify the loss or partial destruction of a packet. This is unknown to the engaged user. After accessing the channel, the user will accept a synchronization signal from the spacecraft communicating its acknowledgement of receipt of the user's packet and transmitting traffic addressed to the engaged user. If this is not detected by the user, a new transmission is generated in order to ensure receipt of the apparently lost traffic.

After the *subscriber transmits* an identification preamble, the spacecraft attempts synchronization. There is no contention for the current user's receiver and the sequence is followed by all traffic stored by the spacecraft control unit. Finally, the subscriber follows with an acknowledgment of receipt of the down-linked traffic and a request for disconnect. The SCU recognizes this and returns to a ready state. If the disconnect request is not received, then the SCU times out and retransmits the stored traffic. If final acknowledgment is still not received after a specified period and a stipulated number of retries, the spacecraft returns to a ready state.

4. Packet Storage and Forwarding

This aspect of message transfer occurs in the spacecraft. Upon arrival of a packet at the spacecraft, it is stored until the SCU is accessed by the addressee. Several factors bear much relevance:

- The delay in message forwarding from originator to addressee may range from seconds to days.
- Message size is of arbitrary length although the maximum length may be fixed (Brachman, 1988, p. 20).
- Packet storage capacity of the SCU is finite.
- Messages may be addressed to other individual subscribers, multiple users or all users.

Due to storage constraints, as the number of users increases, storage may become scarce. For example, if a packet is addressed to a group of users, it might be beneficial to store single copies of messages with more explicit routing instructions rather than a single copy for each.

C. NETWORK DESIGN DETAILS

This network has associated with it several design issues. Channel access is influenced by the number of users with the spacecraft in view concurrently attempting to access the net, the possibility of collision, the distribution of the duration of the synchronizing procedure as well as the occurrence of bit error and resulting retransmissions of data. Data transfer is influenced by packet length, the occurrence of bit error, propagation delay, the extent of error detection and correction as well as the speed of the SCU's processor. The store-and-forward problem is affected by the number of subscribers, packet routing instructions, bit packet length, and storage capacity. An enumeration of specific design questions and their associated measures of effectiveness is provided in the next chapter.

1. Channel Access

Given the absence of coordination among users, it is reasonable to assume that each will independently initiate synchronization attempts in accordance with some arrival process. An outline of the channel access process is shown in Figure 2.

For a situation in which a geostationary satellite is involved, users have continual access to the spacecraft. In this case, the model may achieve an equilibrium in which attempts to establish communications may be well represented by a carefully selected arrival process. However, because many users are aware of the time at which the spacecraft comes into view, the first attempts by each may be governed by a different timing algorithm

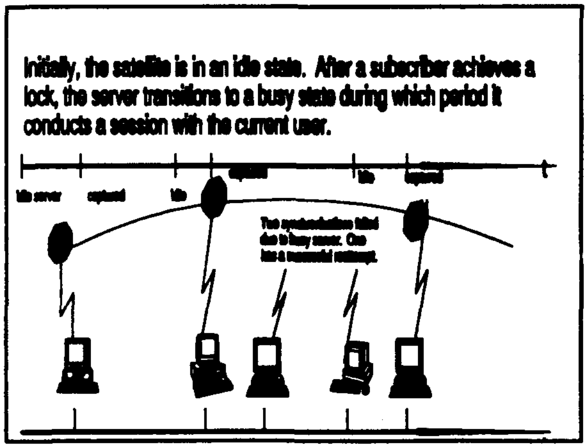


Figure 2 *Contention for channel access.*

than subsequent bids, depending on the occurrence of a success. After "arriving," the synchronization process takes place.

When in the ready state, the SCU's receiver is continuously scanning the spreading sequence for the transmission of a synchronization signal. This is a 128 bit sequence which is transmitted until an attempt is sensed. At this point, the receiver compares the received pseudo-noise sequence with the expected progression as seen through the current sequence. If there is no match, then the receiver will shift its scanning of the band by a predetermined duration of time and compare again. This is continued iteratively until the receiver attains a lock. The characteristics of the clocking sequence of the pseudo-noise generator dictate the specific quantity of time elapsed during this process.

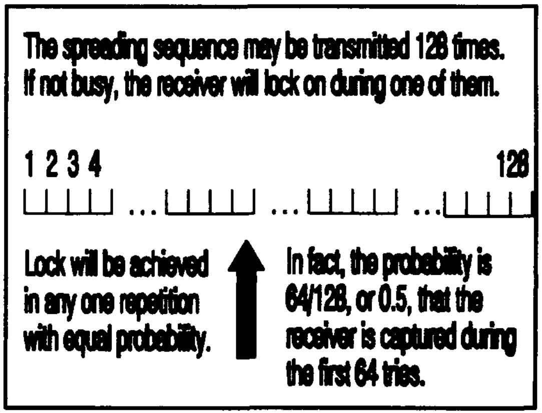


Figure 3 *Illustration of the synchronization process.*

Between initiation of the synchronizing process and the capture of the channel, there is a non-zero probability of collision. The occurrence of a collision is a function of the distribution of subscribers initiating simultaneous attempts to access the SCU and the distribution of the number of repetitions of the synchronizing sequence which must be completed to achieve lock (Woerner, 1991, p. 128). Regardless of the collision event, multiple users attempting to access the net increases the effective noise in the RF environment. Increased noise causes a deterioration in the link margin and may give rise to increased probability of bit error in session transmissions.

2. Data Transfer

This feature of the network is affected by decisions regarding packet size, error detection and correction, acknowledging message receipt and the establishment of a half- or full-duplex channel.

Decisions concerning packet length have ramifications throughout the operation of the network. Regarding packet transmissions from a subscriber or from the spacecraft, not only do longer packets require a greater amount of time for transmission but they have a greater probability of experiencing bit error. Furthermore, the length of packets impacts the SCU storage capacity. Options include establishing fixed message lengths, maximum message lengths with variable length packets, or leaving message size unconstrained. Each of these considerations may be viewed in light of the bit error rate. Because the occurrence of bit error is not independent among individual bits, the greater the size of the bit packet, the higher the probability of the packet incurring bit error.

The worst-case scenario is that any incident of bit error results in the loss of a packet. However, unless some error detection is instituted, the absence of error in the message header is satisfactory for a message to be received at the destination. This is insufficient for reliable networks (Tanenbaum, 1988, p. 202). To institute negative acknowledgements requires retransmissions and lengthens the span of the session. However, introduction of error correction such as Hamming codes lengthens the packet to more than three times its original length (Tanenbaum, 1988, p. 208), and would also be very likely to have a significant impact on the duration of a session.

The final aspect to be discussed in analyzing the network data transfer is the implementation of a full-duplex as opposed to a half-duplex channel. The two scenarios are depicted in Figures 4 and 5. Regardless which channel type, subscribers independently attempt to synchronize with the spacecraft's receiver. Only if successful will a user be able to conduct a session with the SCU. The session differs conditioned on whether or not the channel is full- or half-duplex.

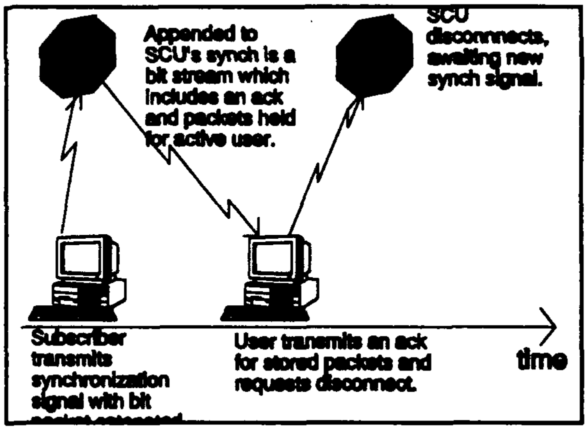


Figure 4 *Full duplex communications flow between SCU and subscriber.*

In full-duplex, the subscriber's receiver must be in lock with the spacecraft's transmitter in order to be able to conduct a session. Once both caller and SCU are in synchronization, communicated by the user as a connection request and by the spacecraft as an acknowledgement, data exchange occurs. While receiving, acknowledging and storing the data transmitted by the active user, the spacecraft retrieves and forwards messages addressed to the active user. If the packets are error-free and successfully received at either end, then acknowledgements are dispatched and a disconnect occurs. However, if errors are detected then negative acknowledgements are sent and packets are retransmitted. Finally, if no acknowledgements are received after a time-out, then the packet is retransmitted.

The half-duplex session is more involved because after each transmission, communications are stopped and the other site must synchronize in order to transmit acknowledgments or data. Specifically, after capturing the SCU and completing the synchronization signal, the active user transmits the

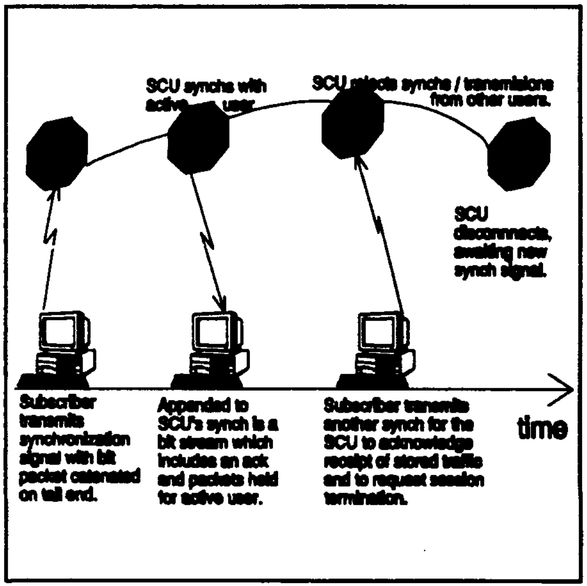


Figure 5 *Half duplex communications flow between SCU and subscriber.*

data packet. Upon broadcasting the packets, the user ceases transmission and waits a period of time commensurate with the transmission duration and turn-around time. The SCU is expected to attempt synchronization and transmit an acknowledgement and any mail appropriately addressed. In the case of error-free receipt of the stored traffic, the user again synchronizes with the spacecraft's receiver in order to acknowledge the mail and request disconnect. Once more, the detection of bit error or occurrence of time-out will necessitate retransmission; however, due to the nature of half-duplex communications, retransmissions must be preceded by a synchronization stream.

During the course of these synchronization attempts with the SCU's receiver, the spacecraft will need to prevent intervening callers' attempts to send traffic while awaiting the active user's synchronization to resume the session.

3. Store-Forward

The receipt of packets by the SCU initiates the process of store-and-forward. After the message arrives, it is routed to storage according to the callsign of the addressee. Packets currently in storage and addressed to the current user are retrieved and transmitted. This process is shown in Figure 6. Issues of interest include message processing time, the storage capacity constraint and network reliability.

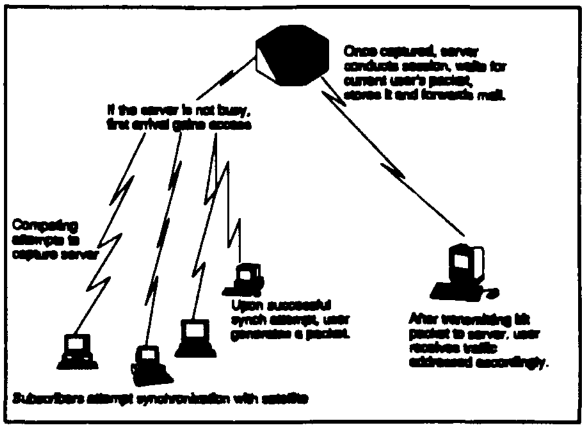


Figure 6 *Overview of the store-and-forward process*

The network will use a source routing procedure. There are three general cases involving packet routing: single addressee, multiple addressees or messages addressed to all users. For single-subscriber addressed packets, once a message has been delivered, processor storage space is made available. For messages addressed to multiple users, a separate listing must be maintained to mark deliveries in accordance with packet headers. These messages may be held for long periods of time.

Regarding the storage constraint, as available memory dwindles, an auto-dump capability ought to be implemented, freeing space for new messages. For effective storage management, packets need to be prioritized in some way, duration of time in storage for example, so that some proportion of the total number of messages are deleted. This brings to light the matter of network accountability in an acknowledged connectionless service. Once the SCU accepts a message, it becomes responsible for delivery of that message. Packets which are dumped due to storage limitations restricts the level of network reliability.

Although straightforward, this communications network has very densely interrelated operating charcteristics. A challenge in modeling and simulating this system is to identify design considerations which may limit operation or which may be altered to enable improved performance. An enumeration of the items of interest and a discussion of the model follows.

II. ENUMERATION OF DESIGN ISSUES

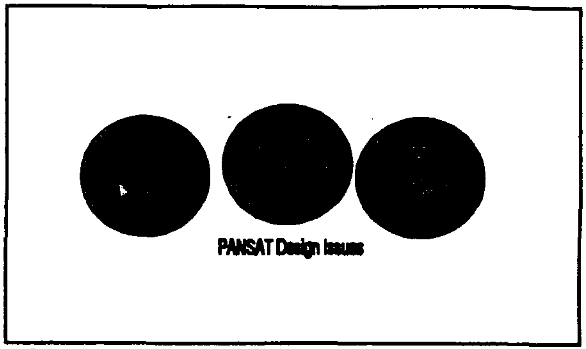


Figure 7 *PANSAT Network Design Issues*

In attempting to create a network which performs well across the areas of channel access, communications flow and packet handling, several questions of interest have emerged. Designers of PANSAT expect that decisions in building the system show significant improvement of performance measures across a broad array of scenarios. Particularly, decision makers seek enhancement in channel access, decrease in session duration and firm assessment of SCU memory requirements. These concerns are enumerated by the following issues and partial listing of applicable design considerations:

- probability of <u>channel access</u> as a function of maximum synchronization sequence length, data transfer rate, the number and distribution of waiting times before retransmission attempts;
- <u>session duration</u> as a function of maximum synchronization sequence length, data transfer rate and maximum (or fixed) packet length;
- SCU <u>storage requirements</u> as a function of maximum packet length and user population density.

As may be determined from this list, there is a strong interdependence among the design issues and operational considerations. In fact, the three areas of activity, access, flow and store-forward, affect one another. Channel access can be expected to be facilitated by shorter sessions. In turn, higher rates of channel access may cut down on variability of the maximum amount of SCU memory in use. To establish the model as a credible decision aid, these issues must be formally defined, analyzed and simulated. This chapter lays out decision makers' questions of interest and measures used in making the determination.

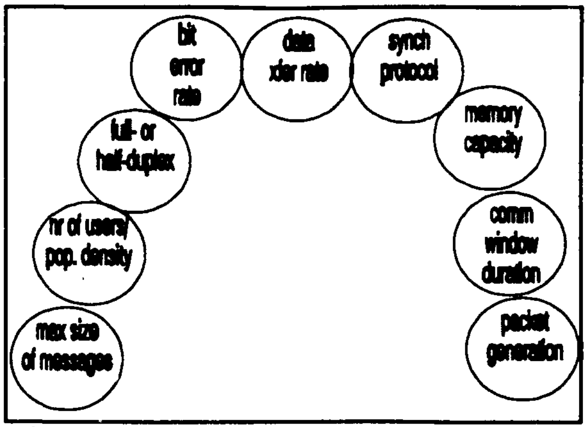


Figure 8 *Influential network design factors*

A. CHANNEL ACCESS

For PANSAT's network to be successful, users must be furnished with reasonable opportunity to capture the server. This may be measured by the proportion of users obtaining a lock during the first attempt, and during subsequent retries. Capture is affected by

- maximum number of repetitions of the synchronization sequence;
- data transfer rate;
- discipline governing retries.

The channel access problem may be interpreted as follows. Given a number of callers who simultaneously have the

The channel access problem may be interpreted as follows. Given a number of callers who simultaneously have the satellite in view, how many attempts, on average, are required to be able to conduct successfully a session with the spacecraft. Alternately, what proportion of users are successful on the first attempt and then on each subsequent attempt.

Underlying the whole channel access question is the concern that the system operator, the Naval Postgraduate School, be assured access to the server. Network design decisions may be implemented to enhance that prospect, but may be found inadequate under the best circumstances. In this case, other means should be developed for activation.

1. Synchronization Discipline

There is no feedback marking the achievement of lock by any transmitter's spreading code. The user receives no indication of success in capturing the server's receiver until at least after transmitting the identification preamble following the synchronizing sequence. Given an idle server, capture after the full 128 iterations of the spreading code is almost assured; as will be shown, the SCU is captured, on average, in 64 iterations. A lower cap not only reduces the excess time spent transmitting the spreading sequence, but in the event of a busy server, also allows for fewer delays in initiating subsequent retries.

2. Bit Rate

It is obvious that an increase in data transfer rate will most likely shorten the duration of a session; doubling the bit rate may halve session lengths. Designers' interest in this relationship between bit rate and channel access reflects the notion that shortening the duration of a session will increase users' access to the server. Other factors are not specifically under the engineers' control. These include the effect of the number of collocated users concurrently desiring access or the ramifications of increased bit error rate. As determined by the engineers' communications network link analysis, two feasible data transfer rates are 1200 and 2400 bits per second (bps). However, either the expected bit error rate may increase or the link margin may decrease for the higher data transmission rate (Morgan, 1989, p. 471). The question is whether the higher bit rate significantly improves the likelihood of a user accessing the server despite increased probability of bit error.

3. Retransmission Regimen

After transmitting the synchronization signal, identification preamble and bit packet, the subscriber is in either of two states. The user

- is engaged in a session with the spacecraft control unit if the server is idle;
- will need to retransmit the entire sequence if the server is busy.

In the event of retransmission, what should govern the amount of time to wait and the number of retries? From a network management perspective, the goal is to allow for the largest number of users to access the channel. This might encourage continual retransmissions until success is obtained. On the other hand, it is important to preserve some circuit discipline and minimize noise contributed by other users' transmissions for access to the channel. Resolution of this question will be implemented in a protocol allowing for the highest access rate coupled with the minimum number of attempts.

B. SESSION DURATION

In the communications flow paradigm, the spacecraft spends a significant proportion of time in a captured state. This is directly analogous to the busy server in a queueing system. Of interest is how the duration of these busy periods vary with the implementation of a full- or half-duplex channel, the data transmission rate, packet size, and bit error rate.

The duration of user sessions directly impacts the number of users who may actually gain access to the net in a finite period of time. So, to a large extent the design parameters and questions enumerated for channel access also apply to the session duration problem. First and foremost is the decision to implement a full- or half-duplex net. In this context, engineers may then determine the direction to pursue regarding the synchronization process, bit rate and maximum packet length.

1. Duplex vs. Half-Duplex

Nominally, the sequence of events required to ensure a successfully completed half-duplex session is longer and more complicated than that for the same session on a full-duplex circuit. The key concept is that all events in a half-duplex channel are serially arranged. In a full-duplex net, some of these events occur simultaneously. Recall, however, that the transmitted power is spread over half of the bandwidth in a full-duplex channel, because the net allows for simultaneous communications in both directions. Contending users' transmissions may contribute greater noise to the environment than in a *half*-duplex net. Sessions may be conducted over a circuit subject to the higher bit error rate resulting from the potentially noisier environment. A question of interest is whether the implementation of a full-duplex network results in significantly shorter sessions regardless of the bit error rate.

2. Packet Length

Shorter packet lengths mean shorter sessions. Not only because the subscriber uplinks shorter messages, but all those stored for download are also shorter. Furthermore, shorter packets have a smaller probability of experiencing bit error than longer packets. This further eliminates the occurrence of sessions extended due to retransmitting lost data.

It is preferred to limit communications as little as possible, however. Placing too restrictive a constraint on packet length may impede a subscriber's utilization of the network. The engineers' objective is to allow for as high an upper bound on packet size as feasible while preserving the goal of minimizing session duration.

3. Spreading sequence and data transfer rates

Pertaining to session duration, these two design issues have a similar impact as discussed regarding channel access. Engineers are interested in determining how much the synchronization sequence must be shortened to significantly decrease the duration of a session. Again, it is somewhat apparent that doubling the data transfer rate will shorten a typical session. But, is this enough to overcome any loss in the margin of the link analysis? PANSAT's designers want to know if doubling the data rate results in significantly shorter sessions despite a higher bit error rate.

C. SCU STORAGE REQUIREMENTS

The driving force behind PANSAT is its utility as an experimental platform. Engineers are concentrating on designing the spacecraft to establish the operability of this low-orbit communications network. Still, the storage of packets poses a design problem. SCU memory used for packet storage varies with the number of users and packet size.

It is important to consider that over the course of its lifetime, interest in PANSAT may grow to the extent that design limits on storage capacity may be flexed to the limit. For example, the satellite's software designers claim that the SCU's operating system will be altered significantly if the storage size exceed 500 kilobytes of data. Is this much space required or will this level be exceeded? Design matters here must show robustness over a spectrum of resolution, introducing greater variability in storage levels.

To determine what storage capacity to design for the spacecraft control unit's memory, engineers are interested not only in a specific measure such as the average or maximum level of storage used. Designing based upon an average does not reflect the range over which the running total walks. As packets are received and are downloaded, observing fluctuations in storage level will generate a mean value; the estimator gives no information on the proportion of observations which exceed this point, or the frequency with which they do so. Similarly, measuring the high-water mark, the maximum level reached by the SCU's memory, provides no description regarding how often this occurs. In any case, the measure of interest is the amount of memory in use at the time of the next packet's receipt.

Decision makers want to know the distribution of memory used. From a design standpoint, the principle factors in this density are the number of users allowed to participate in the net and determining the maximum packet length. These two parameters may be readily used in an analytical solution. However, the frequency with which SCU storage varies over a range of values is very much scenario dependent. For a given number of subscribers and packet size selection, designers want the SCU to accommodate a reasonable proportion of the total number of messages over a number of diverse scenarios.

D. HOW A MODEL HELPS

In summary, a partial listing of influential design parameters follows:

- data transmission rate ;
- user population and population density distribution ;
- bit error rate ;
- minimum, maximum and fixed packet length ;
- synchronization attempt discipline ;
- SCU storage capacity ;
- full- or half-duplex communications.

Complications arise in trying to assess the interdependency of these design factors and their effect on the network. With this level of complexity, as depicted in Figure 9, what kind of numbers may be generated by a model? How will the observed simulated activity differ from specified probability models simulated activity differ from specified probability models applied to each question of interest?

For the model's results to be credible, a high degree of resolution must be incorporated in the representation of network communications. In analyzing the system and creating the objects which will emulate the flow of activity, certain characteristics emerge which suggest a common-sense approach or analytic probability model both of which may resolve a design issue more quickly and as effectively as a simulation run. The model's three levels, common sense, analytic and simulation, complement each other.

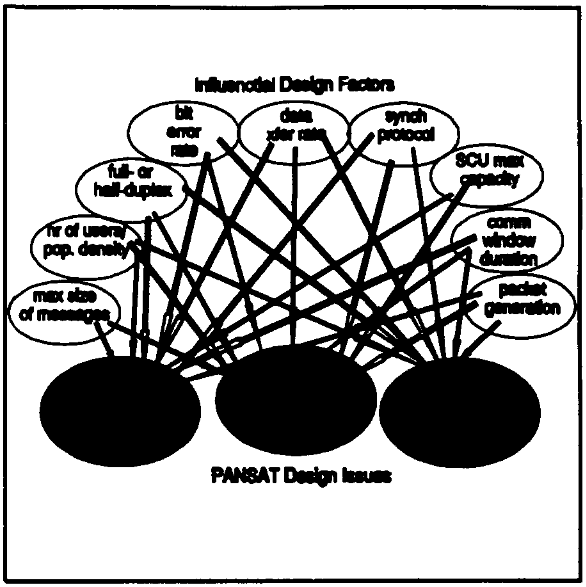


Figure 9 *First (solid arcs) and second order(hollow) effects are densely related.*

For each measure of performance, obtaining expected values may be consistent between the probability models and the simulation. However, as a descriptor of performance, the average value falls far short. In essence, the merit behind thorough representation of network activity is the insight into system variability afforded the decision maker. This is where the anticipated divergence is between computer runs and paper or blackboard results. In any event, the working model major design decisions which may be further substantiated by a high-resolution simulation.

III. INTRODUCTION TO THE MODEL

This communications network may be modeled with a great deal of fidelity as a complicated stochastic model implemented in a simulation. The simulation is written in reusable, object-oriented code so that other design issues may be explored experimentally and so that new studies can be pursued as scenarios are developed by PANSAT's sponsors. Accompanying probability models are incorporated to validate the simulation.

The simulation contains user objects which act independently and the SCU object which stores and retrieves packets. The model also explicitly emulates the synchronization process and full conduct of a user-SCU session both in full- and half-duplex. After a brief outline of the principal objects in the model, a more detailed discussion of the model design follows.

A. MODEL OBJECTS

1. Users

The network is activated by users attempting to capture the satellite. They are uniquely identified by the following attributes:

- callsign, for addressing purposes ;
- synchronization attempt process, dictating the interattempt waiting period and number of retries ;

- location, either isolated or collocated in a population center.

The model accounts for these essential characteristics as well as the user's network activities by creating each user as an autonomous object. In this regard, operations of these users are encapsulated in a series of object methods which define their impact on the network, summarized in Figure 10.

Channel access, packet flow and message handling, are significantly affected by subscriber actions. Successful synchronization causes the SCU to become busy and conduct a session. Subscribers generate messages. Message size and frequency of generation affect both the duration of the session as well as storage by the SCU. Transmission of the packet requires the passage of time. This influences the session duration and in turn affects other subscribers' ability to access the net. A user's traffic receipt process has several ramifications across the network. Successful receipt of packets from the spacecraft completes the end-to-end packet flow and also allows

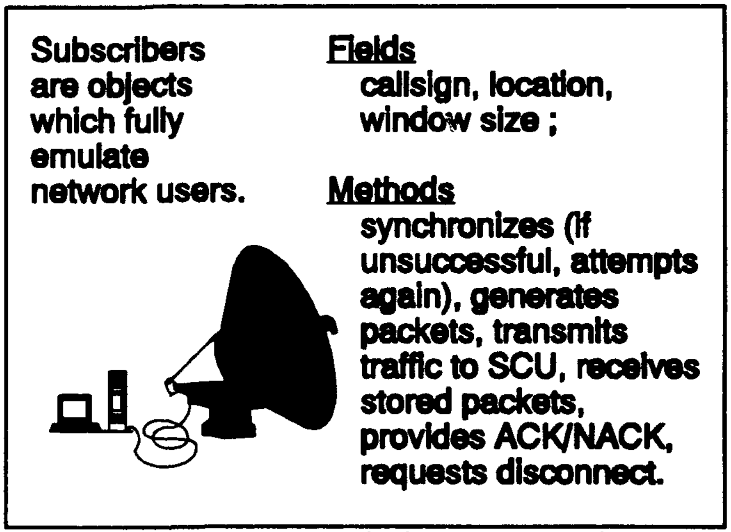


Figure 10 *User activity affecting the network's state includes generating packets and attempting net access.*

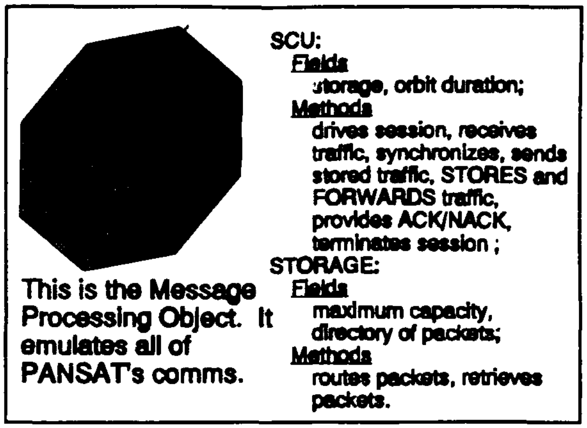
the SCU to free storage space for future use. If packet receipt is obstructed by bit error, session durations become extended and endpoint-to-endpoint communications flow may be disrupted. Finally, the procedures of acknowledging and requesting disconnect prompt the end of a session and close the loop on packet flow. These essential activities were selected for inclusion in the model because they

- fully describe the network activity of the users;
- affect the state of the network in all areas, channel access, communications flow and packet handling;
- preserve a high level of resolution in the model by reflecting actual network operation.

2. Spacecraft Control Unit

The SCU object contains two sub-objects, the user interface and message storage area. These two entities have attributes and procedures which allow for fully analyzing the SCU and its role in the network. Figure 11 illustrates the relevant aspects of both the processor and storage units.

The message processor is the user interface. As discussed in the network description, it drives the session with the active user. When the SCU object conducts a session, it waits for packet transmission by the active user, commands all packet storage and retrieval, manages any acknowledgement procedures and terminates the session. In short, it completely emulates PANSAT's network communications.



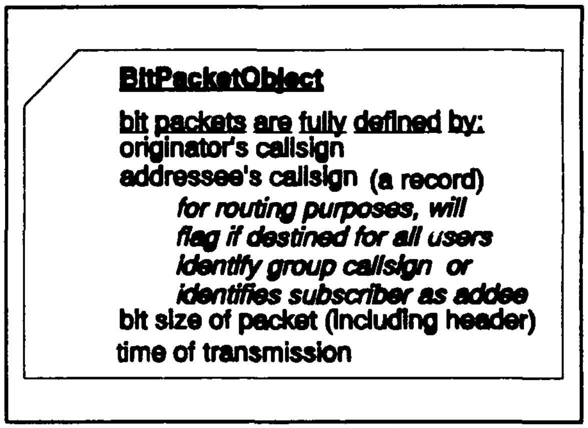
This is the Message Processing Object. It emulates all of PANSAT's comms.

SCU:
Fields
storage, orbit duration;
Methods
drives session, receives traffic, synchronizes, sends stored traffic, STORES and FORWARDS traffic, provides ACK/NACK, terminates session ;
STORAGE:
Fields
maximum capacity, directory of packets;
Methods
routes packets, retrieves packets.

Figure 11 *List of attributes owned and procedures carried out by the SCU.*

Similarly, the storage object within the spacecraft module mimics all salient features of PANSAT's SCU storage. Once commanded by the control unit, the storage manipulates the messages and identifies all packet addressees by callsign. The amount of packet storage space utilized is readily monitored; the value may be accessed at any time. These features fundamentally cover the activity of the storage unit in network operations.

3. Bit Packet



BitPacketObject
bit packets are fully defined by:
originator's callsign
addressee's callsign (a record)
for routing purposes, will flag if destined for all users identify group callsign or identifies subscriber as addee
bit size of packet (including header)
time of transmission

Figure 12 *The bit packet object exhibits all characteristics of actual packets in the network.*

The characteristics which define a unique packet are shown in Figure 12. Just as in the actual network, the bit packet is generated, transmitted to the spacecraft, received, stored and retrieved and downlinked to the destination. It is subject to bit error at ends of the communications flow. Once the packet is routed to storage, space is allocated; upon forwarding, space is deallocated.

All network operations which influence the movement of bit packets are reflected with a high degree of fidelity in the model. This is essential to the model's utility in decision making. Properties of the model which prove crucial to its ability to properly imitate the network are discussed in the next section; these are followed by a listing of network features implemented in PACSIM.

B. MODEL FIDELITY AND RESOLUTION

To create a credible model, a number of concepts relevant to network analysis must be incorporated in the simulation. Simulation is a unique tool, allowing the decision-maker to view the model network operation under varying conditions. The model includes flexibility in a number of areas which impact the questions of channel access, packet storage and endpoint-to-endpoint connectivity. They include:

- capturing the SCU;
- packet generating environment;
- occurrence of bit error;
- geographically sensible population density distribution;
- dynamics of a low-orbit spacecraft.

These processes have consequences throughout the network. Although some assumptions are made, the idea is to minimize the model's dependence on them by incorporating as much of the known communications structure as possible. This allows for substantial benefits in consistency of results across varied input assumptions.

1. Capturing the SCU

The amount of accuracy built into this process is applied on three levels. Synchronization, initial attempts at access and subsequent retries are subprocesses which define the fidelity of capture.

a. *First Attempt*

When the spacecraft comes into view for a user, there is a non-zero probability that it is busy. The model allows engineers to choose the delay between the first moment a user has the spacecraft in view and the time the user first attempts synchronization. For an arbitrarily selected user, the first attempt at channel access may occur after:

- an insignificantly small time interval;
- a random period of time which is of the same distribution as any interattempt distribution;
- a random interval according to a pre-arrival distribution which is different than that of the ensuing interattempt periods.

Modeling the first attempt as any of these has varying advantages and disadvantages.

Because the spacecraft comes into view at a known time, it is reasonable to expect that the initial attempt will occur within some small period of time. This is easy to model. The case in which the first attempt follows a waiting period which is of the same distribution as the interarrival, or backoff, periods is also straightforward but not realistic. It is not reasonable to expect the typical user to wait some extended random interval prior to the first attempt. The last paradigm is the most realistic but difficult to model because selection of this unique pre-arrival distribution is arbitrary.

b. Synchronization

An attempt to capture the idle SCU is not necessarily successful because the satellite's receiver discriminates based upon the spreading sequence, not the order of arrival (Pursely, 1987, p. 116). The spacecraft's receiver will start to correlate itself with the first subscriber's attempt. However, if a subsequent synchronization is more closely aligned with the receiver, this will capture the SCU first.

If the uplinked 128 bit spreading code is not correlated with the satellite's expected string, the receiver slides one bit and checks again. The best case is achieving a lock without requiring retries; the worst is 128 iterations of the spreading code before lock. Because the user can not be assured of achieving a lock until all iterations are complete, the synchronizing protocol encourages transmission of the maximum number of repetitions. As discussed, a cap may be placed on the maximum number of iterations of the spreading code to be transmitted. This level of accuracy is available in the model. PACSIM accounts for capturing the receiver before completion of the spreading sequence. Once in lock, the SCU beomes busy, but actual conduct of the session is delayed until the balance of the spreading code has been transmitted. If the cap has been attained, synchronization ceases, irrespective of whether the receiver has been captured.

c. Retries

If the first synchronization attempt is unsuccessful, the subscriber waits an interattempt backoff period. This is a random interval established by the communications protocol. The reason for randomness in backoff is to preclude multiple users from backing off in lock-step. Typical distributions for backoff are exponential, arithmetic, and geometric among others. After the random wait, another synchronization is attempted and the SCU will again be found either busy or not. The decision maker may select the backoff period distribution as well as the number of retries allowed per user.

2. Packet Generating Environment

To accurately reflect potential network activity , it is important to minimize assumptions and to implement expected characteristics in the model. Because packet creation and routing is at the crux of the operations, it is particularly important to impose a high degree of fidelity in the following areas which comprise the packet generating environment:

- packet generation;
- packet sizing;
- packet addressing.

Specific elements of the packet generating environment implemented in PACSIM are listed in the next section.

a. *Packet Generation*

There are several schemes available in modeling this aspect of the network. One dictates that all users continually have a need to enter messages into the network.

Impact of Packet Generation on the Model

```
process              event                                  time

ORBIT |---------------(     )---------------(     )-->
                        view                   view

NEED TO
GENERATE|-------------------------/\---------------->
                                 need
                                generated

USER'S
SESSION |-------------x---------------------x--------->
                    will only              will also
                    download               generate and
                    stored                 transmit
                    traffic                traffic
```

1 *Outline of a user's message generation requirement.*

This will aid in simulation model validation. Users attempt to access the net and transmit a packet for handling by the SCU. This is the heaviest traffic generating paradigm. The circumstances for this will arise in the course of spacecraft operations, but may not be present in the actual network in equilibrium.

More reasonably are the following approaches for modeling subscribers' need to communicate:

- deterministic -- after specified intervals, a day for example, a generating mission arises;
- probabilistic -- this paradigm establishes a random period of time between missions. These periods may be very long, influenced by the total user population, independent and memoryless; this suggests the use of a gamma distribution in defining inter-generation intervals; this is the probability distribution used in PACSIM;
- scripted -- specified scenarios envisioned for packet generation ought to be implemented for analysis.

If the user has the spacecraft in view, an attempt is made to establish a session and generate a packet for entry into the system. If the spacecraft is not in view, then the caller waits until the communication window opens and then proceeds as described above. Once the packet generating mission has been initialized, the issue of sizing and addressing the packet come into play.

b. Packet Length

PANSAT's engineers want to place as few constraints as possible on packet length to allow subscribers the opportunity to communicate an unrestricted quantity of information. Because of a slow data transfer rate in the network and finite communications windows as well as protocol restrictions, a finite maximum packet length will be implemented. How can one best express the actual distribution of the packet size?

By design, the model should be robust enough such that the choice of distribution will alter the face of the model imperceptibly. Because there are minimum and maximum bounds on message length, the actual packet size may be considered uniformly distributed between these limits. This covers a large proportion of the packets generated and accommodates enough variability that the realistic packet lengths are included.

c. Packet Addressing

By default a model may be created in which packet addressing is equiprobably distributed among all users. This is straightforward for developing a probability model to validate the simulation but stretches the notion of realistic packet addressing.

More reasonable is the idea that some users are much more likely to be addressed in a packet than others. Superusers, such as the Naval Postgraduate School, the network system operator, can expect to receive a significant proportion of the traffic. Likewise, more packets will be exchanged within geographic regions or other social groupings of users. Finally, the recipient of a packet may be likely to transmit another packet to the first message's originator. These packet volleys may persist for several exchanges. All of these are readily set in motion in the simulation and provide a great amount of fidelity with a minimum of assumptions.

3. Occurrence of Bit Error

The probability of error occurring in data transmission is principally a function of signal-to-noise ratio. The derived bit error rate in the link analysis is 0.00001 errors per bit (Panholzer, 1992, p. 3). Multiple users transmitting simultaneously create increased noise in the radio-frequency environment, thus increasing the bit error rate. Occurrences of bit error may be in the header, the information packet or both. Error in the header may cause loss of the entire packet; error in the information frame may cause a loss of data; error in both may also cause loss of the packet.

At the user and spacecraft receivers, the packet is to be sampled for the occurrence of bit error. Because error does not occur independently among bits, representation of P_e, the probability of bit error, is given by a uniform sampling of the bit packet. For example, a 1000 byte information packet, consisting of 8000 bits of data, $P_e[\text{packet}] \approx 0.0800$.

On a round trip from user to spacecraft to addressee, the probability that this packet experiences bit error is 0.1536. This has the following implications for the network:

- to preserve data flow, retransmissions will be required ;
- channel access may be restricted due to extended sessions;
- network reliability will deteriorate if the protocol does not ensure end-to-end communications to a certain level.

All of these ramifications of bit error are included in the simulation model.

4. User population distribution

Decision makers have sought to identify the potential user base for PANSAT in order to substantiate design decisions. Initial survey results showed a tremendous amount of enthusiasm for the program, predominantly in high population density, metropolitan regions. Unfortunately, enthusiasm in a survey does not necessarily map accurately into active participation in a financially capital-intensive network. Simulation may be the superior course of action in assessing network performance over various user population densities.

For model validation, subscribers are uniformly distributed over the orbit of the spacecraft as is characteristic of a Poisson process. This archetype is suitable if the following are true:

- **orderly arrivals** -- users attempt to access the net one at a time ;
- **stationarity** -- the distribution of the number of attempts made is a function solely of the time interval investigated and is independent of when this interval starts;
- **lack of after-effects** -- the number of attempts in a given interval is independent of the number in previous and subsequent disjoint intervals.

Based on the network description in chapter one, the first assumption is plausible. The credibility of stationarity is questionable when examining the behavior of the network in its full orbit. Some population centers are more dense than others. Intervals including activity in these user bases might differ significantly from observations of others. However, among collocated users, stationarity may be a reasonable supposition. During the period when collocated subscribers hold the spacecraft in view, the intensity of users attempting to access the network may be consistent among disjoint sub-intervals. The third assumption required for a Poisson process does not hold.

Disjoint time intervals are not independent. All are tied to

- session duration; extended sessions are highly interdependent and severely impede channel access. Reattempts add to the number in contention during subsequent intervals and packets for download accumulate in the SCU. The consequence is more extended sessions ;
- the number of users; with a small number of collocated users, each successfully completed session results in fewer attempts to capture the SCU in future intervals.

> This indicates some correlation between the number attempting channel access in one interval and the number in subsequent intervals.

Within a population center, it is reasonable to assume orderliness and stationarity among subscribers contending for channel access. It is more difficult to justify all Poisson assumptions of stationarity, orderliness and independent increments for the spacecraft's complete orbit.

5. Network Characteristics of a Low-orbit Spacecraft

Subscribers are collocated in population centers. During certain orbits, the spacecraft's footprint may cover more than one of these regions concurrently. This reflects what is expected in actual operations of a low-orbit satellite communications system. PANSAT will have a bounded footprint allowing only a portion of the users access at any given time. Furthermore, the sinusoidal nature of its orbit creates a situation in which users will not necessarily have a view of the spacecraft for most.

Periodicity in the spacecraft's orbit also yields varying window durations. A user will have the spacecraft in view for an interval lasting between four and ten minutes, depending on the position of the satellite in its orbit. Combined with the variability of session duration, the channel access problem becomes more realistic. These dynamics have implications throughout the network and are implemented in simulation.

C. WHAT WAS AND WHAT WAS NOT IMPLEMENTED

To effect the level of accuracy described in the previous section, the following were implemented:

- the first attempt was modeled to follow a very small period of time after the spacecraft comes into view of a population center;
- the proportion of users selecting to attempt access during an orbit is input;
- a cap on the number of synchroniation iterations is established as an input parameter;
- the exponential backoff algorithm was used, but the mean backoff time is an input parameter;
- the choice of the packet generating modes is available; the probabilistic approach makes use of a gamma distribution shaped by the number of users and, as with the deterministic mode, the rate of generation is input by the modeler;
- the lifetime of packet generating missions is also selected by input;
- packet length is determined by a uniform sampling of an interval, the upper bound for which is input, enabling emulation of fixed packet lengths by setting the bounds equal;
- packet addressing is divided into the proportion of messages to be addressed to the Naval Postgraduate School, a superuser, the proportion to be addressed within the goegraphic area, and those to be addressed to any user in the network; these proportions are input;
- the bit error rate is input;
- the number of user population centers, their locations, geographic size, and number of users are input;
- finally, PANSAT's orbit periodicity, identification of location's views during a period, as well as minimum, maximum and average footprint durations are input.

In addition, some elements of a high-resolution representation of the network were not used. These include:

- group broadcast in which a single message is routed for all or a group of users;
- building a superuser object who would have the ability to address single messages to groups of users;
- selecting the maximum number of synchronization retries;
- using a sinusoidal function to determine the occurrence and duration of spacecraft views;
- the ability for the model to read an input, scripted network scenario;
- implementating protocol-specific, such as AX.25 or TCP-IP, communications activity;
- differentiating among modem-specific synchronization processes aside from the rate of achieving lock.

The level of model accuracy has been firmly established. Although some elements of network activity have not been exactly implemented in simulation, the model has established a level of credibility such that solutions provide very high confidence guidelines for making design decisions. A list of verification experiments and results are presented in the next chapter.

IV. PACSIM VERIFICATION AND MODEL VALIDATION

To ensure that the simulation model "operates in the way that the model implementer thinks it does" (Bratley, 1987, p. 8), PACSIM's evolution as a simulation program has been marked by a process of verification. "Verification is determining that a simulation computer program performs as intended ... [and] checks the translation of the *conceptual simulation model* (eg. flowcharts and assumptions) into a correctly working program." (Law, 1991, p. 299) This chapter outlines the techniques and procedures used in verifying PACSIM as a program and validating it as a model.

A. MODULAR PROGRAMMING, DEBUGGING AND TESTING

PACSIM is separated into more than 40 distinct modules, compiled individually and linked as a program. The initial manifestation of PACSIM featured one, two and three user scenarios and traced the entire process of channel access, session conduct and message storage and forwarding of a motionless spacecraft. Once a very high degree of confidence in the model was obtained, larger user population scenarios were used. Sensible output was confirmed as each of the following improvements and levels of resolution were added:

- cities -- determining if contention among users was being resolved properly;

- orbits -- ensuring that users could attempt access to the SCU only when the spacecraft was in view;
- proportion of users attempting access -- checking for user synchronization attempts during the appropriate views;
- packet generating environment -- confirming that each of the different packet generating schemes and missions had the correct impact on system activity; for example, the further the model departed from the heavy traffic generating scenario, both SCU storage levels and average session durations decreased.

B. VARYING PARAMETERS AND SENSITIVITY TESTING

The following is a partial list of parameters whose values were changed in validating PACSIM's performance:

- number of users;
- number of cities;
- packet length bounds;
- data transfer rate;
- bit error rate;
- proportion of users attempting access to the SCU;
- spacecraft orbit periodicity;
- number of views per spacecraft orbiting period;
- full- or half-duplex sessions;
- backoff rates;
- the maximum number of synchronization iterations.

Experiments have generated a wide range of values for system performance measures by varying these parameter inputs. The results are discussed in the following chapter. Analysis yielded the conclusion that varied inputs led to changes in not only the measures themselves but their variability as well.

C. CHECKING AGAINST KNOWN SOLUTIONS

The model was run "under simplifying assumptions for which its true characteristics are known (Law, 1991, p. 303)." An analytical model has been applied to the following issues in the PANSAT network:

- establishing the average number of messages in SCU storage in equilibrium;
- characterizing session durations by a distribution function;
- treatment of the channel access problem as a single server system with no queue.

The results provide a foundation for verifying simulation results.

1. Number of Packets in Storage

For the analytical model of this issue, the following assumptions are made:

- there are N independent, identical users;users access the
- network no more than once an orbit;
- addressee selection is equiprobable among all users, that is P[packet is addressed to a specific user] = 1/(N-1).

To make PACSIM simulate this tractable model, the following features wre altered:

- the spacecraft is in view for the entire run;
- all users are located in a very small interval;
- sessions are modified to require a minimum amount of time to prevent second-order influence on the statistic of interest; specifically, data transfer rate is at 2400 baud, packets are no longer than 100 bytes and a full-duplex channel is used;
- the default, heavy communications traffic flow scenario is used;
- addressing is uniform among all users.

a. The Tractable Model

The first objective is to define the distribution of the equilibrium number of messages being stored by the SCU for an arbitrarily selected user.

For any user, there may be k messages in storage, for any k = 0, 1,.... The only transitions which may occur are as listed in Table 1 and depicted in Figure 13. In all of the cases outlined in Table 1, the status of the future state of the mailbox is fully determined by the transition probabilities from the current state space. Because this is simple system Markovian, the probability distribution for k may be readily derived. Letting π_k represent the equilibrium probability that a user has k messages being stored by the SCU,

$$\pi_0=\frac{N-1}{N}\pi_0+\frac{1}{N}\pi_1+\frac{1}{N}\pi_2+\frac{1}{N}\pi_3+\ldots$$

Table 1. TRANSITIONS FOR NUMBER OF USER'S MESSAGES IN SCU

Transition	Probability	Explanation
k to (k + 1)	1/N	P[pkt sent to i | a user other than i arrived] = (1/(N-1))((N-1)/N)
k to k	(N-2)/N	P[pkt not sent to i | a user other than i arrived] = ((N-2)/(N-1))((N-1)/N)
k to 0	1/N	P[i arrives]
0 to 0	(N-1)/N	P[{i visits an empty mailbox} $\cap$ {pkt not sent to i} | {user other than i arrived}] = 1/N + (N-2)/N

which may be written as

$$\pi_0=\frac{N-1}{N}\pi_o+\frac{1}{N}\pi_{\neg 0}$$

where $\pi_{\neg 0}$ is the probability of one or more messages are being stored. This yields two equations and two unknowns:

$$\pi_0 + \pi_{\neg 0} = 1 \qquad \text{and} \qquad \pi_0 - \pi_{\neg 0} = 0$$

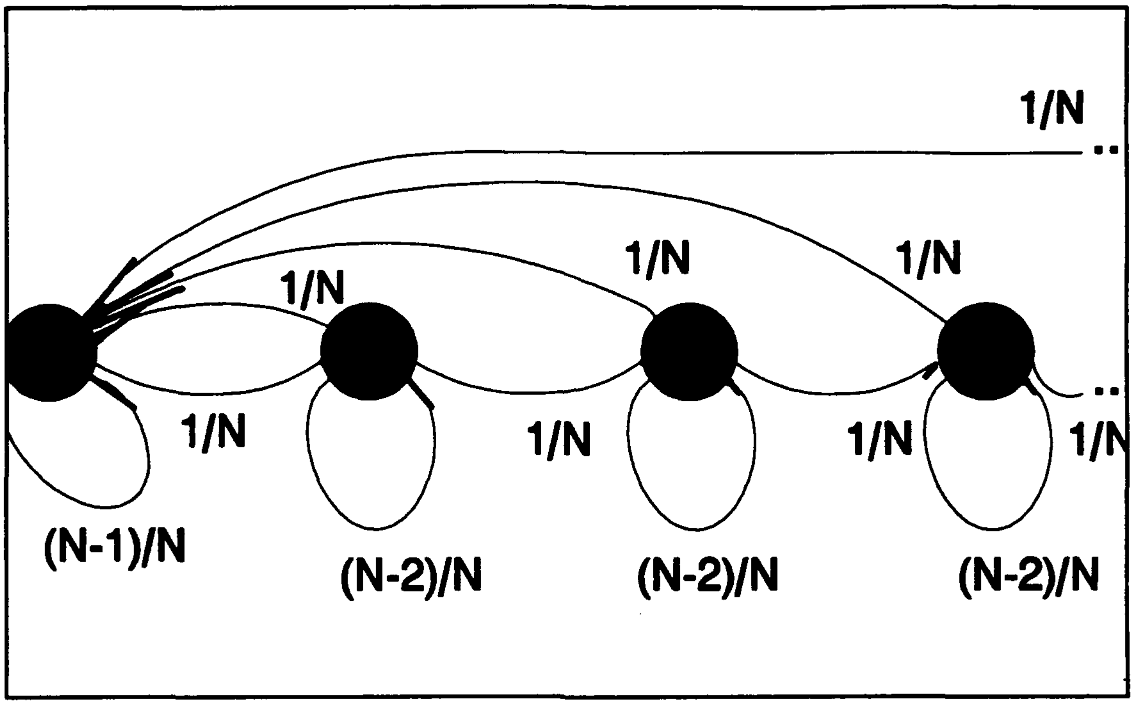


Figure 13 *State space and transition probabilities for the number of messages in the SCU for an arbitrary user.*

these two equations yield the stationary probability that the user has no messages in SCU storage, $\pi_0 = 1/2$ and the rest are as follows:

$$\frac{1}{N}\pi_0+\frac{N-2}{N}\pi_1=\pi_1\rightarrow\pi_1=\frac{1}{2}\pi_0$$

$$\frac{1}{N}\pi_1+\frac{N-2}{N}\pi_2=\pi_2\rightarrow\pi_2=\frac{1}{2}\pi_1=(\frac{1}{2})^2\pi_0$$

or in general, K, the equilibrium number of messages in storage for an arbitrarily selected user is a geometric random variable with parameter p = 1/2 and k = 0, 1, ... The expected value is

$$E[K]=\frac{q}{p}=1.000$$

with variance

$$V[K] = \frac{q}{p^2} = 2.000$$

b. PACSIM Results

Confirmation of the geometrically decaying number of messages stored for a user is provided in Table 3. P_K is the proportion of users with K messages in SCU storage and π_k is the equilibrium probability that there are k messages being stored. Furthermore, the estimated expected value

$$\hat{E}[K] = \sum_{k=0}^{\infty} k \hat{P}_k = 0.999 \approx 1.000$$

Table 2 CONFIRMING THE DISTRIBUTION FOR THE NUMBER OF A USER'S MESSAGES IN SCU

K	0	1	2	3	4	5	6+
P_K	.502	.226	.138	.075	.034	.011	.012
π_K	.500	.250	.125	.063	.031	.016	.015

and the estimated variance

$$\hat{V}[K] = \hat{E}[K^2] - (\hat{E}[K])^2 = 2.926 - 0.998 = 1.928 \approx 2.000$$

compare very favorably with the analytical result.

2. Expected Session Duration

To verify the expected session duration, sessions extended due to message retransmissions should be eliminated from PACSIM's outcomes. The following simulation features were altered to provide a scenario for verifying session duration distribution:

- bit error rate was reduced to zero, precluding the occurrence of bit error and any retransmissions;
- all other elements of PACSIM were implemented in the full-duplex communications channel scheme.

a. *Tractable Model*

event	**duration**
balance of spreading code	uniform random
identification preamble	fixed
user message upload	uniform random, given a need to generate
SCU acknowledgement	fixed
user retransmissions	uniform random, given bit error occurrence
SCU message download	geometric number of uniform random periods
user acknowledgement	fixed
SCU retransmissions	uniform random, given bit error occurrence

2 *Enumeration of a session as a series of independent events.*

The full duplex session is a series of random and fixed length subevents, enumerated in the box above. It is a sequence of fixed values and random variables. The expected duration of the session, S_t, is the sum of the expected values of the lengths of the subevents. The computation of these values are listed below.

event	**expected duration**
balance of spreading code	E[synchronization duration]
identification preamble	constant
user message upload	E[size of message in bits] x transmission rate
SCU acknowledgement	constant
SCU message download	E[number of messages stored] x E[size of message] x transmission rate
user acknowledgement	constant

3 *Listing of expected values of session subevents.*

b. PACSIM Result

Computing the time required for downloading messages from the SCU invoked Wald's equation. The expected amount of data for transfer in equilibrium is the expected number of messages for download multiplied by the expected value of the size of these messages. The expected size of the messages is based upon the assumed uniform distribution for message length. Determining the expectation of session durations provides insight into error-free performance of the network. This result has direct ramifications for treatment of the tractable model as a queuing system, as will be shown in the next section. As can be seen in Table 3 , all session durations observed in PACSIM are within two percent of the tractable model's result.

Table 3. COMPARING EXPECTED AND OBSERVED SESSION LENGTHS

Communications Channel Settings	Analytical	Observed
1200 Baud, 2Kbyte Maximum Length	15.47	15.63
2400 Baud, 2Kbyte Maximum Length	7.57	7.45
1200 Baud 1Kbyte Maximum Length	8.13	7.96
1200 Baud, 1Kbyte Fixed Length	14.13	14.33

3. Channel Access as a Queueing Problem

For a tractable queuing model to be simulated the following factors were implemented:

- users access attempts were distributed as Poisson arrivals;
- user synchronization attempts are sure events;
- there are no population centers, the spacecraft is in view for the entire run, with the footprint covering all users;
- all other elements of a full-duplex system were used to emulate the M/G/1 queue.

a. Tractable Model

PANSAT's engineers want users to have ready access to the network. Because there is only one channel for conducting sessions and users must synchronize with an idle SCU to capture it, the channel access problem may be viewed as a queueing problem. Specifically, channel access occurs when the server is idle. The probability that the SCU is idle, P_{idle}, is

$$\begin{aligned} P_{idle} &= 1 - \frac{\lambda}{\mu} \\ &= 1 - \frac{E[\mathit{session\ duration}]}{E[\mathit{interattempt\ interval}]} \\ &= 1 - \frac{E[S_t]}{E[T_a]} \end{aligned}$$

where λ is the rate of users attempting to access the SCU and μ is the reciprocal of the mean session duration. S_t is the session duration, and T_a is the interattempt interval. To increase channel access, engineers will seek to shorten session length or increase backoff periods.

b. PACSIM Results

These verification experiments situated between 50 and 400 users randomly over a 5500 second orbit. Because Poisson arrivals see time averages, the ratio of orbit duration to number of users yielded the mean interattempt interval. In Table 4, P_{idle} reflects the tractable model's solution, while P_{obs}, the proportion of users accessing on the first attempt, is given in the bottom row. The observations confirm results of the tractable model. This further verifies the model as an accurate representation of PANSAT's communications network.

Table 4. FIRST ATTEMPT CHANNEL ACCESS AS A QUEUING SYSTEM

Number of Users	50	100	150	200	300	400
$E[S_t]$	8.38	8.27	8.14	8.25	8.28	8.38
$E[T_a]$	110.0	55.0	36.6	27.5	18.3	13.8
P_{idle}	.924	.850	.778	.700	.548	.391
P_{obs}	.985	.843	.776	.703	.572	.398

V. PACSIM RESULTS

A. DATA COLLECTION

PACSIM ran nearly 200 different scenarios to explore the design questions enumerated in Chapter II. All observations were recorded during steady state in order to evaluate the system's long-run behavior. Session duration and channel access observations were measured at the completion of transactions while SCU memory observations were taken when messages were being received by the SCU. The following experiments were run:

- measuring the quantity of SCU storage used with a 1000 and 2000 byte maximum message length while increasing the number and population density of subscribers;
- comparing half-duplex channel and full-duplex channel session durations, at a data transmission rate of 1200 baud under varying bit error rates;
- comparing full-duplex session durations at data transmission rates of 1200 and 2400 baud under varying bit error rates;
- measuring session durations with maximum message lengths of 1000, 2000 and 4000 bytes;
- measuring session durations with the maximum number of synchronization sequence repetitions set at 128, 96 and 64 iterations;
- identifying the rate of channel access at data transfer rates of 1200 and 2400 baud in a full-duplex circuit;
- comparing the rate of channel access while varying exponential backoff rates of 15, 30, 45 and 60 seconds;

- identifying the rate of channel access while varying the maximum number of synchronization sequence iterations among 128, 96 and 64.

B. SCU Storage

PANSAT's designers sensed that an increased number of users and larger maximum message sizes require a greater quantity of SCU storage. PACSIM confirmed these ideas and provided further insight into this design issue. Figure 14 summarizes the conclusions as follows:

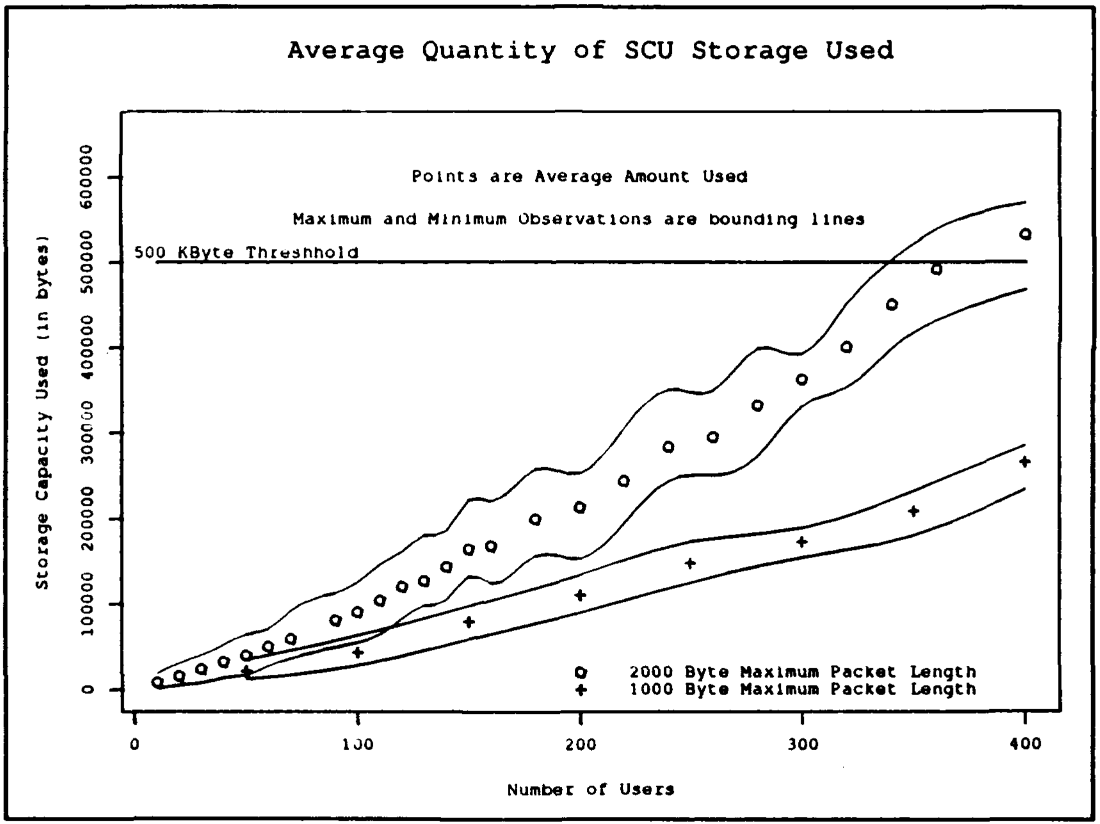


Figure 14 *Average amount of SCU storage used as a function of user population and maximum message length.*

- in a heavy message traffic scenario and 2000 byte maximum message length, the initial 500 kilobyte memory threshhold set by the communications designers becomes an issue when there are more than 300 users in the network; the envelope is pushed further out for the 1000 byte message limit;

- variability in the quantity of memory used increases with increased user population density; all experiments used four population centers -- increased channel contention is associated with a decreased rate of access, creating an opportunity for messages to accumulate in storage;
- for the 2000 byte maximum message length, memory usage increases superlinearly with the number of users; this corroborates the idea that channel access is linked to SCU memory usage.

This measure reflects only one scenario for network user activity. Observations ought to be made when

- message generation is less intense;
- users exercise the option not to access the SCU ;
- a greater proportion of messages are addressed to superusers.

C. SESSION DURATION

Efforts to shorten session lengths and increase communications duty cycles are concentrated on shifting from a half- to full-duplex circuit, increasing bit rate, shortening maximum message length and truncating the synchronization process. These sessions were run under the heavy message generating environment, in which users uploaded a message and, on average, downloaded one message.

1. Full-Duplex vs Half-Duplex

Originally, PANSAT was to utilize a half-duplex communications circuit. When the decision was made to focus engineering efforts on a full-duplex channel, shorter sessions were expected to occur. PACSIM revealed several other ramifications of this design decision, as shown in Figure 15:

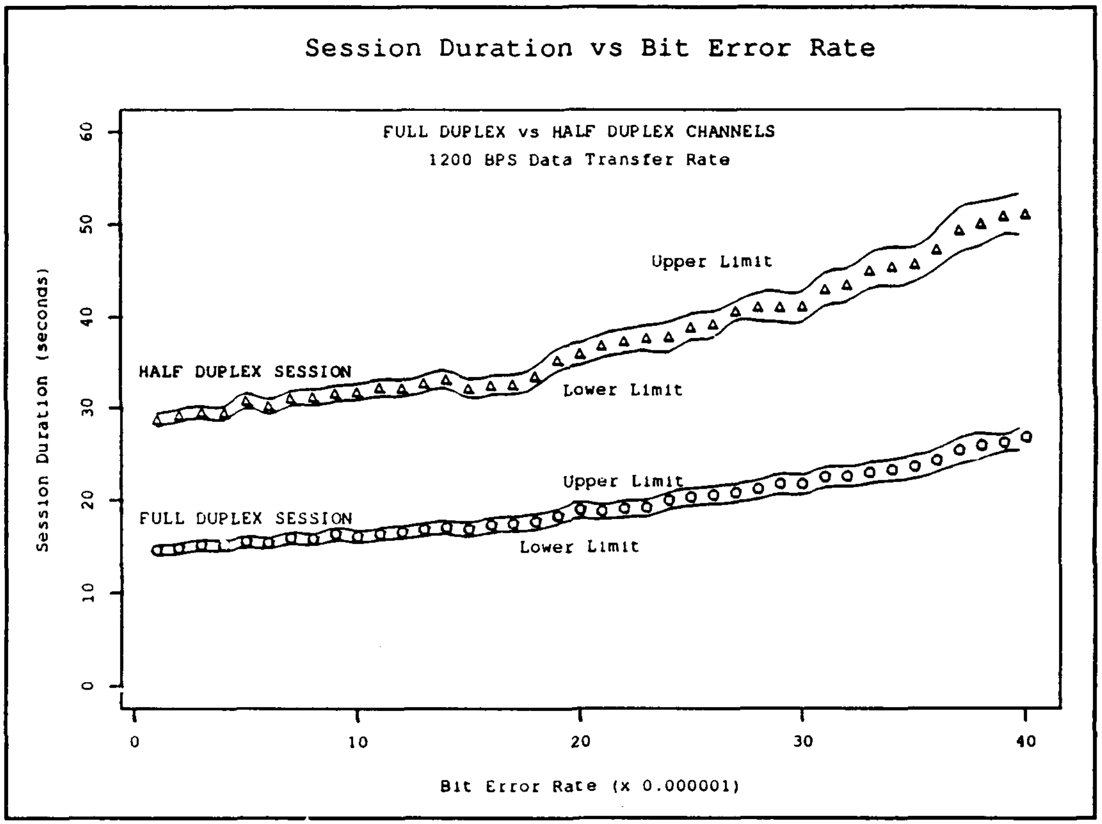


Figure 15 *Comparison of full- and half-duplex channel average session duration as a function of bit error rate.*

- full-duplex is very robust against increases in bit error rate;
- full-duplex sessions have a significantly smaller rate of increase in duration as bit error increases;
- due to a greater number of prolonged sessions, half-duplex experiences more variability as bit error increases;

- on average, full-duplex sessions are shorter, even at bit error rates exceeding three times that of half-duplex sessions.

2. 1200 Baud vs 2400 Baud

Developing PACSIM gave rise to discussions on the effectiveness of a half-duplex circuit. Once engineers started thinking in terms of operability of the network, the next step was to consider increasing the data rate. Figure 16 depicts the obvious improvement in shortening the average session. Additionally, the following conclusions may be drawn:

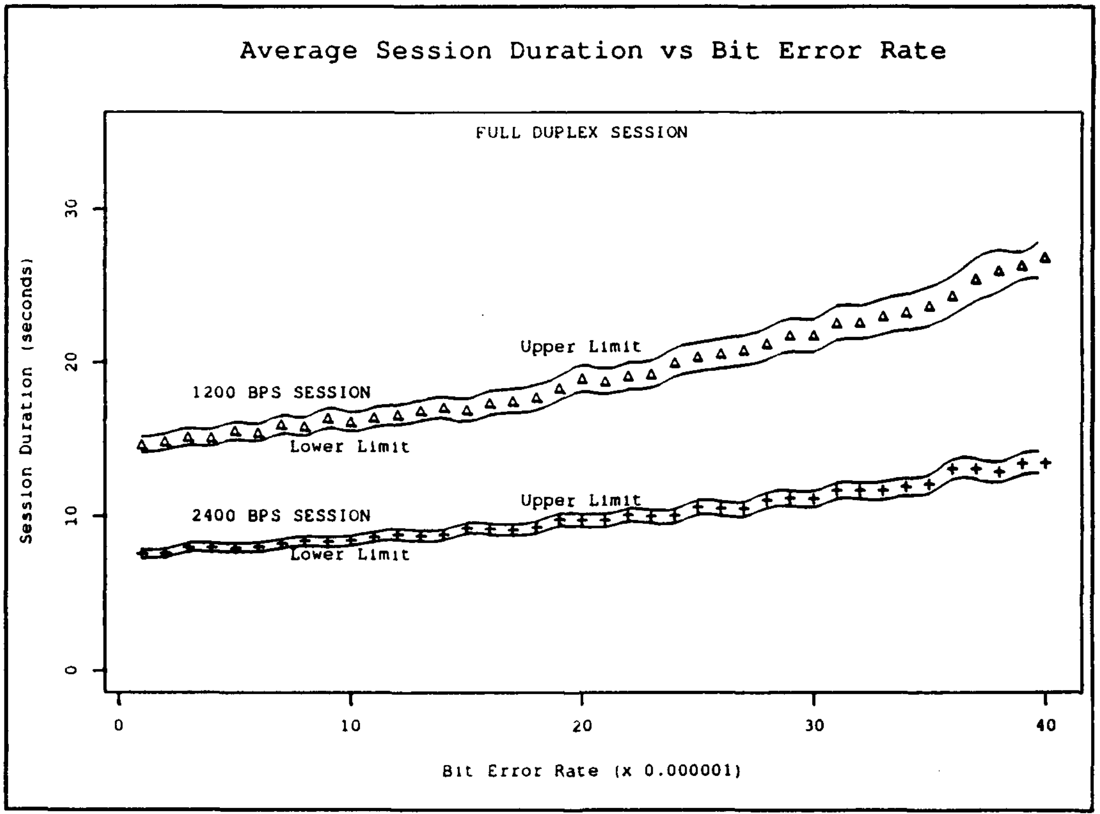


Figure 16 *Comparing effects of 1200 baud and 2400 baud full-duplex channels on average session duration as a function of bit error.*

- 2400 baud communications are even more robust against bit error than the 1200 baud data transmission rate;
- increases in session duration are almost insignificant even at a bit error rate four times the bit error rate assumed in the link analysis;
- if the assumed link margin remains constant, the 2400 baud circuit outperforms the 1200 baud circuit at a signal to noise ratio which allows for quadruple the bit error rate.

3. Packet Length

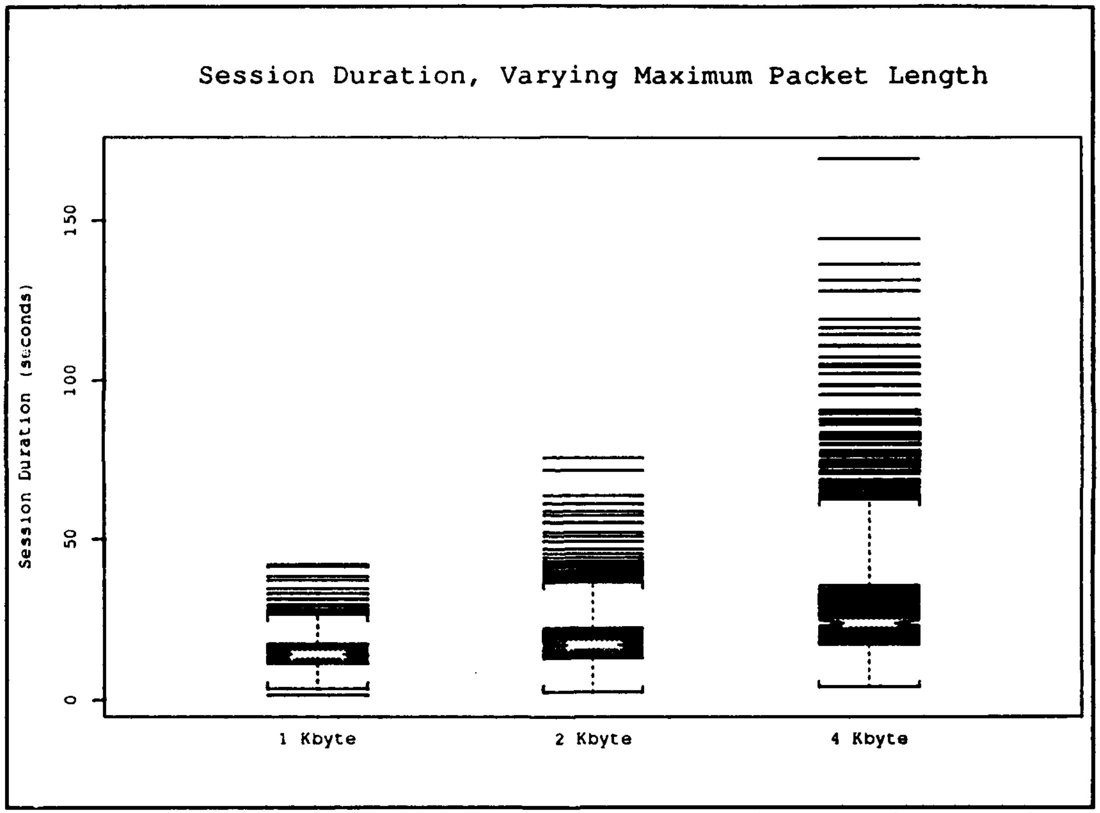


Figure 17 *Comparison of session durations using maximum message length as the parameter.*

Engineers expect that restricting the maximum length of messages requires less transmission time and yields shorter sessions. In addition, longer messages have a greater probability of incurring bit error which extends sessions due to retransmissions. PACSIM substantiates these notions, as shown in Figure 17; other conclusions include:

- 75 percent of sessions exchanging messages limited to 1000 bytes require fewer than 25 seconds; on the other hand, 50 percent of the 2000 byte message exchanges and 75 percent of the 4000 byte transfers exceed 25 seconds;
- larger messages for transfer yield much more variability in session duration;
- average session duration under greater maximum message lengths shows significant increase, but provides little insight into their distributions.

In lighter message generating schemes or under higher data tranfer rates, differences may be less pronounced.

4. Synchronization Protocol

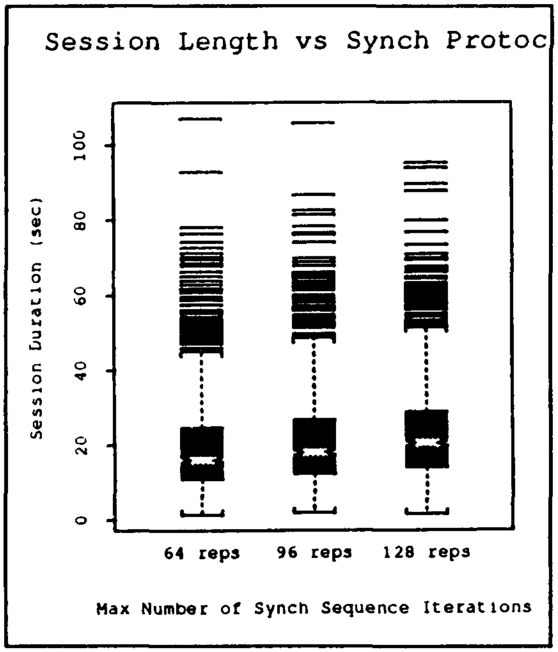


Figure 18 *Session duration distributions as a function of synchronization protocol.*

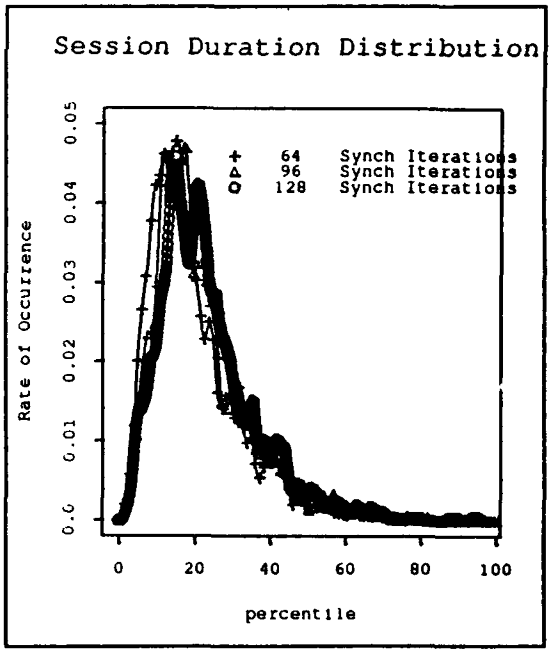


Figure 19 *Session duration density functions using the synchronization parameter.*

Figures 18 and 19 depict the distribution of session durations while varying the maximum number of synchronization iterations. The following conclusions may be drawn:

- because of the relatively short duration of this process, varying the synchronization protocol has little impact on the duration of sessions;
- there is no significant difference in session duration even if the maximum number of synchronization iterations is cut in half.

If the primary purpose of altering synchronization protocol is to shorten sessions, there is nothing to be gained as shown by the insignificant difference in results.

D. CHANNEL ACCESS

As discussed, design decisions with respect to channel access revolve around the following issues:

- the likelihood that the Naval Postgraduate School will be able to access the SCU unimpeded;
- reduction in the number of attempts users make to access the spacecraft -- with each try, more noise is created on the channel;
- what proportion of users can expect to access the spacecraft.

The engineers can improve overall channel access by shortening the duration of sessions or increasing the interval between users attempt at capturing the SCU. Specifically, PACSIM ran scenarios measuring channel access against changes in bit rate, backoff rate and synchronization protocol.

1. Bit Rate

Figure 20 depicts channel access as a function of data transfer rate. It has been shown that an increase in data rate significantly shortens session duration. Of particular note:

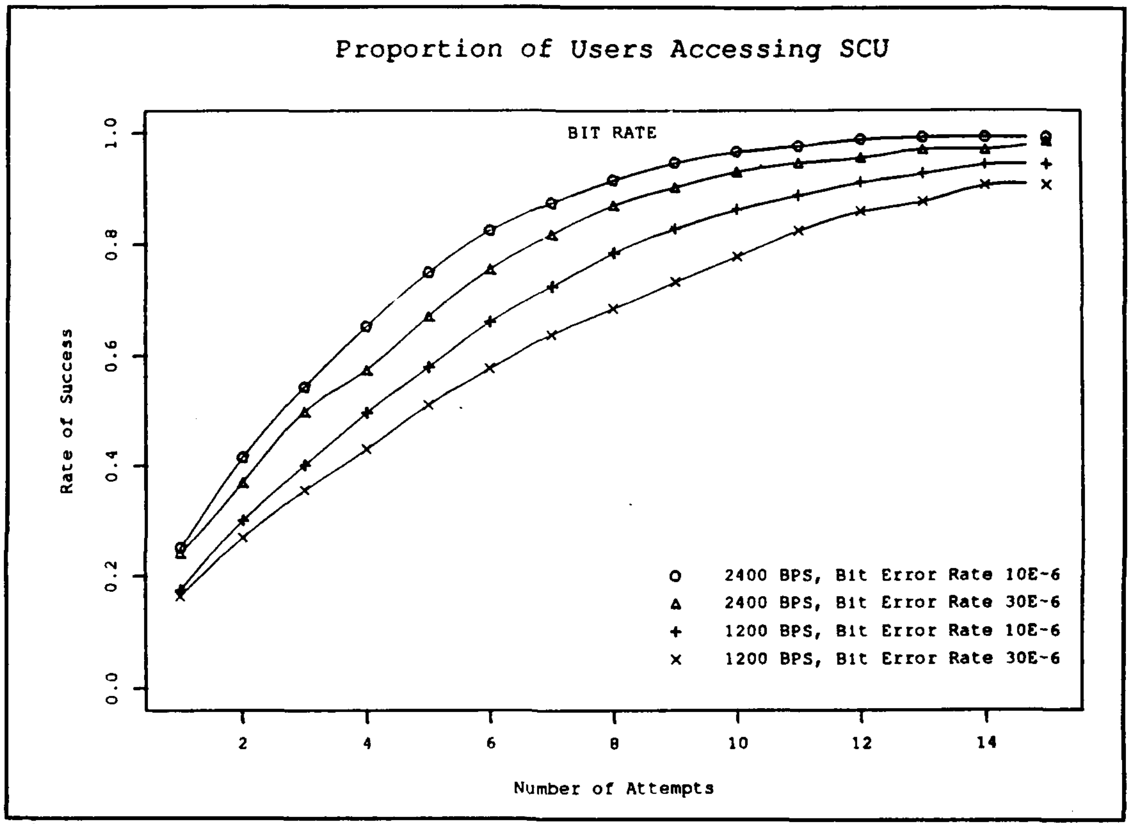


Figure 20 *Probability of successful channel access for a given attempt as a function of data transfer rate.*

- even at three times the bit error rate, channel access is significantly better in a 2400 baud circuit than one at 1200 bits per second;
- at 2400 bits per second, overall channel access is 90 percent successful after eight attempts, while this level of success is attained after 14 tries in a 1200 baud net.

2. Backoff Rate

According to the analytical result for this issue, as the interattempt period is increased, the rate of channel access improves. This experiment used a half-duplex net at 1200 bits per second and a bit error rate of 10E-6. The average session duration for this scenario is 30 seconds. PACSIM shows this improved channel access, but in addition, it is evident that:

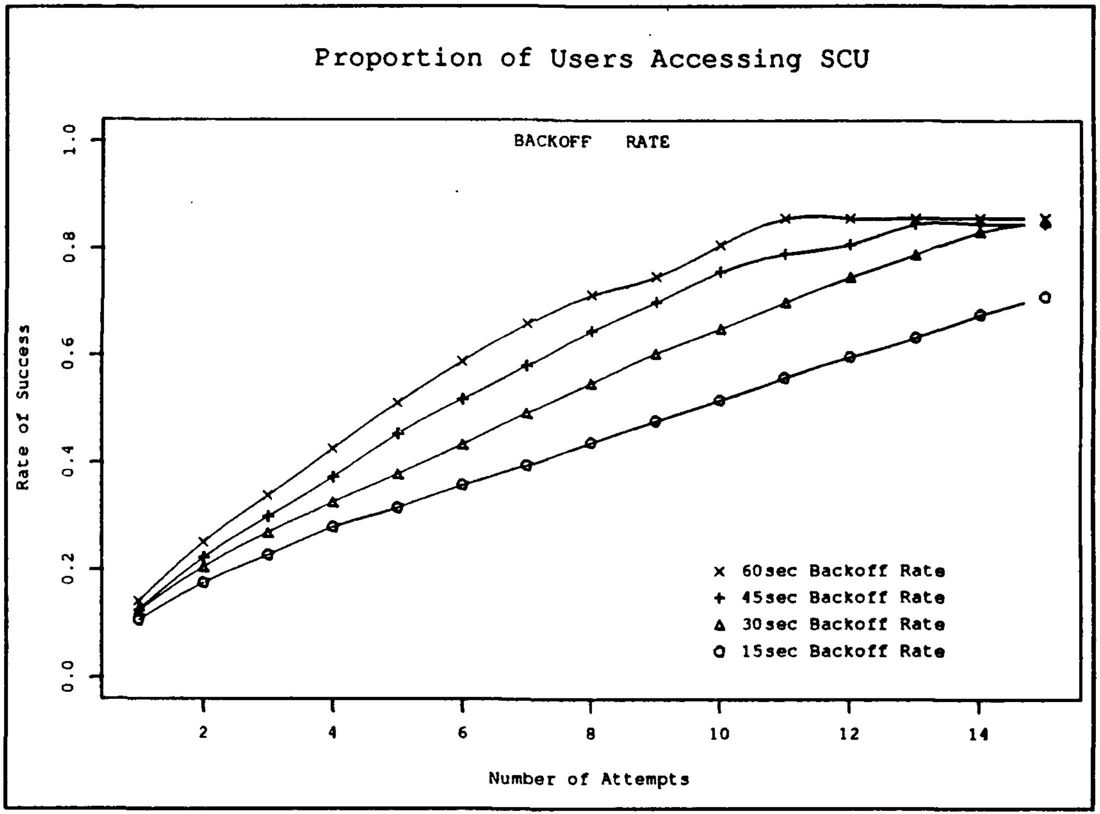


Figure 21 *Probability of successful channel access for a given attempt as a function of backoff rate.*

- there is no significant difference in successful first attempts;

- session duration creates an upper bound on the success of retries;
- a backoff protocol in which users continually retry at intervals much shorter than the expected session length show poor rates of success.

3. **Synchronization Protocol**

PACSIM shows that altering the synchronization protocol has no significant effect on channel access. This further shows the point that session duration drives channel access. Even though the synchronization sequence was truncated to the point at which the probability of capturing the SCU was one-half of the 128 iteration process, success rates changed insignificantly.

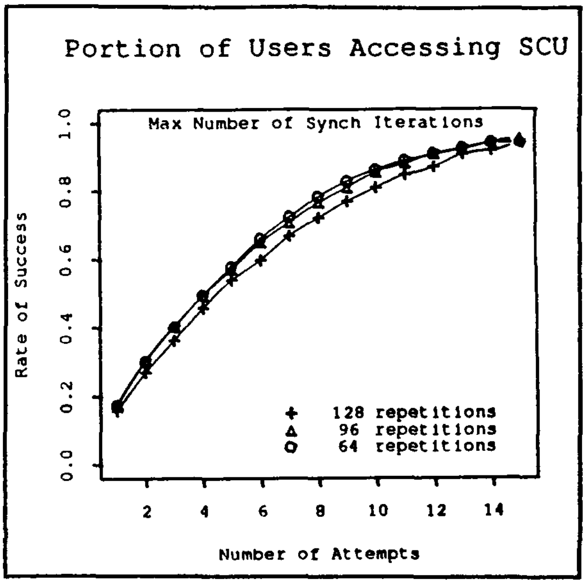


Figure 22 *Probability of channel access as a function of synchronization protocol.*

VI. SUMMARY AND CONCLUSION

A. SPACECRAFT NETWORK DESIGN

PANSAT's engineers are designing a satellite communications network to operate in an environment characterized by uncertainty. From PANSAT's onset, designers were developing a half-duplex, 1200 baud, store-forward system to accommodate:

- a user base unknown in number, location and population distribution;
- random network activity;
- arbitrary message generating and addressing;
- impediments to connectivity such as the occurrence of bit error or an inability to capture the SCU.

The goal was to design a functional spacecraft for this highly unpredictable communications flow. The first step was to identify PANSAT's operational characteristics.

By establishing a paradigm of network activity,engineers were able to concentrate on operations despite the random environment. We specified channel access, communications flow and SCU storage as the fundamental network elements. This highlights the simplicity of the communications network but provides little insight into the strong interdependence of design issues and fails to reflect the extensive impact of uncertainty on operability.

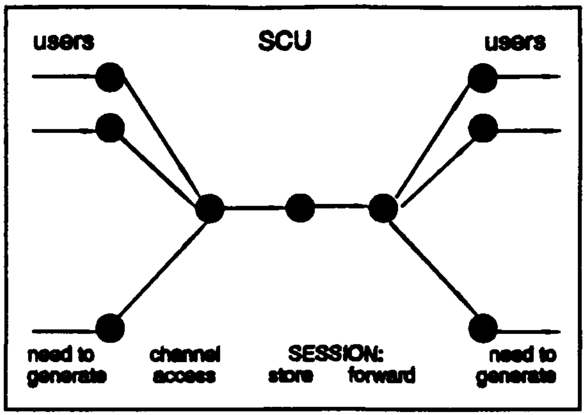


Figure 23 *Flow of information through the PANSAT network.*

Figure 23 summarizes the nominal flow of information from users to the SCU and back to users. Nodes signify concurrent network activity, arcs depict the flow of data. User activity, the source of the data flow is subject to the uncertain, bursty, non-stationary nature of communications networks. What happens to the flow of messages when the number of users varies, network activity changes, or message addressing is altered? *System performance becomes entirely scenario dependent.* Flow from preceding states determines the nature of communications at subsequent points. Successful spacecraft network design takes these features into account.

B. PACSIM'S DEVELOPMENT

Once the network's underlying complexity was established, PACSIM was developed to emulate the system's communications and to provide a basis for comparing design decisions among different scenarios. "When a simulation model and its results are accepted by the ... client as being valid, and are used as an aid in making decisions, we call the model *credible.*" Law and Kelton provide a methodology for establishing model credibility (Law, 1991, pp. 299-310). The following list documents the construction of PACSIM as a decision aid.

- Interaction with design team: When PACSIM was initially developed, the engineers' focus was not on operational issues, much less what the model was going to provide. As results emerged which confirmed and expanded on decision makers' notions, their interest and involvement in PACSIM were enhanced. Decision makers provided input on treatment of bit error, flexibility in packet generating and user selectivity in channel access. These were incorporated in the simulation program, further strengthening its validity.

- Structured walk-through: A walk-through document specifying the essential elements of the network and outlining all network activity was presented to the spacecraft project's principle investigator, project lead and systems engineer. The meeting resulted in confirmation of model assumptions, awareness of network activity and guidance for PACSIM's development.

- Conversations with system "experts": In addition to over 250 hours of meetings with PANSAT's engineers, nearly 400 hours were spent researching, discussing and studying network communications. Before programming, an extensive analysis of network design indicated the need to reassess the development of the 1200 baud, half-duplex system.

- Existing theory: There is a voluminous amount of literature available on packet communications. Queuing theory applications provided strong background in identifying the stochastic nature of a network and prompted PACSIM's verification.

- Experience/Intuition: PACSIM pre-dates the network it is modeling; in addition, PANSAT will be a unique system. The foundation and fidelity of the model is backed with over 75 years of spacecraft, satellite and communications network design experience of the engineering team.

C. EVALUATING PACSIM AS A DECISION AID

The crux of this issue is credibility. According to Fossett, et al., the level of confidence in a simulation model is bolstered by its ability to:

- reflect and take as input important features of the system being analyzed and its environment;
- produce results that make sense;
- minimize discrepancies between results and real-world observations (Fossett, 1991, p. 714).

The first two points have been covered in Chapters III and V. This last point is very difficult to address PANSAT's network is both unique and not yet in existence. Instead, the following questions may apply in evaluating PACSIM as a decision aid for this project:

- why conduct a simulation study?
- what is the decision-making environment?

a. *Simulation Study*

Reasons for using simulation as a decision aid is based on:

- characteristics of performance measures;
- treatment of assumptions;
- number of scenarios to consider;
- complexity of PANSAT operations;
- design team's confidence in PACSIM.

PANSAT performance measures are highly non-deterministic and have no applicable data for analysis. Examination required a model which incorporates the interdependent design issues and factors as well as the random features. The study is particularly suited for the use of an object-oriented program to specify the behavior and attributes of important network features.

The input data and distributions selected have been previously substantiated. Packet length is the only random input which may not duplicate the real-world size distribution; the use of a uniform random variable provides enough variance to cover a large range of values within the established bounds. Proper imitation of message generating and addressing is arbitrary. A goal is to provide the flexibility to balance assumptions with the ability to alter the scenarios. In order to augment engineers' confidence in the model, the impact of probabilistic assumptions was minimized.

Operation of PANSAT's communications network will be carried out in a multitude of environments. Features include varying numbers, locations and activities of users, noise-induced bit error and spacecraft orbital characteristics. Some features may complement each others' effect on operability while others may be neutral or opposite in their influence. The outcome of a combination of any two alterations may be anticipated. Network performance under several features' changes is much less intuitive and requires experimentation through simulation.

Finally, the network's complexity and the model's crediblity make PACSIM a valued tool. Identifying the nature of PANSAT operations, confirming and measuring the design team's intuitive appraisals, providing meaning to performance variability, and elucidating previously unrecognized system characteristics have strengthened the engineers' ability to make design decisions. Specific improvements in the decision making environment are presented in the next section.

b. Decision Making Environment

The decision makers are engineers with vast experience in space systems. Conclusions based on their intuition benefit from a working knowledge of PANSAT's design issues. PACSIM's first step toward credibility was confirmation of the intuitive assessments:

- a larger number of users leads to increased SCU memory requirements;
- shifting from half-duplex to full-duplex or increasing the data transfer rate shortens sessions.

The next step was to provide an understanding of variability in design issues:

- increased contention for the SCU yields increased frequency of extended sessions and larger swings in SCU memory used;
- longer messages not only increase session durations but experience greater variability in session duration due to retransmission requirements.

This also allowed for discussions of significant differences between performance measures for different designs. Finally, PACSIM has brought to light several issues which make it a useful tool for satellite network design and analysis:

- Multiple attempts are required to obtain a reasonable chance of accessing the SCU. If the Naval Postgraduate School ground control center wants to be assured of access, some other means, such as secondary frequency or coded access, will need to be implemented.
- Network design issues and factors are very densely interrelated. Session duration was expected to have a strong effect on all areas of communications flow. However, in a heavy traffic scenario, it has emerged over the course of experiments to be the driving force behind channel access and SCU utilization.
- Efforts to shorten session duration by improvements in effective data rate make the network more robust against bit error.

At this point in PANSAT's development, the insight into and measurements of characteristic network performance under various design decisions and operating scenarios cannot be obtained anywhere else. PACSIM is not a panacea, however. Numerical results are very much driven by scenario and cannot be extrapolated or predicted when applied to others. This is the reason for providing multiple levels of resolution to the model. Unfortunately, there is no way to ascertain whether enough reality has been implemented or if the correct scenarios have been incorporated in the simulation. It is difficult enough to forecast the utilization of a system which has been operated previously. PANSAT will be the first of its kind.

In any event, PACSIM provides a structure to analyzing the potential operating environment of PANSAT and a means of assessing improvements and degradations based upon design decisions. This tool was not previously available to the design team. A model is a foundation and sets the tone for building a successful network. PACSIM provides a window on previously unforeseen communications and allows the engineers to make more informed decisions.

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