DIRECT SATELLITE COMMUNICATIONS

FINAL REPORT

by

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IMPLEMENTATION STATEMENT

This implementation statement covers two phases of a project entitled "Direct Satellite Communications". The final report for the first phase was published as AK-RD-87-01 and dealt primarily with voice-grade communications applications for DOT&PF and other State agencies. This report is the concluding phase of the work and deals with data-rate transmittal using the same Mobile Satellite System (MSS).

Together both reports describe a technology that is mature but, not yet available to the State as a practical solution to its current communication problems. These reports are most important however, because they lay all of the necessary ground work that DOT&PF and other State agencies would require to take advantage of MSS as soon as it becomes commercially available. It also defines the argument which could be used to help persuade the FCC and others that MSS has a constituency and has applications waiting.

We recommend two further steps be taken at this time to help advance the implementation of MSS technology:

1) A small study be made to develop the special antenna design suitable for utilizing MSS at Alaskan latitudes.

2) An advisory committee be formed from representatives of the various State agencies which would benefit from eventual implementation of MSS. This group could follow the evolution of MSS on a number of levels to assure that Alaskan needs are considered as commercial ventures are formed.

Communications are too important to Alaska for State government to consider anything but the most advanced and reliable systems. Alaska was a leader in the original civil satellite communications evolution. It should continue to be at the forefront for the next advance in the technology to assure the highest possible level of benefit to Alaskans.

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ABSTRACT

The characteristics of a variety of data communication protocols are examined to determine the protocols' usefulness in mobile satellite service. The expected performance levels of the protocols are compared. Both fixed assignment and random access techniques are discussed. Two specific data communication applications have been identified as candidates for use by the state system. Of the protocols examined, the ones most appropriate for use in the candidate applications are listed.

INTRODUCTION

Mobile satellite service (MSS), which has great potential for Alaska, will soon make it possible to communicate with radios which are installed in vehicles (mobiles) or radios that can be carried in backpacks (transportables) virtually anywhere on the continent. It is anticipated that the impact on communication services in the state's rural and remote areas will be substantial.

Direct satellite-to-mobile service will be made possible by one or more satellites in geosynchronous orbit operating in the 1.5 GHz band with high effective radiated power. Narrowband, power efficient modulation techniques will be needed. Mobile units will need low noise receiver front ends and antennas with modest gain. Other ground stations, fixed or transportable, will be able to use the system if they have the same attributes.

The new technology will perform best in nonurban areas, where there will be few path obstructions. In urban areas, where buildings can cause path blockage and multipath problems, performance will not be as good. Mobile satellite service is seen as a way to dramatically improve many communication services outside metropolitan areas, filling the gaps left by present terrestrial systems.

Technical Aspects

Communication satellites transmitting radiated power levels high enough to be usable by mobile and transportable stations will make mobile satellite service feasible. Operation will be at L-band (1.5-1.6 GHz). Direct communication links will be established between a satellite and: mobiles, transportables, gateway earth stations, base earth stations, and a control earth station. Each base earth station will serve a dispatch console, and each "gateway" will provide connection to the public switched telephone network. The control earth station, an operations center, will perform satellite and network control.

The network structure will accommodate four kinds of communication:

1. Mobile to mobile
2. Mobile to base
3. Mobile to public switched telephone network
4. Satellite and network control

The network must serve a large number of mobiles, a smaller but still large number of base stations and gateways, and the operations center.

Because L-band spectrum is in short supply, it is likely that L-band will be used only for communication with mobile units. SHF, either C-band (6/4 GHz) or Ku-band (14/12 GHz), will be used by base stations, gateways and the control station.

Mobile transmissions on L-band will be translated by the satellite to SHF and then retransmitted to a base station or gateway. Similarly, fixed station (base station or gateway) uplink transmissions on SHF will be translated to L-band and then retransmitted to a mobile. All mobile-to-fixed and fixed-to-mobile transmissions will involve a single hop, but mobile-to-mobile transmissions will require a double hop. One mobile's transmission on L-band will be retransmitted to the base station on SHF. It will then be switched at the base station and transmitted back to the spacecraft on another SHF frequency, and retransmitted to the second mobile on yet another L-band frequency.

Satellite voice channels will be assigned automatically and dynamically as they are needed. Under this "demand assignment multiple access" (DAMA) approach, all functions will be performed automatically by user stations and by the operations center. The operations center will answer requests for channel assignments, make channel assignments, perform billing functions, and generally control the network.

A mobile or fixed station initiating a voice contact will use a common signalling satellite channel to automatically request service from the operations center and specify the unit being called. The operations center will assign a satellite channel from a pool of available channels and notify both requesting and called stations to switch to that channel. When the conversation is complete, the operations center will be notified so that billing functions can be completed and the channel can be returned to the pool.

The mobile satellite technology can also be used to provide data communication service. A packet-oriented service might be used to transmit sensor data, position information, or data entered from a keyboard. At low data rates, the service would probably be quite inexpensive.

In order to make mobile satellite service technically feasible, the spacecraft must provide sufficient radiated power in the direction of the coverage area. Radiated power depends on the power available aboard the spacecraft and the gain of the spacecraft antenna. First generation satellites will involve modest antennas and no more than a few beams. Such a satellite might use a 3 to 10 meter UHF antenna. A three beam pattern covering the United States and Canada would require a 5.5 meter antenna.

Circular polarization will be used because of Faraday rotation caused by the E- and F-layers. Further, some degree of cross polarization isolation can be achieved using left-hand circular and right-hand circular polarization. This will facilitate frequency reuse in later generation systems.

In the future, perhaps at the turn of the century, spacecraft may use very large antennas to provide a multitude of spot beams. NASA is planning an effort intended to lead to the development of such a spacecraft. A multiple beam configuration will allow frequency reuse, which will, in turn, mitigate the spectrum scarcity at L-band. With frequency reuse, the same set of frequencies can be used in a number of different beams, but not in two adjacent beams, because interference would result where the beams overlap.

The spacecraft necessary to provide mobile satellite service will be owned and operated by a satellite carrier, which may have as owners wireline common carriers, radio common carriers, and private users. Operating within the present mobile telecommunications industry structure, this company will act as a "carrier's carrier," leasing satellite capacity to wireline common carriers (telephone companies) and radio common carriers, which will market mobile telephone service. The wireline and radio common carriers will provide equipment to their customers and will own and operate the gateways which will allow interconnection to the public switched telephone network.

The satellite carrier will also lease capacity to private users of radio service. These users will own and operate their own mobile equipment and base stations. It is anticipated that existing and new equipment suppliers will manufacture and sell mobile, portable, gateway and base station equipment and antennas.

Signal-to-noise and frequency stability considerations will be paramount in the design of mobile radio units. Since the signal power received from the satellite will be small, low noise receiver front ends will be used, some antenna gain will be required, and modulation techniques will be needed that make the most of available signal power. In addition, narrow channel spacing will allow little room for frequency drift. The National Aeronautics and Space Administration (NASA) and the Jet Propulsion Laboratories (JPL) have started work aimed at developing technology to meet these requirements.

A likely analog voice modulation technique is amplitude companded single sideband (ACSB). Efficient spectrum utilization is necessary for mobile satellite service, and ACSB requires only 4 or 5 kHz channel bandwidth. It is most likely that 5 kHz channels will be used. In addition, ACSB provides very respectable signal-to-noise performance, and it is modest in its use of the limited power available aboard the spacecraft.

Since guard bands will be small, frequency stability is critical. It is likely that a central frequency reference will be used, and all stations will lock to this reference. Doppler shift will be a problem in the case of aeronautical mobiles, for which special frequency correction circuitry will be required.

Low noise receiver front ends and antenna gains of 4 dBi or more will be needed. Two classes of mobile antennas, steered and non-steered, are envisioned. Non-steered antennas (4-8 dBi) will be omnidirectional with regard to azimuth. Steered antennas (with more than 8 dBi gain) will be directional with regard to azimuth and will track the satellite being used as vehicles move about. Besides providing higher gain, steered antennas will also allow more than one satellite to serve the same geographical area on the same set of frequencies. Both antenna types must provide rejection of earth reflections to avoid multi-path fading.

Transportable stations, capable of being carried by a person, will be similar to mobile stations, except that transportable antennas will be able to incorporate high gain without being steerable. It will be possible to set up a transportable antenna and direct it toward the satellite. The antenna will not need to be repointed until it is moved to a new location.

Candidate Applications

Based on interviews with state personnel, two very promising data communication applications of MSS by state agencies have been identified.

Within the Department of Natural Resources, the Division of Geological and Geophysical Surveys operates remote seismic monitoring stations which transmit low speed data. These presently must be located so that they can be connected by VHF to existing microwave facilities. MSS could also provide the communication link, and with MSS, the stations could be located virtually anywhere. This is a telemetry application and its traffic will have stream characteristics with low data rates.

Ships operated by the Marine Highway System are within the Department of Transportation and Public Facilities. The Marine Highway System is interested in expanding its computer-based reservations system to include computer terminals and personal computers located aboard the ships. These must be linked, through a data communication circuit, to a computer ashore. MSS appears to be an ideal way to provide the necessary data communication link. This is an interactive application and the traffic will be bursty in nature.

FIXED ASSIGNMENT TDMA and FDMA

Like conventional satellite communication, mobile satellite service will be capable of providing dedicated data links. Either time division multiple access (TDMA) or frequency division multiple access (FDMA) might be used to provide such fixed assignment links. Today TDMA is frequently the technique of choice, but it is quite possible that in the case of mobile satellite service, FDMA will be used. This is because voice channels will be separated in frequency rather than time.

Fixed assignment TDMA or FDMA links may be appropriate for data traffic which has stream characteristics, particularly where data rates and duty cycles are high. Operation will be similar to that on any fixed satellite link. At the physical level, the only characteristic which will differ from terrestrial operation will be the satellite propagation delay, approximately 270 milliseconds for a single hop and 540 milliseconds for a double hop.

At the link level, it will be appropriate to take measures to compensate for the satellite delay. In order to explain such measures, two approaches to flow control are considered: stop and wait and sliding window.

With stop and wait flow control, a frame of data is sent, and the sender waits for an acknowledgment from the receiver before sending another frame of data. Link utilization is degraded if there is much idle time while the sender waits for an acknowledgment. Degradation can be serious on satellite links because of their long propagation delay.

Utilization is given by

$$U = \frac{1}{1 + 2a}$$

where a is frame transmission time divided by link propagation delay.[5]

It is clear from the above relationship that utilization degradation due to a satellite link's long propagation delay can be overcome only by using a comparatively long frame time. This, however, may be incompatible with traffic characteristics, or the link's bit error rate may necessitate frequent retransmissions. Thus, stop and wait flow control is not generally considered suitable for satellite links.

With sliding window flow control, multiple frames can be transmitted by the sender without receipt of an acknowledgment, and transmission of acknowledgments is overlapped with transmission of frames. The window size N is the number of frames that can be sent without receipt of an acknowledgment. Link utilization is given by

$$U = 1 \text{ for } N > 2a + 1, \text{ and}$$

$$U = \frac{N}{2a + 1} \text{ for } N < 2a + 1$$

Thus, to achieve high utilization, it is necessary to use a window size large enough to compensate for a link's propagation delay.[5]

A link protocol can handle error control by any of three techniques:

- stop and wait ARQ
- go back N continuous ARQ
- selective repeat ARQ

Stop and wait ARQ achieves error control through the use of acknowledgments sent according to the stop and wait procedure described above. It is generally unsuitable for use on satellite links.

The remaining two techniques use the sliding window procedure described above for the transmission of error control acknowledgments (ACK) and negative acknowledgments (NAK). With go back N ARQ, when the sender receives a NAK, it retransmits the bad frame and all succeeding frames. With selective repeat ARQ, the only frames retransmitted are those for which the sender receives a NAK.[5] Selective repeat ARQ can deliver higher link utilization than go back N ARQ but the magnitude of its advantage depends on window size, propagation delay relative to frame size (a), and error rate.

As described in the foregoing discussion, sliding window flow control with either go back N continuous ARQ or selective repeat ARQ error control is generally needed in a satellite link control protocol. Fortunately, link control protocols which provide these features are available.

One example is the high-level data link control (HDLC) protocol developed by the International Organization of Standardization (ISO). HDLC is a bit-oriented protocol with the flexibility to handle a wide variety of situations. HDLC allows both go back N ARQ and selective repeat ARQ, but go back N ARQ is most often used. HDLC provides a maximum window size of either 7 or 127. These window sizes are adequate to prevent satellite propagation delay from reducing utilization in a wide variety of satellite data communication situations.

RANDOM ACCESS TECHNIQUES

In satellite data networks where traffic is bursty and/or duty cycles are low, use of fixed assignment techniques will result in high channel idle time and consequent low channel utilization. In such cases, packet-oriented random access techniques are more appropriate. A single high speed channel is shared by a large number of users, each of which uses the channel for short periods of time. The channel is accessed by the users randomly on an as-needed basis. There must, of course, be a way to resolve the conflicts which occur when two or more users try to access the channel simultaneously.[6]

An example of such a technique is the ALOHA scheme, developed at the University of Hawaii in 1970. A user may transmit at any time. If it receives an acknowledgement from the central computer, it knows that the transmission was received correctly. Otherwise, it waits a randomly determined delay period and then tries again. When transmissions from two users collide, neither will be acknowledged, and the random delay will reduce the chance of a second collision. ALOHA can achieve a maximum channel utilization of 18%. At low traffic levels, average delay approaches one hop, or 270 ms.[1,5]

A variation is slotted ALOHA, in which time is divided into slots one packet length in duration. A user may begin a transmission only at the beginning of a slot. A global timing system is needed. Slotted ALOHA can achieve a maximum channel utilization of 36%. As with ALOHA, average delay approaches one hop at low traffic levels.[1,5]

A further variation is reservation ALOHA, which also divides time into slots. A user which successfully uses a slot is entitled to use the next slot, during which all other users must remain silent. This continues for as many successive slots as are needed by the user. When there is no transmission in a slot, the next slot is available to any user and is accessed in normal slotted ALOHA fashion. Reservation ALOHA is appropriate for stream traffic, but it is an inefficient way to handle bursty traffic.[1,6]

Distributed Reservation Techniques

Three specific reservation techniques designed for use with distributed control have possible application in satellite data networks.

Roberts' scheme divides time into slots, but some slots are divided into a number of small slots which are used for reservation purposes. All other slots are data slots. Users contend for the small reservation slots in slotted ALOHA fashion and use them to reserve future data slots. Data slots are used without conflict. The frequency of occurrence of slots used for reservations can be varied according to load requirements.

In Roberts' scheme, each station must keep track of which data slots are reserved and which are not. Data slots are reserved on a first-in first-out basis. This scheme is capable of good channel utilization and reasonable delay performance.[1,5,6]

A similar technique is Binder's scheme, in which data slots are assigned to using stations in normal TDMA fashion. Since there are always more slots than stations, there are also some additional unassigned slots. When a station transmits data in a slot, it also sends a header, which indicates the number of additional packets still waiting in the station's queue. A zero count indicates that the slot is free and available, along with the unassigned slots, to be used by other stations. Available slots are used by the stations in round-robin fashion. Binder's scheme can accommodate a mix of stream and bursty traffic with reasonable utilization and delay. Both Roberts' scheme and Binder's scheme can achieve channel utilizations in the 70 to 90% range. The two reservation schemes have a minimum average delay of two hops.[1,5,6]

A third distributed reservation scheme, which can also be used with centralized control, is called priority-oriented demand assignment (PODA). With this technique, each frame includes a number of data slots and a number of smaller reservation slots. A station may use a reservation slot to reserve a single data slot, or it may make a "stream reservation," which reserves data slots for the indefinite future. Reservations may also be piggybacked onto data packets.

When there are a small number of using stations, reservations slots are pre-assigned in TDMA fashion. Otherwise, stations contend for the slots using slotted ALOHA. Since PODA is so complex, all using stations must keep track of all pending reservations. Depending on traffic characteristics, PODA may provide some performance improvement over Binder's and Roberts' schemes.[1,5]

Application of Distributed Random Access Techniques to Mobile Satellite Service

Any of the techniques described above could be adapted for use with mobile satellite service. There is a complication, however, which arises from the structure of a mobile satellite network. Mobile-to-mobile communication can take place only through a fixed earth station. Thus, a channel could be shared by a number of mobiles only when the fixed station provides a connection from a SHF downlink channel to a SHF uplink channel. This would effectively connect an L-band uplink channel to an L-band downlink channel. In this way all mobiles could access a common channel.

The arrangement described above will result in twice the propagation delay experienced in a conventional multiple access satellite network. Thus, single hops become double hops, double hops become quadruple hops, etc. The minimum average delay for ALOHA and slotted ALOHA would be 540 ms, and the minimum average delay for the reservation techniques would be 1,080 ms.

Centralized Reservation Techniques

Since a mobile satellite network is inherently a centralized network, it is natural to consider centralized reservation schemes. Both ALOHA and slotted ALOHA, for example, can be used in a centralized network. In fact, ALOHA was first used at the University of Hawaii in a centralized system. In a centralized system, contention will occur only on inbound links from remotes to the central controller. The central controller has no competition for access to outbound links.

Stallings describes a centralized reservation scheme developed by NASA for use with five to 20 earth stations and capable of handling three traffic types: voice and telemetry, file transfer, and interactive. The scheme, which uses TDM, provides for the dynamic allocation of virtual circuits on an as-needed basis. The NASA scheme is optimized for stream traffic.[5]

Li and Yan have proposed a centralized reservation scheme intended specifically for mobile satellite service. Called the adaptive mobile access protocol (AMAP), it is oriented to the 5 kHz channels anticipated for mobile satellite use.[3]

The technique is similar to the reservation schemes described above, but it uses frequency channelization for compatibility with present mobile satellite plans. With a low gain antenna (3-5 dBi gain), a data rate of 2.4 kbps will be possible in a 5 kHz channel.

AMAP divides the available 5 kHz channels into data channels and reservation channels. Using stations send reservation requests to the central controller using either ALOHA or slotted ALOHA. When a reservation request is successfully received by the central controller, it makes a data channel assignment using a special acknowledgment channel on which there is no congestion. The controller also indicates when the using station may begin transmitting.

AMAP also provides for the reassignment of reservation channels and data channels as dictated by traffic conditions. All stations must, of course, be notified of such reassignments, and time must be allowed for the stations to readjust.

AMAP is not a developed and tested scheme. It is, instead, a proposal, some of whose details have not yet been worked out. Nevertheless, Li and Yan have estimated the performance levels that might be achieved with AMAP. Delays comparable with those experienced in ALOHA can be anticipated, but utilizations may be as high as 50 to 60%.[3]

Of the random access techniques investigated here, AMAP is the one which appears to have the greatest potential to accommodate a wide variety of traffic types in a mobile satellite environment. Its performance is likely to surpass the other schemes that have been described.

CONCLUSIONS

Mobile satellite data communication applications which involve high data rates and duty cycles will probably use fixed assignment. Although TDMA is possible, it is most likely that FDMA will be used. Mobile-to-fixed links will be single hop (270 ms propagation delay) and mobile-to-mobile links will be double hop (540 ms propagation delay).

On such fixed assignment links it is important that link protocols be used which prevent satellite propagation delay from degrading link utilization. Sliding window flow control and either go back N continuous ARQ or selective repeat ARQ should be used. In each application, it should be assured that window size is adequate.

One widely used link control protocol which has the required characteristics is the high-level data link control (HDLC) protocol. HDLC provides window sizes of 7 and 127, which will be adequate in a wide variety of situations.

When traffic is bursty and/or duty cycles are low, random access techniques will be appropriate. Although there may be some applications for which distributed techniques will be effective, it is expected that centralized techniques will generally be most appropriate.

Where only low channel utilizations are required, simple techniques like ALOHA and slotted ALOHA may be adequate. Where stream traffic is involved, reservation ALOHA may provide acceptable performance.

The random access protocol which appears to hold the most promise is the adaptive mobile access protocol (AMAP) proposed by Li and Yan. Although AMAP is, at this point, still a proposal which has not been fully tested, it is likely that it will provide excellent performance over a wide range of traffic types. Link utilizations as high as 50 to 60% may be achieved.

Two candidate data applications of mobile satellite service have been identified, the Department of Natural Resources (DNR) telemetry application, and the Department of Transportation and Public Facilities (DOT&PF) interactive application.

For the telemetry (DNR) application, the following protocols should be considered:

- ALOHA
- slotted ALOHA
- reservation ALOHA
- AMAP

A protocol should ultimately be selected based on traffic characteristics, link utilizations required and cost. Reservation ALOHA may be useful in this application because it performs well with stream traffic.

For the interactive (DOT&PF) application, the following protocols should be considered:

- ALOHA
- slotted ALOHA
- AMAP

A protocol should be selected based on delay performance required, link utilization required and cost. Assuming that AMAP is fully developed and available, it is likely to provide the best performance, perhaps at the highest cost.

FURTHER RESEARCH

The work reported here and in the Phase I and Phase II reports has helped to position the State of Alaska to appropriately utilize mobile satellite service. One additional research effort will help to insure that the new service can be used from Alaska's high latitudes. This is an antenna design effort which would be aimed at the development of mobile and portable antennas with low elevation angles.

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