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ABSTRACT

Conventional communication satellites, using transponders, can provide high efficiency communications in an unstressed (low noise) environment between terminals of the same type. However, such satellites are not suitable for providing such capabilities as anti-jam protection or interconnectivity of messages between terminals of different types, both important for military communications purposes. On-board satellite signal processing can provide these and other capabilities. This report discusses on-board processing's advantages and costs, and shows how it can be incorporated into a system concept.

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APPENDICES

(To be published in a separate Volume)

1. Introduction

On-board signal processing for satellite communications provides both advantages and costs which must be weighed when designing system architectures. On-board processing allows capabilities to be achieved beyond those which have been realized with simple transponder satellites. These improvements, to be described in this report, are listed in Table 1.1. In exchange, on-board processing requires additional spacecraft power and weight. However, this cost may be offset by improved communication link efficiency, allowing a reduction in the power and weight required by the satellite transmitters and antennas. Certain of the capabilities which can be achieved by on-board processing can also be implemented by a combination of processing on the ground and less extensive on-board processing; or a reduced capability can be realized with simpler on-board processing. The services which a satellite communication system is required to perform and the trade-offs inherent in the above discussion must be considered together in evaluations of processing satellites.

The purpose of this report is to clarify issues concerning the benefits and costs of on-board signal processing.

Briefly outlining the contents, Section 2 describes the advantages which on-board processing can provide, both for unmodified existing terminals and for upgraded AJ terminals. An upgraded terminal in this context may employ a different modulator, modem, control, etc., than existing terminals, but would not generally require changes such as a new antenna installation or RF receiver/transmitter unit. On-board signal processing has the potential for improving communication by providing AJ protection, message bit interconnectivity between terminals of different types, easy crossbanding, and efficient utilization of satellite EIRP. Moreover, many of these advantages can be provided for unmodified, existing terminals. Section 3 briefly and qualitatively discusses the costs of processing. Section 4 carries the cost discussion further, detailing the power and weight for a particular processing satellite example. This "strawman" design is described in terms of its capabilities, and also its power and weight compared to that of conventional transponder satellites.

TABLE 1.1

ADVANTAGES OF ON-BOARD PROCESSING

Interconnectivity between terminals of different types

RFI protection and AJ protection through frequency agility

More efficient satellite EIRP utilization

- increased data rate or decreased EIRP possible
- elimination of small signal suppression
- no power robbing

Increased capability for half-duplex users

Reduced intermodulation product problems

Maximum AJ protection

- largest J/S
- protection for many users simultaneously
- interconnection of AJ uplink to unmodified terminals

Efficient use of resources

- downlink matched to receiving terminal's capability
- close packing of unsynchronized FDMA users

Channel switching

Message switching

Packet switching improvements

Flexible satellite resource management

Easy crossbanding

Many of the numbers used here were determined via a hardware development program at Lincoln Laboratory. Section 5 presents alternative systems with various levels of on-board processing, providing various combinations of capabilities. Section 6 summarizes the report and discusses some remaining questions. Certain details, as referred to in the text, are covered in appendices. These are listed in the Table of Contents.

On-board signal processing covers a wide range of functions in this report. Among those considered are frequency dehopping, demodulation/remodulation, deinterleaving/interleaving, error correction decoding/encoding, demultiplexing/multiplexing, channel switching, message switching, reformatting, buffering, signal sampling, and crossbanding. Each of these functions and combinations of them provide certain useful communications capabilities and cost some amount of spacecraft power and weight, as discussed in this report. Adaptive antenna nulling is also an on-board processing function, but is not included in this report except as it may impact one of the other aspects of signal processing.

2. On-Board Processing Advantages

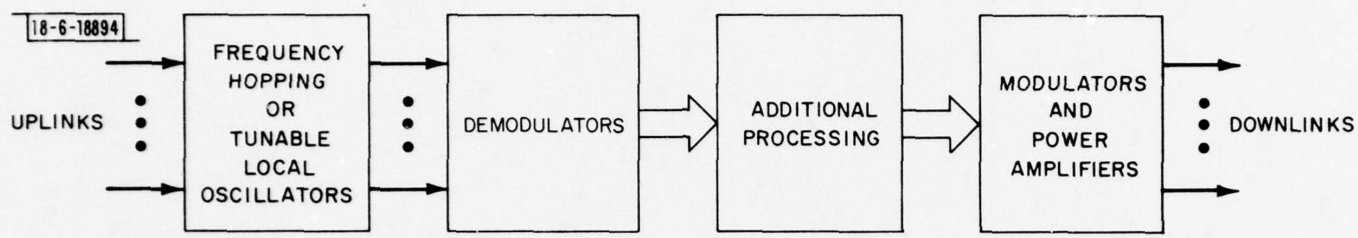
The advantages achievable through on-board signal processing may be divided into two classes: those available to unmodified (existing or planned) terminals, and those which would require an upgraded terminal or terminal modifications. The major advantages for unmodified terminals include interconnectivity of terminals with different modems, RFI protection, a modest level of anti-jam (AJ) protection, and more efficient utilization of satellite EIRP (under some conditions). A system containing upgraded terminals would additionally gain the greatest AJ protection possible consistent with the available spread bandwidth, and the ability to connect such AJ uplinks to downlinks for unmodified terminals. Moreover, this AJ protection would be available to a large number of simultaneous users. This section discusses these features, and other advantages realized by on-board processing, primarily for UHF communications. The general form of the type of processing satellite which is mainly discussed in the following is shown in Fig. 2.1.

2.1 Advantages for Unmodified Terminals

2.1.1. Interconnectivity

Interconnectivity, as used here, is the ability to communicate message bits between terminals of different types. Interconnectivity is a necessary, but not always sufficient, step toward interoperability. Interoperability includes the additional requirement that the message bits must make sense to the receiving terminal, in the context of net protocols, preambles, conventions, cryptographic protection, I/O formats etc. Figure 2.2 illustrates various interconnective paths.

On-board demodulation and remodulation of uplink signals provides a channel bit stream from each uplink at the processing satellite. These bit streams may be connected to whichever downlinks are desired, providing a very flexible interconnective system. For example, a signal arriving at a satellite from a Navy terminal with a WSC-3 at 300 bps PSK is normally retransmitted unchanged to a NAVCOMSTA receiving with a WSC-5. The 300 bps uplink at the satellite can simultaneously be demodulated and buffered for transmission to an ABNCP's



NOTE: (1) UPLINKS MAY DIFFER IN NUMBER AND MODULATION FORMAT FROM DOWNLINKS

(2) DOWNLINKS MAY TDM DATA FROM SEVERAL UPLINKS

(3) UPLINKS MAY BE CONNECTED TO ANY (or more than one) DOWNLINK

(4) VARIETIES OF ADDITIONAL PROCESSING DEPEND ON OBJECTIVES, DIFFICULTY OF IMPLEMENTATION, etc.

Fig. 2.1. General structure of a processing satellite.

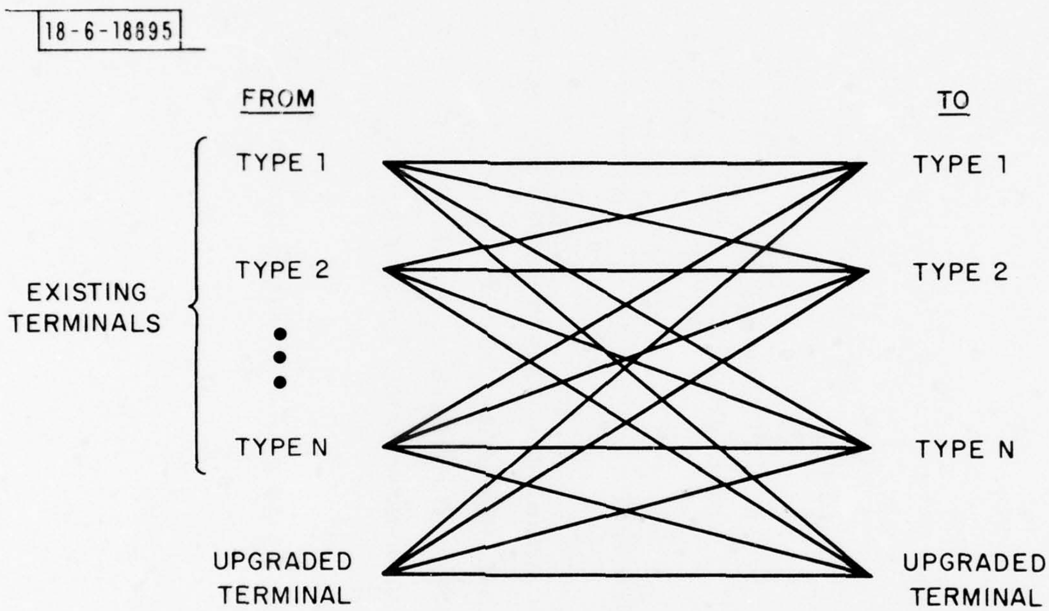


Fig. 2.2. Interconnective paths.

ASC-21 at 75 bps FSK (for finite length messages). This interconnectivity is impossible without either on-board demodulation or a central ground station. In the latter option, messages to be interconnected are sent via a downlink to a ground station equipped with both types of terminals, re-formatted as necessary, sent up to the satellite again, and then re-transmitted at UHF to the receiving terminal.

Interconnectivity between uplinks and downlinks with different levels or types of error correction coding may also be accomplished with no terminal modifications. In addition to on-board demodulation/remodulation this feature requires on-board decoding/encoding (similar comments apply for interleaving). This feature, with on-board frequency dehopping, allows interconnection of upgraded, uplink hopping, AJ terminals (using coding) with unmodified terminals (without decoders). Such an interconnection would be useful during a stressed period (not necessarily war) when uplink interference was present. Commands from AJ terminals would still be receivable by all units, although non-AJ terminals might not be able to report-back. Interoperability, the interconnection of terminals operating in different net disciplines, may also be achieved by on-board processing, specifically by the spacecraft re-formatting messages according to particular net protocols. These features may also be implemented via the ground-station approach, with the satellite being correspondingly less sophisticated.

2.1.2 Frequency Agility

Protection against RFI is achievable for unmodified terminals which have the capability of choosing any one of a number of frequencies for their transmissions. The satellite requires only the inclusion of command-tunable receive local oscillators. This system concept could also easily include a means of monitoring the downlink to detect RFI problems in order to command an uplink frequency switch. Frequency changes for this purpose would generally occur only occasionally, and could be done manually.

An expansion of this concept, along with a central ground station, can provide a modest level of AJ protection to unmodified terminals. A terminal's uplink frequency would be governed by a code book, listing the frequencies to be used depending on the time and date. The frequencies would be chosen in a secure manner, changing infrequently enough to not become a burden operationally. While the uplink is frequency agile, the downlink is at a fixed frequency. The uplink signal (encrypted for security) is received (via a tunable receive L.O.), sampled and digitized, and the digital samples "covered" before retransmission to prevent a jammer from probing the uplink to determine the uplink frequency by observing the downlink. The covered samples are transmitted to the central ground station at SHF, decovered, demodulated, decrypted, validated, re-encrypted, and remodulated for transmission to the satellite at SHF with AJ protection. This uplink is despread by the spacecraft and analog crossbanded for retransmission to the intended receiving terminal at UHF.

As an example, the above system would increase the margin against jamming (compared to a non-frequency agile system) by about 30 dB for those Navy UHF terminals whose frequency is tunable over 20 MHz on 25 kHz centers. Upgraded terminals with fast frequency hopping ($\sim$ 100 hops/sec), coding, and interleaving, operating with a dehopping, demodulating/remodulating satellite would provide approximately 15 dB of further improvement in AJ margin.

A more complete discussion of the issue of frequency agility, is provided by Bucher (to be published).

2.1.3 Efficient EIRP Utilization

An efficiency comparison between hard limiting transponder satellites and satellites with on-board processing depends on the particular situation of concern; i.e., whether the communications are signal-to-noise uplink limited, downlink limited, and/or bandwidth limited. In any event, a demodulating/remodulating satellite decouples the effects of noise and interference on the uplink from that on the downlink. The usefulness of this decoupling is the main topic of this section. Demod/remod also allows the uplink and downlink frequencies, modulations, and multiple access formats to be separately optimized for whatever forms of RFI, jamming, multipath, or terminal constraints each must face. Figure 2.3 pictorially depicts the points of the following discussion. (This

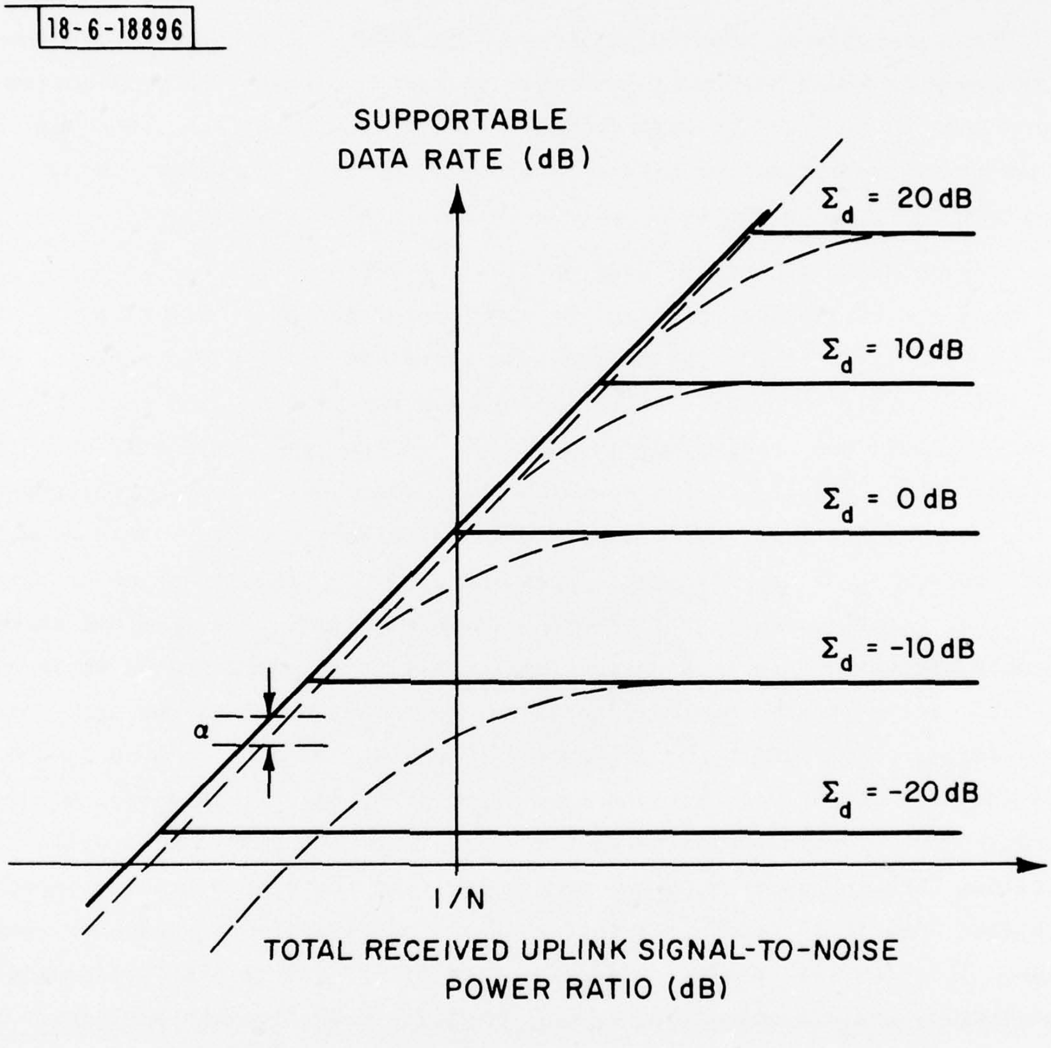


Fig. 2.3. Comparison between hard-limiting transponder (dashed line) and demod/remod satellite (solid line).

figure assumes N equal EIRP users; Σ_d and α are defined in the following. Unequal EIRP users, or power imbalance, is discussed later in this section.)

When the ratio of total signal power received at a transponder to the noise power in the transponder bandwidth is large, little EIRP utilization improvement is realized by demod/remod. However, uplinks from low power terminals (e.g., submarines or aircraft) or uplinks being jammed or subject to interference often do not satisfy this large signal criterion.

Transponders, except for some nonlinear effects which lead to small signal suppression,* retransmit power in the same proportion as it was received. In other words, if the total uplink received signal-to-noise power ratio is small, then only a small proportion of the downlink power is dedicated to signal power, with this small amount divided among signals in the same ratio with which they arrived on the uplink. If the downlink power received is very large compared to the downlink receiver noise (approaching a perfect downlink) then even though a particular signal may have been apportioned a very small fraction of the downlink power its received signal-to-noise ratio may still be sufficient to provide adequate reception. In this uplink limited situation, demod/remod would allow the data rate supported to be increased by an amount equal to the small signal suppression, from 1 dB in the presence of Gaussian noise up to 6 dB in the presence of a strong constant envelope interfering signal. However, with either a transponder or demod/remod satellite such a powerful downlink is wasteful of satellite EIRP. This is apparent particularly in the case of the transponder satellite when it is recognized that most of the EIRP is being used to retransmit noise. Therefore, in trying to increase the efficiency of EIRP utilization one must examine the effects of decreasing satellite EIRP from the near perfect downlink situation above. As satellite EIRP is decreased to a certain extent both the transponder and demod/remod satellite continue to be able to support

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* It should be noted that this small signal suppression, eliminated by demod/remod, can reduce the signal-to-noise ratio (at the output compared to the input) by up to 6 dB for a hard-limiting transponder. The 6-dB worse case suppression of a small user occurs when a strong constant envelope user or jammer signal is present in the received bandwidth.

the same data rate as above (and within 1 to 6 dB of each other). However, as the satellite EIRP is decreased further, the data rate supportable by the transponder falls off considerably before the demod/remod satellite suffers the same effect. More specifically, if the above small uplink signal-to-noise ratio applies, and the downlink is not so strong as to be near perfect, demod/remod provides large advantages. Quantitatively, if the total power received from the transponder satellite is small compared to the receiving terminal's receiver noise power in the transponder's bandwidth, and the small uplink signal-to-noise ratio case applies, then a demod/remod satellite can support a data rate $1/\alpha\Sigma_d$ greater than a transponder satellite. α, the small signal suppression factor, equals 0.8 for Gaussian noise and 0.25 if a strong constant envelope signal is present, and Σ_d is the ratio of total received power-to-receiver noise power in the transponder bandwidth at the receiving terminal. This gain, achievable on links from low power terminals (or uplinks subject to jamming or interference) to small terminals (with low G/T), can be quite large. In situations which are between uplink and downlink limited operation, the most efficient operating point (in that no terminal or satellite power is being wasted), demod/remod exhibits about a 3-dB advantage.

Demod/remod advantages over transponders may be realized as an increased data rate supported for the same satellite EIRP (as long as a bandwidth limitation is not reached), or as a decrease in the EIRP required to support the same data rate. A 1w decrease in EIRP results in about a 2w decrease in satellite prime dc power; therefore, the power saved in this way by on-board processing should be considered when the power requirements of on-board processing hardware is discussed.

The above comparisons between transponders and demod/remod processing focused on hard decision demodulation in the demod/remod satellite and receiving terminals which also made hard demodulation decisions. When error correction coding is used the situation is slightly altered. In the decoding process, soft decision information can yield improved performance. On-board hard decision demodulation effectively costs 2 dB in required uplink signal-to-noise ratio (given that coding is used) against white noise compared to a processing satellite which either transmits soft decision information on the downlink or does on-board soft decision decoding. The cost for the first option (soft decision information on the downlink) is increased downlink transmission rate and bandwidth (and possible modification of the receiving terminal), while the second option requires an added on-board processing function, increasing the spacecraft weight and power. Note that the first option is not feasible in a situation downlink limited in either power or bandwidth. If the total received uplink signal-to-noise power ratio is large and performance is uplink limited, the 2-dB cost of on-board hard decision demodulation can mean that a transponder may perform better, since it preserves soft decision information. In those cases above where hard decision demod/remod had a large advantage over a transponder, however, the transponder would remain at a disadvantage. And, for comparison of a transponder with a processing satellite with on-board soft decision decoding, the original hard decision remarks hold. It should be noted that in the presence of certain jamming strategies, the 2-dB cost above may in fact be greater, but the comments of this discussion still apply. In a satellite with on-board decoding, after decoding the information bits may be encoded with the same code as used on the uplink (for use by terminals previously using end-to-end coding without any modification); they may be left uncoded and remodulated (to provide interconnectivity between terminals which use coding and those without a decoding capability); and they may be encoded with a different code than was used on the uplink (thereby optimizing uplink and downlink coding separately depending on the interference faced by each).

This section focused on the comparison between a processing satellite and one with a hard-limiting transponder. Other types of transponders exist, but the hard-limiting type provides the most appropriate comparison. For a detailed discussion of this entire topic, see Heggestad [1976].

Another advantage of demod/remod is the elimination of the need for any margin added to the satellite EIRP to account for power imbalance among FDMA users, to provide sufficient downlink power even for a low power uplink signal which otherwise would receive too small a proportion of downlink power if other uplinks are stronger. A demod/remod satellite can provide equal power to users regardless of uplink power ratios, eliminating this "power robbing" effect, and can even be made to adjust power among different downlink data streams to provide more energy per bit to those destined for low G/T terminals. Alternatively, a non-demod/remod solution to this particular problem also exists, namely a bank of frequency selective limiters with individual AGC loops operating within a wideband transponder.

2.1.4 Improvements for Half-Duplex Users

A half-duplex terminal (one which cannot transmit and receive at the same time) operating in a TDM net is constrained as to the number of simultaneous circuits which it can support in that net. This stems from the requirement that the TDM slot assignment algorithm avoid those situations which expect the half-duplex terminal to concurrently receive and transmit. A processing satellite can mitigate this constraint. A number of possible approaches exist, one of which (for unmodified terminals) is for the satellite to delay every received TDM frame by one time frame interval minus twice the average terminal to satellite propagation delay (260 msec for a geostationary satellite). This added delay allows greater flexibility for TDM slot assignments for half-duplex terminals. This concept is discussed more fully in Appendix VIII. The cost of this increased capability for half-duplex users is a somewhat decreased system throughput efficiency due to the large (40 msec) guard intervals that would be required between time slots within a frame. The effect of this concept on voice transmission is to increase the turn-around time (the time between one user ceasing to speak and the start of his hearing a reply) from two TDM frame intervals to double that time. This doubling may or may not be acceptable, depending on the length of the TDM frame and the requirements of the particular TDM communication system in question. It should be noted that this doubling can be avoided via other approaches involving some terminal modifications (see Appendix VIII).

2.2 Additional Advantages with Terminal Modifications

2.2.1 Intermodulation Products

A problem with any satellite is the generation of intermodulation products (IM) among downlinks at different carrier frequencies. Demod/remod can help this situation for the case of a number of FDM users. After demodulation, these FDM user signals can be multiplexed into one or a few TDM downlink bit streams, for retransmission via remodulation. In other words, the ability of demod/remod to allow conversion of FDM uplinks to TDM downlinks can reduce the number of downlink carriers, ameliorating the severity of the IM problem. This feature, however, requires terminal modifications in order to gain its benefits (e.g., adding time division demultiplexers to terminals not so equipped).

2.2.2 Anti-Jam Performance

Terminals operating with FDMA uplinks, using error correction coding, interleaving, and frequency hopping have the potential for the maximum AJ protection possible consistent with the spread (hopping) bandwidth. To achieve the full potential AJ protection under all conditions such terminals must operate in a system with a processing satellite. Moreover, a processing satellite is one way of providing good AJ protection to a large number of users simultaneously.

As described in Section 2.1.3, on-board demodulation/remodulation is required to make the most efficient use of satellite EIRP, and hence provide the best protection against jamming. This is especially true when the total uplink signal power is small compared to the noise power over the received bandwidth (as in the case of jamming) and the downlink is also weak (e.g., to low G/T terminals or if downlink jamming exists). A 2-dB advantage may be gained by on-board deinterleaving and soft-decision decoding, instead of end-to-end coding and interleaving with on-board hard decision demodulation. Even larger gains are achievable under non-white noise jamming. On-board deinterleaving and decoding also allows interconnection of message (information) bits from upgraded terminals with uplink AJ protection due to hopping, interleaving, and coding, to unmodified terminals without suitable equipment (hopping L.O.s, deinterleavers, decoders). This AJ uplink interconnectivity to unmodified terminals, along with the large number of potential simultaneous AJ accesses (to be discussed in the following), may in some cases be more important AJ related advantages of on-board demod/remod than an increase in J/S (a measure of AJ protection for a particular link). This is due to the fact that although demod/remod increases J/S by the same amount as it increases the efficient utilization of satellite EIRP, as pointed out in Section 2.1.3 this increase may be small (between 1 and 6 dB, due to small signal suppression). It should be noted that this interconnectivity may also be provided through a processing central ground station, an option discussed further in Section 5.

As an alternative, a satellite which can dehop fast hopping (< 240 msec dwell time) uplink signals, coupling them to a narrowband transmitter but including no additional processing can also provide significant AJ protection. Although it does not make the most efficient use of its downlink EIRP, a satellite with a bank of relatively narrow (25 kHz) transponders and hopping local oscillators can provide AJ protection to terminals which frequency hop and use end-to-end coding and interleaving. The J/S of such a satellite would not be much increased by on-board demod/remod and decoding. The main limitation of such a satellite involves the number of users which can simultaneously achieve this AJ protection via orthogonal accesses (e.g., FDMA). Although the exact numbers depend on the link of interest and the power balance between users, in general only a very few uplink signals may be handled by each transponder, as discussed in Appendix I. The results of this Appendix are shown in Fig. 2.4 for a particular example. The results shown by this figure were arrived at by assuming a constant envelope jamming signal, small total received uplink signal-to-jammer power ratio (when few users are present), and that all downlink power except that due to the user signals can be treated as in-band noiselink interference (a conservative assumption). The number of circuits supportable by full processing (on-board demod/remod and decoding) is constrained by the total number of bits which can be transmitted on a 26-dBw EIRP downlink (limited by the received signal-to-noise ratio). The difference in relative AJ performance exhibited by the curves of Fig. 2.4 for small numbers of users

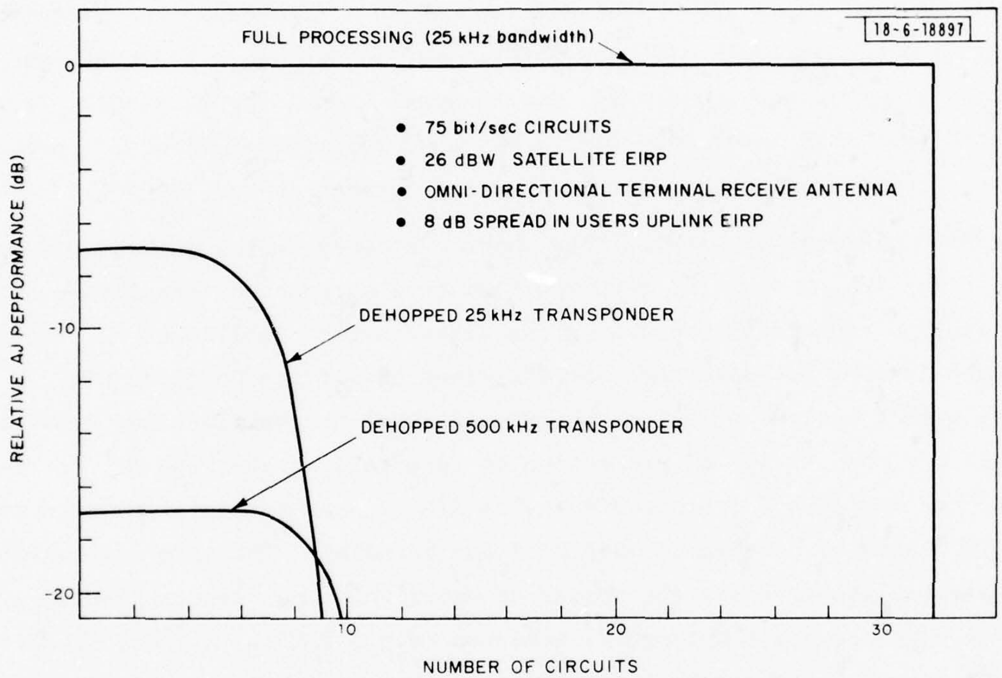

Fig. 2.4. Relative AJ performance and capacity.

(circuits) is due to small signal suppression effects and the large proportion of satellite power dedicated to retransmitting the jamming interference. The premature roll-off of the transponder curves (compared to the full processing curve) is due to the power imbalance among the various users.

Since the number of on-board transponders is limited ($\lesssim 10$) in a practical satellite design by intermodulation product considerations, the above simple attempt at providing AJ protection yields somewhat less AJ protection to a given user than is achievable with a demodulation/remodulation satellite and can provide such protection to only a small number of users simultaneously (on the order of 10). If each uplink is used to TDMA N signals in an effort to increase the number of AJ protected accesses to the satellite, the level of AJ protection is reduced by a factor of N, because of the N times higher burst rate (assuming peak power limited transmitters). A processing satellite, on the other hand, could allow a large number (on the order of 100) of AJ protected uplinks to simultaneously access the satellite via FDMA. Each uplink would be separately demodulated. The channel bits from a number of FDMA uplinks would then be TDMed onto one of a small number of downlinks (to avoid the intermodulation product problem).

It should be noted that while TDMA cannot substitute for processing for the purpose of increasing the number of simultaneous AJ accesses to a satellite it may be a useful technique for either a processing or transponder AJ system. A frequency-hopped TDMA channel may provide sufficient AJ protection (even with the factor of N degradation) in the face of a small scale jamming attack. As the jamming attack becomes more serious, AJ protection can be maintained by decreasing the number of users of the TDMA channel. This technique can provide a graceful changeover into an AJ mode of operation.

Frequency hopping was chosen over pseudonoise as the spread spectrum technique due to its less demanding timing requirements, better protection against narrowband RFI, and lack of dispersion related problems. Frequency hopping is also more applicable for use with antenna nulling systems, which generally cannot easily provide good nulls over wide instantaneous fractional bandwidths

($\gtrsim$ 3%) as would be needed with a pseudonoise system. FDMA was chosen over TDMA and CDMA as the multiple access technique for use in conjunction with frequency hopping. FDMA has an inherent factor of N advantage in AJ protection over TDMA for N users, as discussed above. CDMA requires a separate multiple access sequence for each user, complicating an on-board processor, and is relatively inefficient in its use of bandwidth. FDMA users may frequency hop as a group according to a common hopping pattern, allowing a single dehopper to be used for many uplinks.

2.2.3 Efficient Use of Resources

In addition to AJ protection for a large number of simultaneous users, other advantages accrue from using an upgraded terminal with a processing satellite. Satellite EIRP is efficiently used by the ability to flexibly match the uplink and downlink channel-bit rates separately to those channels. Of particular interest is the ability to create a TDMA downlink whose burst rate is variable from slot to slot depending on the capabilities of the terminal to receive that slot of the downlink. This may be accomplished regardless of the uplink rates of the bits being transmitted (within limits).

This upgraded terminal-processing satellite system also allow efficient bandwidth utilization in that it allows close frequency packing of many poorly power controlled, time unsynchronized FDMA users, due to the use of on-board demod/remod and TDM downlinks. Close packing of these unsynchronized users may be achieved through the use of a low crosstalk modulation [White, Kalet, and Heggestad, 1977]. This feature is important when AJ protection is needed (necessitating FDM uplinks as discussed in the previous section), since hardware speed considerations for on-board digital hardware favor narrow total bandwidths (and hence lower sampling rates), and for the advantage of being able to pack many signals into the bandwidth of a nulling processor.

2.3 Discussion

Interconnectivity between unmodified terminals and between upgraded AJ protected terminals and unmodified ones has already been mentioned as an advantage of a processing satellite. It should be noted that such interconnectivity may be more sophisticated than simply channel switching. Message switching may also be accomplished. This means that a particular message may be demultiplexed from one TDM uplink and injected (possibly after buffering and additional processing to change its format) into slots on any of a number of different TDM downlinks.

Packet switching does not require a processing satellite for its implementation. However, it has been shown that on-board processing can dramatically increase the throughput efficiency of a packet switched system [DeRosa and Ozarow, 1978]. Slotted ALOHA systems typically operate at less than 36% efficient utilization of downlink EIRP. Processing multiple uplinks into a single downlink increases this efficiency to almost 100%.

Besides the advantages already discussed, on-board signal processing allows flexible satellite resource management and enables an evolutionary transition from old to upgraded terminals. A general design for a processing spacecraft includes a bank of demodulators, intermediate channel bit processing to perform all the functions discussed above, and a number of modulators and power amplifiers. Each uplink is demodulated using an appropriate demodulator and the resulting (possibly further processed) bits are connected to whichever downlink modulators are desired. Demodulators and modulators may be constructed to function in a variety of modes by command, in order to be used for a number of modulation rates and types. Therefore, varying requirements can be met by commanding the demodulator and modulator modes and/or by reconfiguring the intermediate channel-bit processing. Similarly, functional reliability is enhanced via this ability to reallocate resources. The satellite processing can also be reconfigured by command to provide a pre-emption capability. This flexibility, together with the interconnectivity available, makes the processing satellite useful for an evolving system. For instance, as upgraded terminals come on-line they may communicate with each other and with older unmodified terminals through interconnections. As more older terminals are replaced, the satellite resources may be gradually shifted more toward serving the upgraded terminals. For example, a larger proportion of the uplink demodulators would be commanded to the mode appropriate for the upgraded terminals.

It should be noted here, and will be further discussed in Sections 4 and 5, that even with on-board processing, many of the communications functions required can still be handled by transponders, particularly clear mode (unjammed), high efficiency TDM links carrying messages not requiring interconnectivity. A processing satellite would bypass its processing to form a transponder channel for such traffic. It will be seen that the ability to form such channels eases the burden on the on-board processing. Specifically, high burst rate, clear mode TDM links need not be demodulated and remodulated. Only those TDM slots requiring interconnectivity are demultiplexed for further processing.

As a final point in this section, mention should be made of the advantages of crossbanding between UHF and SHF (X-band) or EHF (K- or Q-band). Crossbanding can be easily accomplished at the channel bit level in a demod/remod satellite, and analog crossbanding is also possible. Crossbanding, allowing the use of SHF for some traffic that otherwise would have used UHF (on the uplink or downlink) has a number of useful features. Crossband operation permits SHF terminals to be used as they are installed, on a terminal-by-terminal basis, with SHF-UHF interconnectivity accomplished by either on-board demod/remod and possibly additional processing or by acquiring SHF terminals with modes compatible with UHF terminals. There is no need to wait until a whole net of users is so equipped. Moreover, the AJ protection available at SHF is much greater than that of UHF and spot beam antennas on satellites are more easily constructed. Also, the use of SHF for traffic between the satellite and SHF equipped users, including command centers, would greatly reduce the traffic to be carried by UHF, thereby limiting the amount of the crowded UHF spectrum required. Examples of system options including crossbanding are given in Section 5.

3. Costs of On-Board Processing

The previous section described some of the advantages to be gained through on-board processing. This section discusses what price must be paid for these advantages. This includes added weight, power, and complexity for the spacecraft and implications for terminal design. Only a brief qualitative discussion is presented here. A more detailed look at this question including power and weight figures and comparisons with a transponder satellite is contained in Section 4.4 for a particular "strawman" system example.

Many of the advantages of on-board processing stem from demodulation and remodulation. In order to provide the flexible interconnectivity discussed in the last section, the satellite must be capable of demodulating a variety of modulation forms and also remodulating in a number of modes. An on-board demodulator and modulator design which allows each device to operate in any of a variety of modes (modulation form and data rate) by command results in the most efficient and flexible use of spacecraft resources. Appendix II discusses such a design further. Also, control of the modes of these multimode demodulators and modulators must be provided (see Appendix III).

In addition to requiring the appropriate demodulator, each uplink modulation to be received requires an on-board acquisition and tracking (time and frequency) algorithm to be implemented. For example, in order to work with existing systems, a processing satellite must acquire and maintain time and frequency to within appropriate constraints for each type of uplink format. This task must be accomplished by algorithms which utilize the preambles presently used by these existing systems (by the receiving terminal) for acquisition and tracking purposes. Appendix IV gives more details about this problem.

On-board demodulation provides the bits which are transferred to the on-board modulators for retransmission. This transfer of bits from an uplink to particular downlinks requires additional on-board hardware for buffering and switching. A Communications Output Processor (COP) is associated with each downlink. It picks off bits at the demodulators' outputs in such a way as to create the desired downlink bit stream, which may be a TDM format involving bits from a single uplink or a number of uplinks. The COP is instructed by a controller (see Appendix III) which is commanded from the ground. Buffering is required to handle necessary format changes. For instance, bits from a 75 b/s uplink must be buffered if they are to be injected into a higher rate TDM downlink slot. Similarly, bits from a high rate uplink must be stored if they are to be retransmitted at a lower rate. The amount of buffering necessary depends on the rates to be used and the length of the messages to be handled in this way. Appendix V details a COP design.

A satellite capable of interconnecting a coded uplink (possibly one with full AJ protection - frequency hopped, coded, and interleaved) to a terminal without a decoder (like many existing terminals) must include on-board deinterleaving and decoding. Decoding must exist for each type of code to be handled in this way. The possibility exists that a decoder may be time shared among bits from more than one uplink by the inclusion of appropriate control, buffer memory, and a Decoder Input Processor (DIP), a COP-like device for choosing bits from different uplinks to form the input bit stream for the decoder. In a similar manner, on-board encoding is necessary to interconnect an uncoded uplink to a terminal which uses a decoder on all received bits. On-board deinterleaving and decoding requires memory and processing capability to be carried by the spacecraft, dependent on the particular deinterleaving and decoding used, with soft-decision decoding involving considerably more memory. The requirements imposed by on-board deinterleaving and decoding are given in Appendix VI.

The RFI (and possibly modest AJ) protection given by frequency agility implies tunable L.O.s on-board the spacecraft. AJ protection with fast frequency hopping necessitates a more sophisticated hopping L.O. In addition, a processing (demodulating) satellite in an AJ system servicing terminals which do not precorrect their transmissions' timing according to their particular propagation delay, requires a special acquisition procedure. This is treated in Appendix VII.

The buffering necessary to increase the capabilities of half-duplex users of a TDM net (via the particular scheme of Section 2.1.4) implies considerable memory on-board the satellite. The specifics of this scheme and others are given in Appendix VIII.

Summarizing the results of Section 4.4 for a particular satellite option, the inclusion of almost all of the above processing in a strawman system leads to the conservative conclusion that the satellite weight associated with a fully processed channel is about the same as that required for two transponder channels.* In order to provide the advantages of on-board processing and not suffer a reduced throughput capacity under a situation where the processing is not required, it is proposed that on-board processing be flown on a satellite in conjunction with transponder channels, with some transponder channels shut off when processing capability is required. A method for an implementation of this concept is included in Section 4.4, and Section 5 discusses a number of alternatives involving varying amounts of on-board processing.

Previous discussion has raised the possibilities of packing signals closely together in bandwidth by utilizing a bandwidth efficient modulation; AJ protection through frequency hopping, coding, and interleaving; and efficient EIRP utilization by the creation of a downlink TDM format which matches the downlink bit rate for each TDM slot depending on the G/T of the receiving terminal. Any of these capabilities necessitates changes from existing terminal designs. However, the required changes involve such items as new modems and different control algorithms, not an entirely new terminal including a different antenna, etc.

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* This assumes equal EIRP downlinks for both processed and transponder channels. As discussed in Section 2.1.3, the improved efficiency of a processed channel may significantly alter the implications of this comparison in favor of on-board processing.

4. Strawman System

A qualitative discussion of the benefits and costs of on-board signal processing has been presented. The points raised will now be discussed further in the context of a "strawman" processing satellite. The strawman satellite is an example of a flexible satellite architecture, capable of servicing both unmodified, existing terminals and upgraded terminals with AJ uplinks. Interconnectivity among all classes of users is possible, and evolutionary changes may be accommodated through ground commanded reprogramming of the satellite processing. Of major importance is the satellite's ability to receive many FDM AJ uplink transmissions from upgraded terminals and retransmit these both to other upgraded terminals and to unmodified terminals simultaneously.

The satellite processing is described and a block diagram presented. The blocks of the system are then described, with some details in appendices. The operation of the processing is given in more detail, in the context of a discussion of how the many types of interconnectivity are accomplished. The capabilities of the strawman system are reviewed, and a power and weight estimate provided. A comparison is provided with a transponder (non-processing) satellite. A description of the upgraded terminal tailored to work best with this strawman system is also included.

It should be noted that this strawman system is by no means a final design. It is an example of one way in which satellite processing can achieve desirable goals (AJ protection, interconnectivity). However, it is also more than just a paper concept. Certain parts of it have been designed in detail and are being breadboarded at Lincoln Laboratory. They will also be formed into a limited bench system to test some of the concepts presented here. These tests will also include some of the key terminal subsystems.

4.1 System Description

Figure 4.1 shows a block diagram of the strawman processing satellite. Signals can arrive at the satellite via frequency hopped* AJ uplinks from upgraded terminals, fixed frequency uplinks from unmodified, existing terminals, and frequency agile (slow hopping) uplinks from existing or slightly modified terminals (as discussed in Bucher [1978]).

A number ($\sim$ 10) of low-pass signals emerge from the satellite receiver front end. These signals, down-converted from UHF, originally had center frequencies which either hopped, changed occasionally, or were fixed. The receiver front end is capable of following any of the center frequency changes. Each low-pass signal can have a bandwidth of either 25, 50, or 100 kHz determined by the IF filters in the front end, chosen by command (and changeable). Depending on the uplink format used, each of these low-pass signals can contain either one wideband signal in its bandwidth (typically this may be a high rate TDM signal) or a number of lower rate FDM signals.

After the front end, each low-pass signal can be switched to any of a number ($\sim$ 5) of DEMOD (demodulator) MODULES. These DEMOD units are able to demodulate one or a group of FDM signals. The number of FDM signals which may be accommodated in a particular bandwidth and subsequently demodulated depends on the crosstalk properties of the modulations used and the data rates, and will be quantified in a later section. The DEMOD MODULES are flexibly designed, so as to be able to demodulate a number of different modulations and data rates, subject to the above constraint. In fact, different modulations and data rates among a group of FDM signals may be handled simultaneously. A design study has indicated that a particular DEMOD MODULE can be configured by command to handle any form of phase modulation. However, a different design is preferable for

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* Frequency hopping in this system occurs at 75 hops/sec. This was chosen as a compromise between fast hopping for interleaver simplicity and slow hopping to minimize the overhead required for synthesizer settling time and an extra reference symbol per hop (required for the phase comparison, low crosstalk modulation chosen).

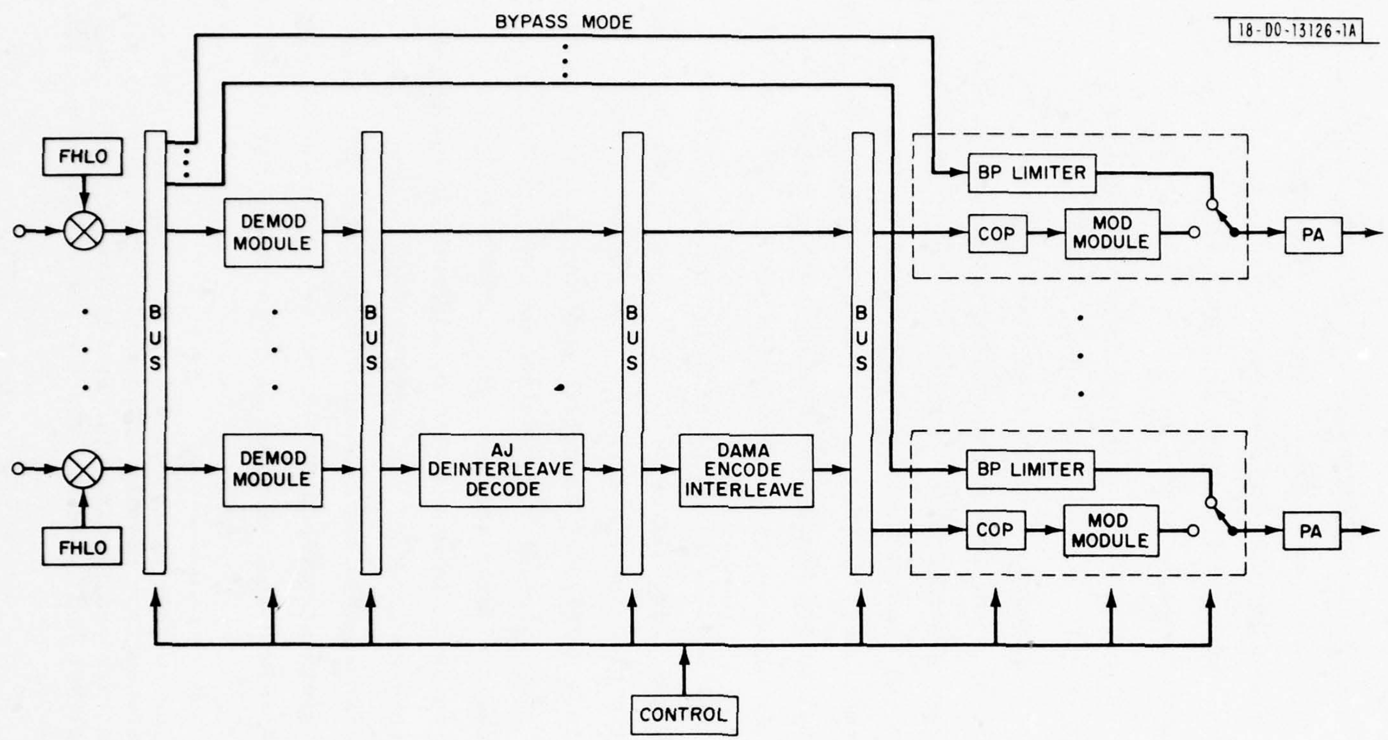

Fig. 4.1. Strawman system concept.

MFSK modulations. A mix of these two DEMODs could be carried on-board, with enough of each type to provide required service under all realistic mixes of uplink modulations. Alternatively, each low-pass signal may be connected, via a bypass mode, directly to a band-pass limiter and power amplifier, creating a hard limiting transponder signal path.* It should be noted that a particular signal channel may be simultaneously connected to a DEMOD MODULE and through a bypass mode in order to provide flexible interconnectivity, a concept to be discussed in more detail in a later section.

After demodulation, the resulting channel bit stream from a particular user (whose signal may have been one in an FDM group of signals) may be passed through a deinterleaver and hard decision decoder matched to the requirements of the AJ uplinks from upgraded terminals or passed directly to the next data bus. This decoder is used to provide interconnectivity between coded AJ uplinks from upgraded terminals and unmodified terminals without the appropriate decoder.

Subsequently, as shown in Fig. 4.1, the option exists to pass a bit stream through a DAMA** encoder and interleaver, to provide interconnectivity between bit streams which are uncoded at this point in the processing and DAMA terminals. Coding is necessary on the downlink to shipboard terminals to combat pulsed RFI. The coded output bits and those not passed through the encoder are all sent to a final data bus.

Each of 5-10 downlinks is transmitted by a power amplifier (PA) whose input is switchable between the outputs of a band-pass limiter (mentioned in connection with the bypass mode of operation) and a MOD (modulator) MODULE. The MOD MODULE can handle any of a variety of phase modulations or MFSK modulation types, with considerable flexibility concerning modulation type and data rate inherent in

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* Actually, the signals sent on the bypass path to the bandpass limiter are at an IF frequency instead of at baseband. The details of this operation are given in Section 4.2.1 and Fig. 4.2.

** DAMA in this report refers specifically to the Navy time division multiple access system being built by Motorola for use with FLTSAT 25-kHz transponders.

the design and changeable by command. The input bit stream to each MOD MODULE is created by a communications output processor (COP). The COP chooses bits from the final data bus shown in Fig. 4.1 to form the desired downlink bit stream. The downlink bit stream may be either the bits from an individual uplink signal (which may contain several TDMed signals) or may be a TDM bit stream consisting of bits from several FDM uplinks, formatted on-board by the COP according to ground command. Sufficient buffering is associated with the COP to accomplish the required rate changes (slowing down a high burst rate TDM signal for transmission on a low-rate downlink, or speeding up a low-rate uplink for transmission on a high burst rate TDM downlink) for the message lengths of interest. Also, it should be noted that the capability exists (for upgraded terminals) for the COP to create a TDM downlink whose instantaneous burst rate varies, in order to provide more energy per bit for messages destined for disadvantaged (low G/T) terminals.

4.2 Component Description

4.2.1 Receiver Front End

The front end of the strawman processing satellite's receiver has three inputs:

1. From a UHF earth coverage antenna
2. From a UHF nulling antenna array
3. From an SHF (or EHF) earth coverage antenna, for use by a transponder or by the satellite processing for crossbanding purposes.

Each of these inputs, after preamplification, is mixed with its own first local oscillator (LO), a fast settling ($\sim$ 500 μsec) frequency synthesizer capable of quickly switching to any frequency over a wide band. The three resulting first IF signals, after filtering, are the inputs to a switching bus, as shown in Fig. 4.2. After this bus additional mixing and filtering occur before a signal reaches a DEMOD MODULE (or a bypass mode path). However, it is at this switching bus that control is exercised over which of the three inputs is to be

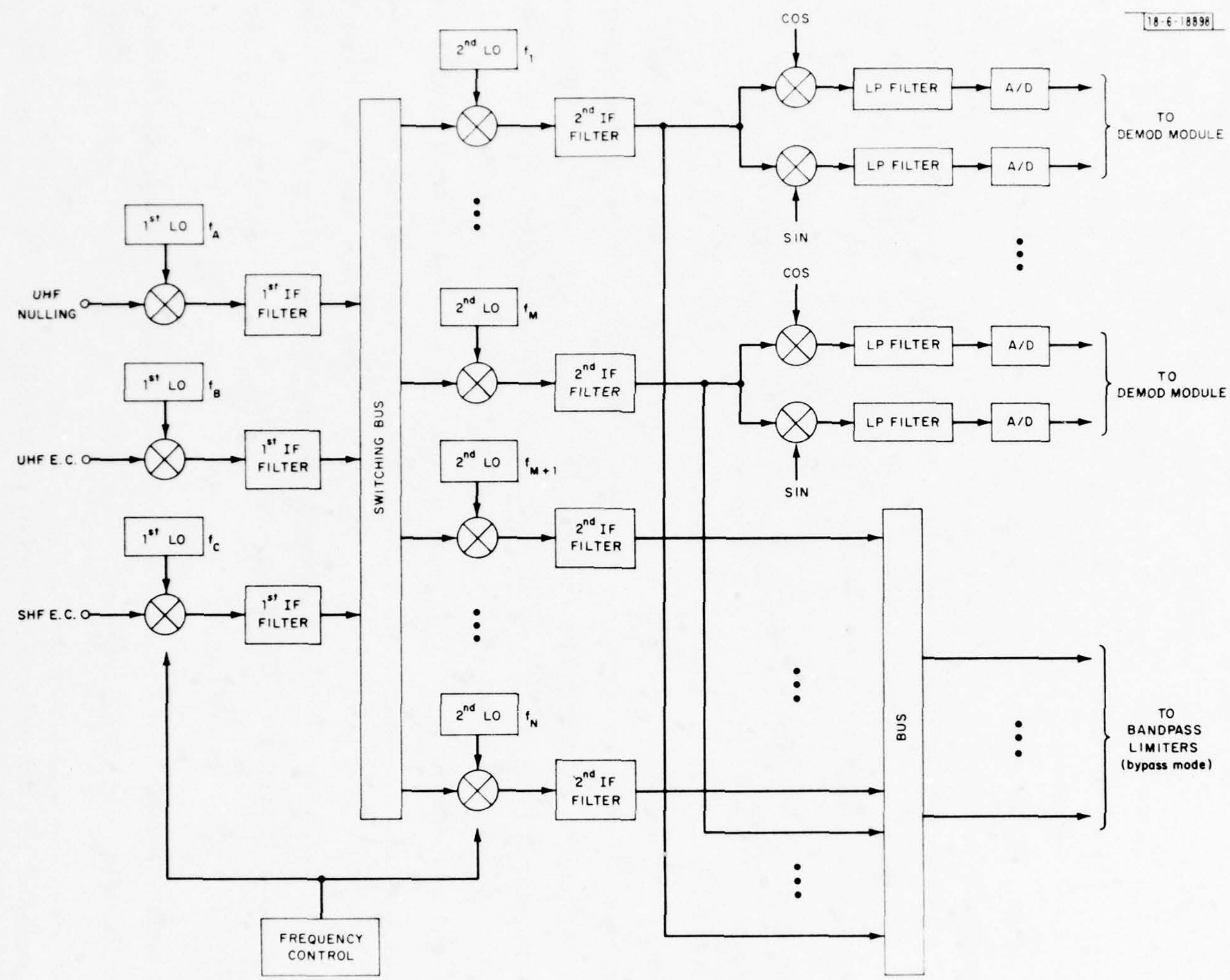

Fig. 4.2. Front end.

connected to each particular DEMOD MODULE. After this choice is made, the signal path to a particular DEMOD MODULE consists of mixing with a second tunable LO, a second IF filtering, mixing down to baseband in-phase and quadrature channels, and digitizing these channels to provide the DEMOD MODULE's input. The second LOs are capable of tuning over a 20 MHz range,* but are not required to switch frequencies quickly. Each second IF filter's bandwidth is chosen by command to be either 25, 50, or 100 kHz. Therefore, the output from any particular second IF filter is a 25, 50, or 100 kHz channel which was centered at any frequency in the UHF band (determined by the two local oscillator frequencies). This output is further processed to become the input of a DEMOD MODULE and is also sent to another bus from which signals may be taken for transmission via the bypass mode.

In order to receive a 25, 50, or 100 kHz channel which is hopping quickly the second LO is held fixed in frequency and the hopping is followed by the first LO. This would be the case for AJ uplinks from upgraded terminals. To receive a fixed frequency bandpass channel the two LOs are set at the appropriate frequencies and maintained there. It should be noted that with the first LO (operating on the signals from a particular antenna) at a certain frequency, a number of second LOs may be set at different frequencies in order to create bandpass channels from the signal out of the antenna which can be scattered throughout a 20-MHz range. This mode of operation would be appropriate for providing a number of FLTSAT-type channels (with added advantages due to processing). Finally, frequency agility may be provided in the same manner as the fixed frequency mode above, but with the second LOs occasionally switching frequencies over their 20-MHz range.

4.2.2 DEMOD MODULE

A DEMOD MODULE is a device which can take a band-pass signal (either 25, 50, or 100-kHz bandwidth) composed of a number of FDM signals and demodulate

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* The numbers in this discussion refer to UHF signals. However, the general concepts hold for SHF (or EHF) also.

all of them simultaneously to arrive at a stream of channel bits for each of the FDM signals. The FDM signals need not all be of the same modulation or data rate. The DEMOD MODULES can handle a wide variety of modulations and data rates, changeable by command, but a particular DEMOD MODULE is constrained to handle either phase-type modulations (PSK, DPSK, QPSK, DQPSK, MSK, PCMSK,* SFSK,** PCSFSK,* etc.) or FSK-type modulations (FSK, MFSK). Appendix II describes a phase-type DEMOD MODULE in more detail.

The number of FDM signals which can fit in a certain bandwidth and be successfully demodulated depends on the crosstalk between signals. Considerations involving digital hardware limitations and antenna nulling (the bandwidth over which a null may be placed is limited) favor the close packing of signals in order to digitally process and provide AJ protection for as many users as possible. It has been found that PCSFSK is an appropriate modulation for this purpose [White, Kalet, and Heggestad, 1977]. For example, this modulation allows a signal to be demodulated even when it is one of a group of time unsynchronized FDM signals, each of which is 20 dB more powerful than the signal of interest, as long as the signals are separated in frequency by $\geq$ 2.6R, (an overbound), where R is the channel-bit rate. Conventional signals (DPSK, QPSK, ec.) require a separation of at least 10R in this situation. Tables 4.1 and 4.2 show the number of FDM signals (with the same bit rate) which may be simultaneously handled by a DEMOD MODULE under these conditions. The following comments apply to these tables:

1) The 25-kHz bandwidth would be chosen if constrained by frequency allocations or if a large number of low data rate users (600 b/s) were being serviced.
2) The 100-kHz bandwidth would be chosen for PCSFSK signals only to provide for more users at high bit rates ($\geq$ 4800 b/s).

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* PC represents "phase comparison."

** Sinsoidal Frequency Shift Keying (SFSK), an MSK-type modulation with a shaped window function.

3) The number of low rate PCSFSK signals in the 100-kHz bandwidth is limited by hardware constraints, namely multiplier and accumulator speed limitations.

TABLE 4.1

MAXIMUM NUMBER OF PCSFSK SIGNALS IN ONE DEMOD MODULE

Channel Bit Rate, each signal (b/s)	Input Channel Bandwidth, kHz 25	50	100
600	**(16)**	16	8
1200	8	**(16)**	8
2400	4	**(8)**	8
4800	2	4	**(8)**
9600	1	2	**(4)**
19,200	1	1	**(2)**

○ = Max. Performance

TABLE 4.2

MAXIMUM NUMBER OF CONVENTIONAL SIGNALS ON ONE DEMOD MODULE

Channel Bit Rate, each signal (b/s)	Input Channel Bandwidth, kHz 25	50	100
600	4	8	8(1)
1200	2	4	8
2400(2)	1	2	4
4800	1	1	2
9600 to 32,000	1	1	1

(1) Only multiply-limited case; others bandwidth - limited.

(2) If terminals' minimum frequency resolution is 25 kHz, these limits also apply to all rates below 2400 b/s.

4.2.3 Communications Output Processor (COP)

There are 5-10 downlinks in the strawman design, each of which is either derived from a bypass mode signal (through a band-pass limiter) or from a stream of bits created by a COP. A COP is a switchboard, data buffer, and downlink TDM formatter. Each COP can combine bit streams from up to 28 sources into one TDM downlink bit stream. One source bit stream consists of the demodulated bits outputted from a DEMOD MODULE derived from one of the FDM signals in the input bandwidth (25, 50, or 100 kHz) of the DEMOD MODULE. The 28 bit streams can come from any or all DEMOD MODULES.

The TDM bits out of a COP can be formatted in an arbitrary manner, subject to the constraints of no more than 700 bits per TDM frame* and a maximum burst rate of 32 kbits/sec. The slots in a frame destined for small terminals (low G/T) can have a lower burst rate. The COP can also insert telemetry, an order-wire, and frame sync and timing pulses into the downlink. The operation of the COP is controlled by commands from the ground, and its flexibility allows for downlink formats to be arranged to meet a wide variety of needs.

4.2.4 MOD MODULE

The MOD MODULE, like the DEMOD MODULE, is a flexible device capable of operating with a number of modulations and bit rates. It is envisioned that most of the downlinks will normally operate with either QPSK or DPSK, capable of servicing DAMA and upgraded terminals. The downlink bit rate is 32 kbits/sec maximum. It should be noted that the MOD MODULE may be modified to be capable of creating a downlink with a low-crosstalk modulation if small spectral occupancy is required.

The strawman system does not specifically include any spectrum spreading for AJ protection on the downlink. However, it could be implemented readily with the hardware described in the form of 32 kHz pseudonoise with data rates less than 32 kbits/sec.

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* This 700 bits per frame limit is imposed only on those downlinks totally created by a COP, not on those using a bypass mode.

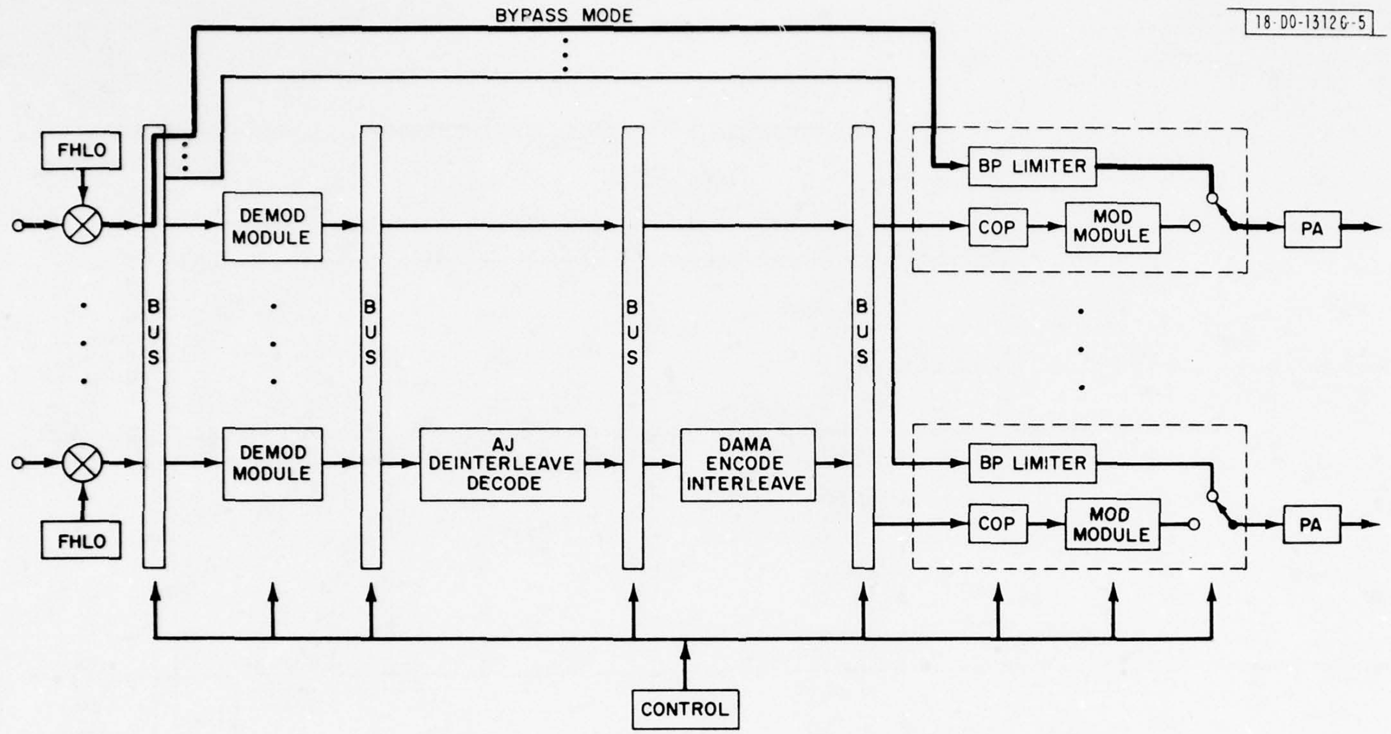
The output of a MOD MODULE or a band-pass limiter is connected to a power amplifier (PA) for downlink transmission. This transmission will have an EIRP of 26-28 dBw.

4.3 System Operation and Interconnectivity

This section describes how the strawman processing satellite system would operate, particularly as regards the signal path routings which would be configured to provide various types of service. This discussion is within the framework of an explanation of how the different types of interconnectivity are accomplished.

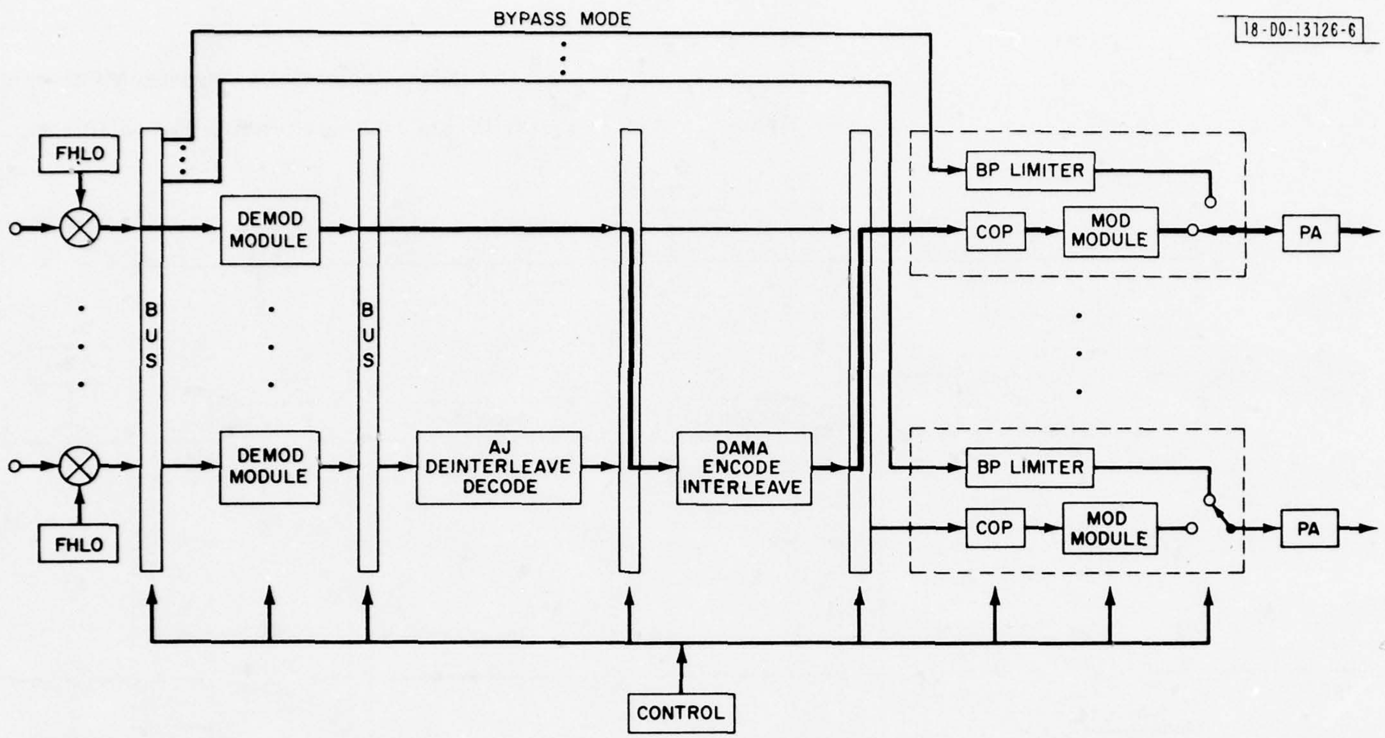
Figure 4.3 shows how signals are routed to provide the bypass mode of operation. For example, Navy DAMA terminals are connected to other DAMA terminals in this way. Effectively, a 25-kHz transponder channel at a DAMA allocated frequency is created and the satellite functions as does FLTSAT. Existing (non-DAMA) terminals may also use this mode to connect with others of the same type over a transponder channel. It should be noted that in the absence of jamming, DAMA's TDM format is an efficient use of satellite resources, and this satellite mode can accommodate its use with no modifications to the DAMA terminals.

Figure 4.4 shows how an existing (non-DAMA) terminal without an encoder can interconnect with a DAMA terminal via an "injection mode." The uplink from the unmodified terminal is sent to a DEMOD MODULE where it is demodulated, instead of through the bypass mode. After being passed through a DAMA encoder and interleaver, to be consistent with the coding expected by the DAMA receiving terminal and protect the downlink from pulsed RFI, the bits are collected by the COP associated with the downlink being received by the DAMA terminals for which the message is intended. This downlink is being used for a DAMA net through a bypass mode connecting its PA and bandpass limiter to one of the other uplink channels (25 kHz at a DAMA frequency). However, with the satellite informed from the ground of the frame timing of this DAMA net, the COP (which has buffered the uplink bits it collected above) can inject the interconnecting bits (through the MOD MODULE) at the appropriate burst rate into a particular



- EXISTING (non-DAMA) TERMINAL TO EXISTING (non-DAMA) TERMINAL (option 1)
- DAMA TERMINAL TO DAMA TERMINAL

Fig. 4.3.



• EXISTING (non-DAMA) TERMINAL TO DAMA TERMINAL – INJECTION MODE

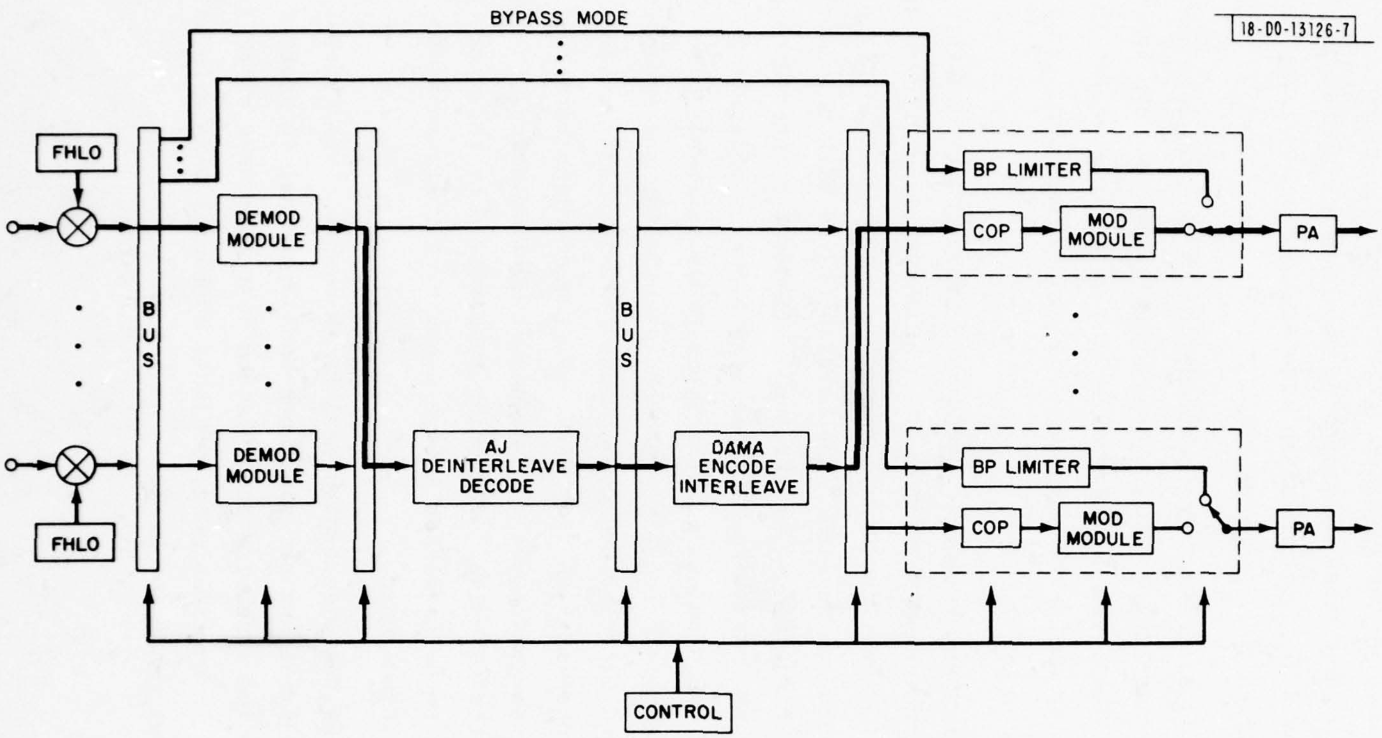
Fig. 4.4.

slot of a DAMA frame as commanded. For this task the MOD MODULE outputs the same modulation as used by the DAMA net. With reasonable amounts of memory for COP buffering, a constraint is placed on the number of DAMA slots which may be simultaneously used in this injection mode (due to the high DAMA burst rate). This will be quantified in a later section.

Figure 4.5 shows a similar interconnectivity option, an upgraded terminal's AJ uplink to a DAMA terminal. The frequency hopping uplink is dehopped and sent to a DEMOD MODULE. Then, the deinterleaving and decoding used for AJ protection is removed, after which the situation follows the previous interconnectivity option exactly.

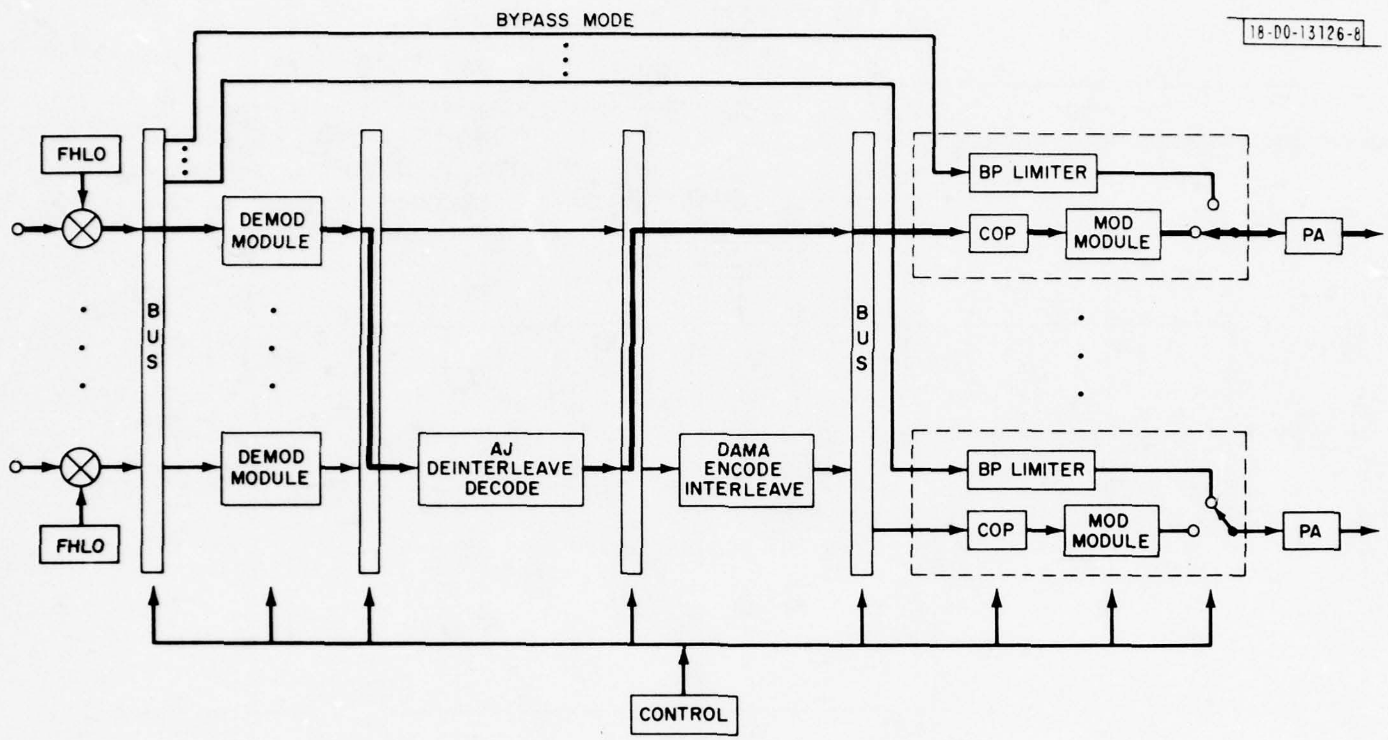
Figure 4.6 represents the interconnectivity from an upgraded terminal's AJ uplink to an existing (non-DAMA) terminal. The connections proceed as in Fig. 4.5 at the start. However, the DAMA encoder and interleaver is not used, so that the downlink bits are uncoded. The COP associated with the downlink for the intended (unmodified) receiving terminal collects the interconnecting bits. If transmissions to the receiving terminal from other existing terminals of the same type are using the downlink via the bypass mode (probably with TDM), the COP injects the interconnecting bits into the downlink at the appropriate time and with the required bit rate and modulation. The satellite must be informed of the TDM timing to accomplish this task. If the downlink bits from the other existing (non-DAMA) terminals are also derived by demodulation, then these are being collected by the COP also. The interconnecting bits represent just one more source of bits to be formatted into a downlink bit stream by the COP, and the injection mode is not used.

Figure 4.7 shows the signal path used for a number of functions, as listed on the figure. The first, an existing (non-DAMA) terminal to another of the same type is the option involving demodulation just discussed above (in reference to Fig. 4.6). It would be more difficult to handle DAMA nets in this way due to the high burst rates involved.



• UPGRADED TERMINAL (AJ uplink) TO DAMA TERMINAL – INJECTION MODE

Fig. 4.5.



- UPGRADED TERMINAL (AJ uplink) TO EXISTING (non-DAMA) TERMINAL – may be INJECTION MODE

Fig. 4.6.

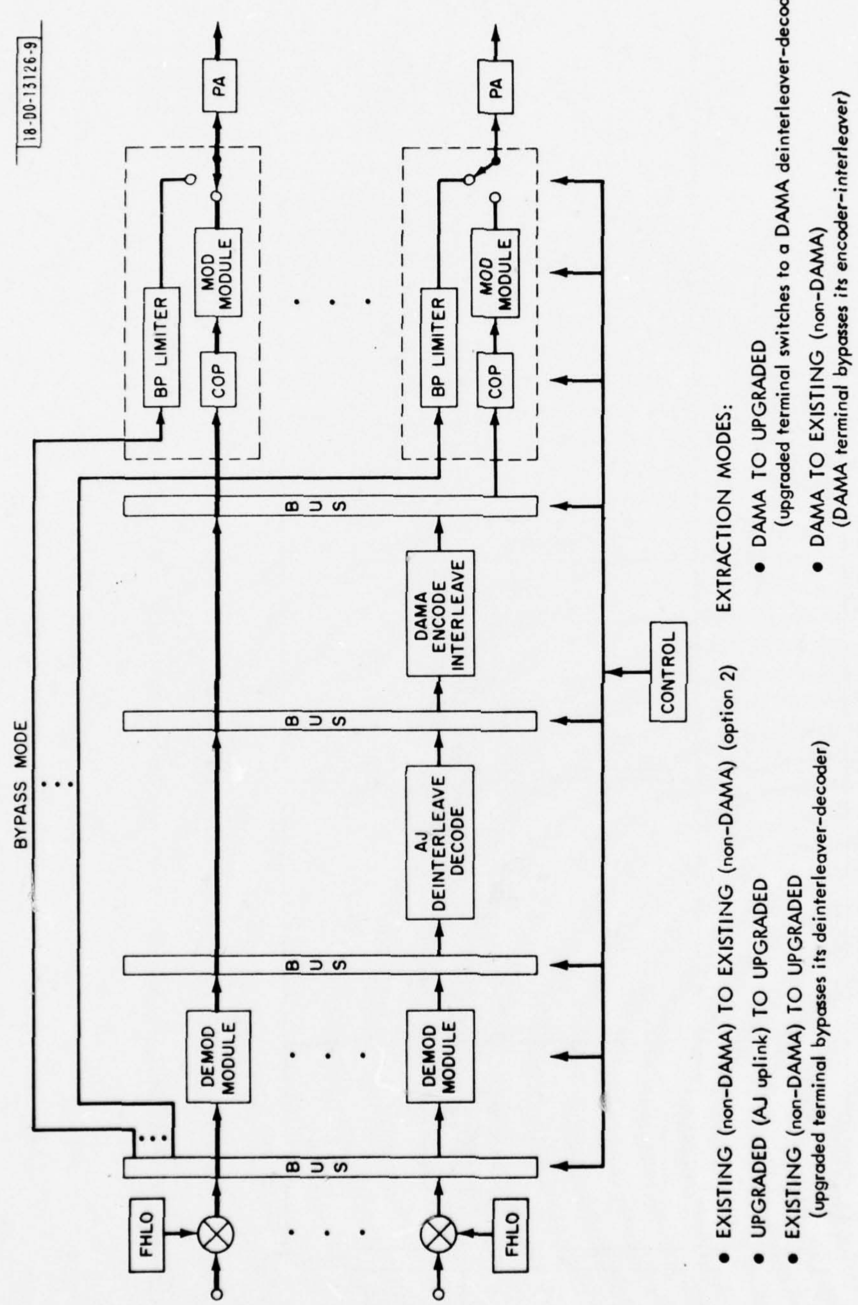

18-00-13126-9
BYPASS MODE
FHLO
FHLO
BUS
BUS
BUS
BUS
DEMOD MODULE
DEMOD MODULE
AJ DEINTERLEAVE DECODE
DAMA ENCODE INTERLEAVE
BP LIMITER
COP
MOD MODULE
BP LIMITER
COP
MOD MODULE
PA
PA
CONTROL
• EXISTING (non-DAMA) TO EXISTING (non-DAMA) (option 2)
• UPGRADED (AJ uplink) TO UPGRADED
• EXISTING (non-DAMA) TO UPGRADED
(upgraded terminal bypasses its deinterleaver-decoder)
EXTRACTION MODES:
• DAMA TO UPGRADED
(upgraded terminal switches to a DAMA deinterleaver-decoder)
• DAMA TO EXISTING (non-DAMA)
(DAMA terminal bypasses its encoder-interleaver)

Fig. 4.7.

Upgraded terminals with AJ uplinks are connected to other upgraded terminals via the Fig. 4.7 configuration. The uplinks from a number of upgraded terminals are closely packed FDM signals in contiguous frequency slots which frequency hop together (in order to include the maximum number of signals in a limited antenna nulling bandwidth). These signals may together span a (dehopped) bandwidth of ∿ 1 MHz at most. The first LO of the front end chain connected to the UHF nulling antenna array follows the frequency hopping pattern, while the second LOs pick contiguous 25, 50 or 100 kHz channels out of the 1 MHz band. A channel containing FDM signals to be demodulated (the number of signals which may fit in the channel is given by Table 4.1) is then connected to a DEMOD module.* The output bits from a particular user's signal are sent to the COP associated with the downlink being received by the upgraded terminals for which that signal is intended (or to more than one COP, a possibility in all cases). The COP collects bits from up to 28 of the FDM uplinks and formats them, as commanded, into a TDM downlink, transmitted at up to 32 kbits/sec using QPSK (or DPSK). This downlink can have a variable burst rate, with downlink slots destined for low G/T terminals being sent more slowly. The COP includes an orderwire in each downlink frame, consisting of frame format information and network control data. Calculations indicate that if the frame format changes no more rapidly than every minute, the orderwire contributes no more than a couple of percent overhead to the downlink, even if it is transmitted with considerable redundancy.

Figure 4.7 also shows the signal path used for transmissions from an existing (non-DAMA) terminal to an upgraded terminal. The uplink bits are demodulated in the same way as for the existing (non-DAMA) terminal to existing (non-DAMA) terminal link (option 2), the first type of interconnectivity listed in the Fig. 4.7 discussion. After demodulation the bits are collected by the COP associated with the downlink being received by the upgraded terminal for

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* The bits from AJ uplinks in previously discussed interconnections were also derived in this way.

which the transmission is intended. The COP buffers these bits and puts them (as commanded from the ground) into the appropriate slots in the TDM downlink bit stream fed to the MOD MODULE, just as if the bits arrived on an uplink from an upgraded terminal. The only difference is that an upgraded terminal must bypass its deinterleaver and decoder when receiving uncoded bits from an existing (non-DAMA) terminal.

Two "extraction" mode interconnections are also shown in Fig. 4.7. These interconnections involve high-rate TDM uplinks from DAMA terminals. Certain time slots of such an uplink are "extracted"* while the entire uplink is sent down to other DAMA terminals via the bypass mode. The extracted slots, containing bits requiring interconnection to existing (non-DAMA) terminals and/or to upgraded terminals, are demodulated. The demodulated bits are collected by the required COPs - the one associated with the appropriate existing (non-DAMA) terminal downlink and/or the one formatting the appropriate upgraded terminal downlink. After buffering, to match the interconnecting bits to the downlink bit rate and format, the bits are transmitted through the MOD MODULE. For the DAMA to upgraded terminal link, the upgraded terminal switches its deinterleaving and decoding to that consistent with DAMA transmissions. The DAMA to existing (non-DAMA) terminal interconnection requires the DAMA terminal to bypass its encoder and interleaver, since the receiving terminal lacks a decoding capability. This is the only interconnection which necessitates any added constraints on existing or DAMA terminals. It should be noted that this extraction mode would operate in an injection mode also if the existing (non-DAMA) terminal was receiving the transmissions from other such terminals via the bypass mode signal path. The number of DAMA slots which can be extracted per DAMA frame depends on the amount of buffering added to the COPs for that

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* The satellite is commanded from the ground concerning the timing of the slots to be extracted. Note, however, that when supporting DAMA or other TDM nets, a processing satellite could be used to define frame timing by generating and injecting the frame sync burst. This simplifies the net control station's burden and also reduces the timing information which must be sent to the satellite for "extracting from" or "injecting into" these nets.

purpose. This will be quantified in the section on weights and powers for the strawman system. The operation of the extraction mode interconnectivities implies that a DAMA TDM slot which is being sent to an upgraded terminal can also be received by DAMA terminals on the bypass mode downlink. However, a slot destined for an existing (non-DAMA) terminal cannot be so received because it is uncoded, unless the DAMA terminals can bypass their deinterleavers and decoders and still survive shipboard pulsed RFI problems. Therefore, it appears that bits to be sent from a DAMA terminal to both existing (non-DAMA) and other DAMA terminals must be repeated in two different TDM slots, once uncoded and once coded.

While mentioned above in reference to some of the possible interconnectivities, it should be stressed that a number of the different interconnectivities can be implemented simultaneously. Also, bits from a particular uplink may be sent over a number of the different signal paths discussed, to be received by a number of different types of receiving terminals simultaneously. One example of this concept, shown in Fig. 4.8, is:

> An AJ uplink from an upgraded terminal may be sent down to other upgraded terminals, and simultaneously to DAMA terminals. Meanwhile, nets of DAMA terminals can be supported.

4.4 Power and Weight Calculations

The power and weight of the components of the strawman system have been estimated, and are presented in Table 4.3.

Section 4.3 discussed how the strawman system may be configured to provide hard limiting transponder channels, and how some downlinks may support transponder channels while others carry signals which were processed (demod/remod and possibly additional processing). As an example of how this capability may be used, consider a strawman satellite with 10 transmitters and 5 DEMOD MODULEs. Note that these numbers are arbitrary and others could have been chosen. In particular, if only a small number of users would ever require processing simultaneously only 1 or 2 DEMOD MODULEs need be included, and certain other processing related components could be simplified. Under unjammed conditions requiring no interconnectivity all 10 transmitters may be used for transponder

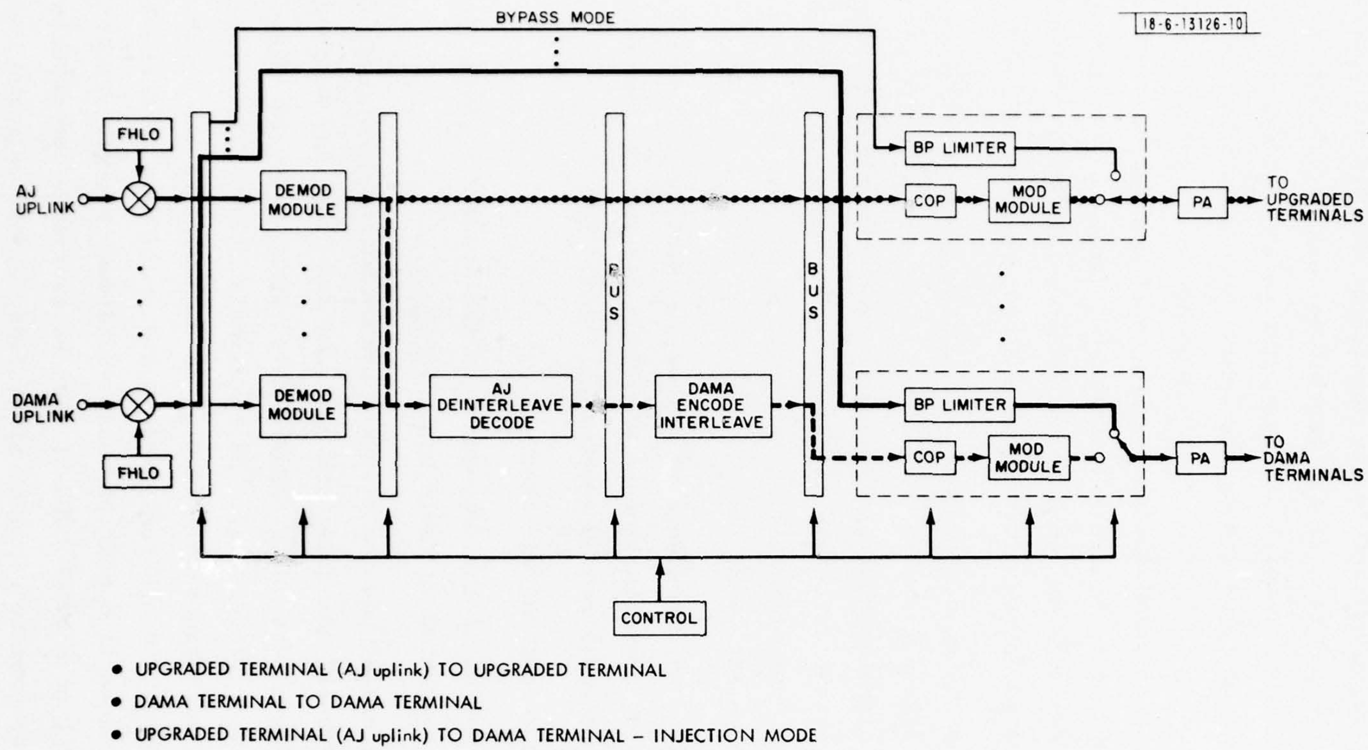

Fig. 4.8. Example of simultaneous interconnectivity.

TABLE 4.3

POWER AND WEIGHT FOR THE STRAWMAN COMMUNICATION SYSTEM ELEMENTS

	Pounds	Watts*
UHF Front End (without nulling)	4	2
IF Circuitry (per uplink channel)	0.8	1.2
DEMOD MODULE	2.5	12
COP (1 per transmitter)	1.6	5.3
COP Buffering (for 16 simultaneous injections or extractions)	3	10
AJ Deinterleaver - Decoder (for 8 users simultaneously**)	5.5	16.5
DAMA Encoder - Interleaver (for 8 users simultaneously**)	--	1
MOD MODULE (1 per transmitter)	1.5	1.5
Transmitter (28 dBw EIRP)	5.5	42
CONTROL	10	35
1^{st} LO	15	12
2^{nd} LO	5	2
Quadrature LO pair (1 pair per DEMOD MODULE)	0.2	1
Transmitter LO (1 per transmitter)	1	1.8

* Not corrected for power conditioning.

** Assuming all simultaneously decoded users employ the same error correction code.

channels, and all the processing related hardware may be unpowered. When conditions change so that some processing is necessary the required processing components can be turned on. In order that additional spacecraft power need not be provided, it is assumed that transmitters (and hence downlinks) are turned off as processing is turned on. Fig. 4.9 shows the results of this strategy. For instance, when no processing components are powered 10 transponder channels can be supported, and the satellite (with no increase in required power) can alternatively support 4 fully processed channels and 2 transponder channels simultaneously. It should be noted that Fig. 4.9 was drawn using the most conservative assumptions, and therefore the number of downlinks which must be turned off in order to buy the advantages of processing may be smaller than shown. Specifically, it was assumed that all the additional COP buffering, deinterleaving-decoding and encoding-interleaving capability, and CONTROL is powered when even just one DEMOD MODULE is turned on. This need not actually be the case. Also, the same 28 dBw EIRP downlinks were assumed for both transponder and processed channels, even though (as previously discussed) a processed channel may make more efficient use of downlink EIRP thereby allowing EIRP reduction while still supporting the same data rate, or serving more users in its processed mode than in its transponder mode which would offset the decreased number of powered transmitters.

The satellite example presented above requires the same spacecraft power as a conventional 10 transponder satellite. A weight comparison shows its communications package to be heavier by 63 lb, implying an increased satellite weight of 107 lb (allowing for affects on other spacecraft systems, based on the model developed by the GPSCS Spacecraft Study Team under SAMSO/SKA auspices). The above powers and weights are based on current flight-qualified technology. As more efficient devices (e.g., CMOS) become available these values will significantly decrease.

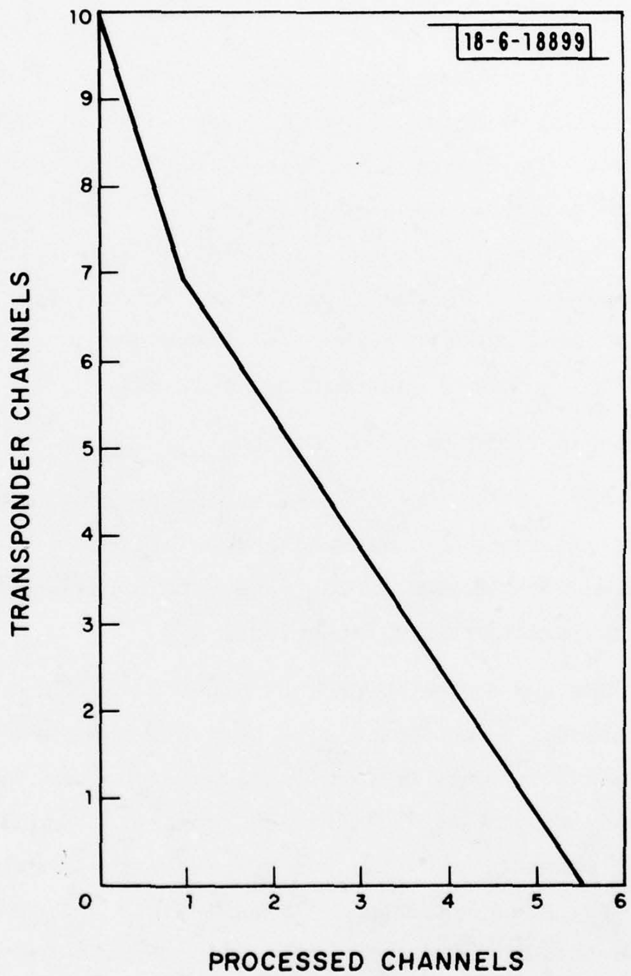

Fig. 4.9. Simultaneous transponder and processed channels for constant satellite power.

5. Consideration of Other Systems

The major advantages gained through the use of the strawman processing satellite outlined in the previous section are AJ capability for a large number of UHF users with upgraded terminals and interconnectivity among different types of existing terminals (including DAMA terminals) and between these and the upgraded (AJ) terminals. The strawman system is also very flexible, allowing reallocation of satellite resources and reconfiguration of the on-board processing to be accomplished by ground command. Now, a whole spectrum of processing options exist between the conventional hard-limiting transponder satellite (no processing) and the strawman presented earlier (with the capability for full processing). Each option has its own capabilities and drawbacks. This section presents some examples of different processing options, points out their advantages and disadvantages, and discusses overall system concepts where relevant. A list follows, with a summary included in Table 5.1.

(1) Conventional Transponder Satellites

a) At UHF. A UHF transponder satellite provides high efficiency for clear mode (unjammed) communications (via a TDM system) between terminals of the same type, but is very vulnerable to both jamming and unintentional RFI.

b) At UHF and SHF with crossbanding and a central ground processing station. A satellite with both UHF and SHF transponders, with analog crossbanding available between them, can provide interconnectivity among different types of terminals in the unjammed environment, with the interconnectivity provided by reformatting at the ground station. Transmissions between the satellite and the ground station take place at SHF for efficiency. Note that reformatting at the ground station allows interconnectivity even among SHF and UHF terminals. The ground station required for this task may be fairly complex, and spacecraft hardware to support the links to and from this station must be supplied.

TABLE 5.1
SYSTEM OPTIONS

	System Description	High clear mode efficiency	Interconnectivity	UHF AJ Protection	No ground station dependence[1]	Impact on terminals
1a)	Conventional transponder	x			x	None
1b)	Transponder with cross-banding and central ground processing	x	x			None
2a)	Sampling repeater with slow frequency hopping	x		x[2]	x	Modification necessary
2b)	Sampling repeater with slow hopping, crossbanding, and central ground processing	x	x	x		None
3)	Transponder with fast frequency hopping	x		x	x	Modification necessary
4)	Demodulation/remodulation	x	x		x	None
5)	Full processing	x	x	x	x	Modification necessary for full AJ protection
6)	Combination	See discussion in text				

1 This refers to a signal processing ground station, which sends a processed version of downlink signals back to the satellite for further retransmission, not a station for satellite control.

2 See text for limitations seen here.

(2) Sampled Channel Satellites with Slow Hopping (see section 2.1.2 and [Bucher, 1978]).

a) At UHF. A sampled channel satellite is not significantly more complex, heavier, or power consuming than a transponder satellite. Its operation consists of downconverting an uplink signal to baseband, sampling it at greater than or equal to the Nyquist rate, and modulating a fixed frequency downlink so as to transmit the digitized stream of samples. When combined with slow frequency hopping and on-board covering of the downlink bit stream (representing the samples), such a satellite yields a reasonable UHF AJ capability. The slow hopping is to introduce jammer uncertainty as to the users' uplink frequency, while not burdening present terminal frequency synthesizers or requiring automated frequency switching. The covering is to prevent uplink probing by the jammer in order to determine the uplink frequency. The UHF receiving terminal for this option must be fairly large ($\sim$ 10 dB receiving antenna gain assuming 26-28 dBw satellite EIRP) and must be capable of decovering the downlink and utilizing the ucovered samples for demodulation, implying a receiver modification to existing large terminals. This mode of AJ communications is not interconnective; it can occur only between similar modified terminals. Also AJ uplinks cannot be sent to unmodified existing terminals on the downlink. The quality of the AJ protection provided (the J/S figure) is not as good as can be realized by the full processing system.

b) With crossbanding and a central ground station. This option proceeds as did 2a, but the downlink is at SHF to a central ground station where it is decovered and may be demodulated. At this point the message may be decoded, reformatted, and/or the modulation altered to provide interconnectivity. The message is then retransmitted at SHF to the satellite with pseudonoise spreading. After on-board despreading and analog crossbanding, this uplink is retransmitted via a UHF transponder at a fixed frequency. This option provides AJ protection (of the same quality as option 2a) to existing terminals which are essentially unmodified [Bucher, 1978].* It provides interconnectivity among different types of UHF terminals (including AJ uplinks to terminals without any hopping capability), and also can interconnect SHF and UHF terminals. In fact, if some of the transponders are at SHF with fast hopping for excellent AJ protection, these uplinks can also be interconnected to various existing UHF terminals, an advantage in an evolutionary transition to higher frequencies. Moreover, given a central ground station capable of reformatting messages according to different net protocols, true interoperability can be achieved. To achieve all these features, the ground station would be quite complex.

(3) Transponder Satellite with Fast Hopping

Adding fast hopping (< 240 msec dwell time) to the satellite of 1a provides AJ protection to terminals which can hop that fast, without requiring covering. Generally, this hopping rate implies modifications to existing terminals. The quality of AJ protection is better than that in option 2, and not significantly worse than that achievable by the strawman (full processing) design. However, the number of users that can simultaneously operate with an AJ capability is limited (see Appendix I). Preliminary study indicates that methods of alleviating this

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* A large antenna gain is only required by the central ground station in this case.

constraint may exist through some added satellite hardware (and further, more extensive, terminal changes).* UHF interconnectivity is not provided, nor the ability to interconnect to SHF users. If SHF transponders (which may be fast hopping) are included in the satellite, analog crossbanding can occur between UHF and SHF terminals with common modulations and formats. However, any further interconnectivity would require a ground station. Note that the inclusion of a ground station really causes this option to be redundant, in that almost the same capabilities are provided by option 2b without requiring new terminals. Similarly option 2a may be redundant, since if a terminal modification is necessary in either case, fast hopping achieves better AJ protection and sacrifices no capabilities.

(4) Demodulation/Remodulation Satellite

This satellite is much like the strawman design of Fig. 4.1, but the LOs in the front end do not hop and no on-board deinterleaving-decoding takes place (the DAMA encoder-interleaver remains). This configuration allows interconnectivity between different UHF terminal types without any modifications and without any control ground station (except, or course, for satellite control). Interconnectivity can extend to SHF terminals also. However, no AJ capability is included.

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* One method would be for frequency hopped FDM signals to be individually bandpass filtered and sampled, with the samples from the various signals TDMed onto one (or a few) downlinks. The receiving terminals, of course, would then be required to time demultiplex the samples and use them to demodulate the signals.

(5) Processing Satellite

This is the satellite described as the strawman design and pictured in Fig. 4.1. It costs only a very small power and weight penalty over option 4, but provides AJ protection at UHF and can also be used for AJ SHF communications. Moreover, the AJ uplinks can be interconnected to unmodified (non-AJ) terminals. The power and weight calculations for such a satellite are included in section 4.4. This is the most flexible configuration, and provides the best AJ (highest J/S) protection to the largest number of simultaneous users.

(6) Combination System

This option makes assumptions which are consistent with the way in which SHF equipment and SHF satellite resources may actually be deployed. The benefits are a certain AJ and interconnective capability, as described below. These assumptions include a satellite with fixed frequency UHF transponders and frequency hopping SHF transponders. In addition, certain (perhaps one) SHF transponders are used for pseudonoise transmissions and have the ability to despread modest pseudonoise ($\sim$ 10 MHz). Also, every platform carrying an SHF terminal carries a UHF terminal too. Frequency hopped SHF communications provides very good AJ protection from one SHF terminal to another. A message from a UHF terminal to a platform carrying an SHF terminal is received by that platform's UHF terminal. An AJ uplink from an SHF terminal destined for a UHF terminal is transmitted over the SHF pseudonoise channel, despread, and analog crossbanded to a UHF downlink. This requires the SHF terminal to match its uplink modulation and format to that expected by the receiving UHF terminal. Pseudonoise was chosen as the AJ technique in order that even coherent modulations can be matched by the SHF terminal. The AJ protection achieved this way is less than that obtainable at SHF with frequency hopping, but is comparable to that obtainable by option 5 with UHF uplinks. It should be noted that a number of FDM signals may be sent to the same pseudonoise despreading SHF transponder with common pseudonoise patterns, as long as they arrive with synchronized pseudonoise transition timing. This FDM capability requires an on-board bandpass filter bank, but should present little problem. This option involves interconnectivity only between SHF and UHF terminals with the same modulation and formats, and not that between different UHF terminal types. A newly designed SHF terminal may be required in order to provide significant interconnectivity (along with a variety of colocated UHF terminals for these SHF equipped platforms requiring large interconnective capability). UHF AJ is not included, the idea being that any platform requiring an AJ uplink is equipped with an SHF terminal.

The above discussion included just a handful of the numerous combinations of on-board processing which can be carried by a spacecraft, and delineated their characteristics. It is apparent that the goals of interconnectivity and AJ protection can be approached in a variety of ways,* some requiring upgraded terminals, some necessitating a central ground station, and some involving processing spacecraft. The approach chosen depends on the communications functions sought, the price willing to be paid (including terminal costs, ground-station dependence, spacecraft weight and power), and such issues as terminal procurement strategies, the willingness to and time frame for transitioning from UHF to higher frequencies, etc. It should be pointed out once again that although particular examples of processing were chosen for presentation, many others exist.**

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* Note that every method of providing interconnectivity to a number of different terminals for the same message, except for the full processing option, requires a message repetition for each of the receiving terminal types.

** In fact, no claim is made that the options presented are the least costly ways (weight and power) to achieve their associated capabilities.

6. Conclusion

As discussed in Section 2 and illustrated by the strawman example of Section 4, on-board processing provides a number of capabilities beyond those of a simple transponder satellite, particularly interconnectivity and AJ protection for a large number of users. The cost for achieving these capabilities through on-board processing was described in Section 3 and detailed for the strawman system in Section 4. For the architecture of that particular example, a satellite can provide transponder channels under unjammed conditions not requiring interconnectivity, and also provide AJ protection and interconnectivity via processing by turning off some downlinks, with no power increase over a conventional transponder satellite necessary and only a 100 lb increase in satellite weight.

For equal power satellites (and equal EIRP downlinks - a conservative assumption), a conventional transponder satellite can provide more downlinks than a satellite whose downlinks are carrying processed signals. However, some type of processing is required to allow any interconnectivity or AJ protection. At the minimum, some form of on-board AJ despreading is necessary for communications in the stressed mode. In order to provide higher quality AJ protection or protection to a large number of users, further processing is required. Interconnectivity implies the ability to at least alter modulation forms, necessitating a demod/remod function. While a full processing satellite includes all needed processing on-board the spacecraft, Section 5 discussed how some of the processing load may be transferred to a ground station, at the cost of dependence on that station and extra uplinks and downlinks for traffic to it. An important point is that, since processing capability can be built up in a modular way (as shown by the strawman example of Section 4), a small amount of processing can be included in a system whose main mode utilizes a transponder satellite option. In this way, at only a small price in spacecraft weight, the capabilities achievable by processing (e.g., interconnectivity) can be provided; the only limitation being the restricted number of users who may simultaneously make use of these capabilities.

The advantages and costs of on-board signal processing are well understood in the context of the strawman example of Section 4. However, some of the alternatives discussed in Section 5 have not been as extensively studied. It appears that a useful continuation of the study of processing would involve further investigation into those and other options, possibly coupled more closely with the projected user requirements which such a system should satisfy.

ACKNOWLEDGMENT

The concepts described in this report were developed through a group effort involving many people in the Communications Division (Division 6) at Lincoln Laboratory. Particular thanks goes to those in the Signal Processing Committee working group.

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GLOSSARY

ABNCP	airborne command post
A/D	analog-to-digital converter
AJ	anti-jam
α	small signal suppression factor
BP	band-pass
CDMA	code division multiple access
COP	communications output processor
DAMA	demand assigned multiple access (specifically the Navy system being built by Motorola)
DIP	decoder input processor
DPSK	differential phase shift keying
DQPSK	differential quadriphase shift keying
EHF	extra high frequency
EIRP	effective isotropically radiated power
FDM	frequency division multiplexed
FDMA	frequency division multiple access
FHLO	frequency hopping local oscillator
FLTSAT	fleet satellite
FSK	frequency shift keying
GPSCS	general purpose satellite communication system
G/T	antenna gain-to-noise temperature ratio (receiving system figure of merit)
IF	intermediate frequency
IM	intermodulation product
I/O	input/output
J/S	jammer-to-signal power ratio (a measure of anti-jam performance)
LO	local oscillator
LP	low-pass
MARC	microprogrammed adaptive routing controller
MFSK	M-ary frequency shift keying
MSK	minimum shift keying
NAVCOMSTA	Naval communication station

GLOSSARY (Continued)

PA	power amplifier
PC	phase comparison
PSK	phase shift keying
QPSK	quadriphase shift keying
R	data rate
RF	radio frequency
RFI	radio frequency interference
SFSK	sinusoidal frequency shift keying
SHF	super high frequency
Σ_d	ratio of total received power-to-receiver noise power in transponder bandwidth at a receiving terminal
TDM	time division multiplexed
TDMA	time division multiple access
UHF	ultra high frequency

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anti-jam	SHF	RFI

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Conventional communication satellites, using transponders, can provide high efficiency communications in an unstressed (low noise) environment between terminals of the same type. However, such satellites are not suitable for providing such capabilities as anti-jam protection or interconnectivity of messages between terminals of different types, both important for military communications purposes. On-board satellite signal processing can provide these and other capabilities. This report discusses on-board processing's advantages and costs, and shows how it can be incorporated into a system concept.

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In the M.I.T. Technical Note 1978-2, Vol. 1 by L. S. Metzger, entitled, "On-Board Satellite Signal Processing," the abscissa of Fig. 2.3 on page 9 is labeled, "TOTAL RECEIVED UPLINK SIGNAL-TO-NOISE POWER RATIO (dB)." It should be corrected to read "EACH USER'S RECEIVED UPLINK SIGNAL-TO-NOISE POWER RATIO (dB)." Also, in the second reference on page 58, the volume notation of "COM-26" should be changed to "Vol. 66".

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