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DATA RETRANSMISSION FROM REMOTE SENSORS USING A UHF COMMUNICATIONS SATELLITE

by
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DEPARTMENT OF COMMUNICATIONS
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ABSTRACT

A preliminary study of the factors affecting the feasibility of using a UHF communications satellite, designed for low capacity two-way voice communication, to relay data from remote sensor platforms to a central central central station has been made. It has been found that one 50 kHz linear voice channel, using FDMA, can relay during an hour 256 bits of data from each of 400,000 interrogated remote sensor platforms at a bit error rate of 1×10^{-6}.

1. INTRODUCTION

This report describes a preliminary investigation of the possibility of using a UHF (300 - 400 MHz or 2.5 GHz) geostationary communications satellite designed for low capacity two-way voice communication to relay data from remote areas of Canada. The data are to be relayed from both manned and unmanned remote stations to a central control station (CCS) for distribution to its final destination.

Several alternatives in modulation and multiplexing techniques, data rates, bandwidth, transmitter power requirements, effects of crystal oscillator instabilities on both frequency and time guard bands, clocked versus interrogated stations, power sources and costs are discussed. Example calculations, based on possible requirements for telemetry from automatic weather stations, demonstrate the feasibility of such a system. They are intended as a baseline design which, it is hoped, will stimulate interest and input from parties wishing to participate in such a system.

2. POTENTIAL APPLICATIONS

There is a potential need for remote unattended telemetry (RUT) stations to transmit the results of sensor measurements to a central location. An example of a RUT station is a weather station such as that planned by the Atmospheric Environment Service, Department of the Environment (AES/DOE), to monitor wind speed, wind direction, temperature, atmospheric pressure and precipitation. Other RUT stations may monitor river heights, currents and temperature; environmental pollution; and possibly, marine traffic in northern waters. The number of data bits to be transmitted, the desired bit rate, readout intervals and frequency of readout varies with the type of RUT station. The number of RUT stations will also vary with time depending on social and political need, user budgets and on the quality and cost of the service that is provided. It is expected that initial participation in a satellite telemetry system would be small since it is a new and unproven service. If the telemetry system is successfully demonstrated however, rapid growth can be expected since data relay from remote areas via satellite is the only practical means of relaying data where large numbers of stations, which are geographically dispersed, are concerned[1].

There is also a potential need for remote attended telemetry (RAT) stations, such as would be operated by survey and exploratory parties in semi-permanent camps who may wish to make seismic or other measurements from appropriate sensors and relay the data back in real time.

3. GENERAL SYSTEM CONSTRAINTS AND CONSIDERATIONS

3.1 TRANSPONDER AND RELATED ASSUMPTIONS

The operating parameters of the transponder and the spacecraft will not be known until an actual design is undertaken. Unknown, as well, are the related parameters of the satellite communications system such as antenna gains, frequency assignments, receiver noise temperatures, etc. At present, the assumptions that have been made thus far for the two-way voice satellite communications system are listed below and form the framework within which this data telemetry system must function.

	SYSTEM 1	SYSTEM 2
Uplink Frequency	2660 MHz	400 MHz
Downlink Frequency	2505 MHz	300 MHz
Required CNR at transponder to overcome front-end noise	20 dB	20 dB
Satellite voice channel bandwidth	50 kHz	25 kHz
Power density in transponder output	0 dBW/50 kHz	5 dBW/25 kHz
CCS receiving antenna gain (30' dish)	45 dB (2505 MHz)	26.6 dB
System noise temperature	800°K	800°K

It has been assumed also that

a) the satellite is in near perfect geostationary orbit to make doppler shift effects negligible and to reduce the antenna mounting and pointing problems, and

b) the transponder is linear to eliminate intermodulation products in frequency division multiplexing.

The constraints imposed by the above assumptions considerably reduce the assumptions that must be made for the transmission of data via the satellite.

The users fall into two groups as mentioned previously, causing variation in the required data rates and format. To accommodate these variations, the CCS should have sufficient temporary storage to buffer incoming data. The computer in the CCS would then format the data at the proper rate or provide a hard copy for the user to pick up. Consequently, the data can be relayed from both the RUT and RAT stations to the CCS using formats and rates which best suit the overall telemetry system. Only in instances for which real-time transmission is required, can data not necessarily be manipulated in this fashion.

The remote station antenna should have a fairly wide beamwidth in order to reduce pointing and mounting problems and consequently, station cost. Thus the maximum desirable antenna size is assumed to be a three foot paraboloid in the 2.5 GHz case.

It is assumed also that the data channel would occupy one complete voice channel and for uniformity, it is assumed that the data system noise temperature is 800°K. This report will consider the use of only one voice channel as a data channel. This data channel can be further sub-divided into data subchannels.

These assumptions are listed below for convenience.

	SYSTEM 1	SYSTEM 2
Satellite data channel bandwidth	50 kHz	25 kHz
Antenna gain at remote station	25 dB (2505 MHz)	12 dB
Antenna type at remote station	3' paraboloid	circularly polarized yagis
System noise temperature	800°K	800°K

3.2 RUT STATION SERVICE ASSUMPTIONS

a) All RUT stations are assumed to be the same as the meteorological stations since information to the contrary is not available.

b) There are 50 or 256 data bits to be read out each time. These values are used since the meteorological stations measure about 40 bits of information which, after minimal formatting, become about 50 bits for transmission. Present meteorological stations, however, use a data format which is not minimal and produce 256 bits for transmission. If 256 bits were transmitted, no modification to the meteorological stations would be necessary.

c) Stations are to be interrogated at least every hour (unless some unusual phenomena are taking place when more frequency readings will be desired) or if clocked, the stations are to be read out every hour.

d) For purposes of determining power supply requirements and stability requirements on local crystal ocsillators, the stations are to operate for a full year without servicing.

e) Ambient temperature range is from -40°C to +70°C.

f) Required bit error rate is $\leq 1 \times 10^{-6}$.

3.3 RAT STATIONS SERVICE ASSUMPTIONS

a) Power availability does not place a constraint on the data rate.

b) Since the stations are manned, servicing can be carried out as required.

c) The amount of data to be read out can either be temporarily stored so that transmission can be interrupted or is small enough to be read out between RUT station transmissions.

d) Required bit error rate is $\leq 1 \times 10^{-6}$.

4. PROPOSED TELEMETRY SYSTEM

4.1 GENERAL

This section discusses modulation techniques, multiple access methods, data rates and formats, frequency and timing considerations, RUT and RAT station operation, power sources, readout times and cost.

4.2 MODULATION METHODS

Many studies have been made comparing modulation techniques in binary communications systems. It is well known that in an unrestricted band, PSK modulation is optimum for the reception of binary signals in white Gaussian noise with a minimum probability of error. Tjung and Wittke[3] have demonstrated that in a restricted band, this is not always the case.

Consider Figure 1 which has been taken from Tjung and Wittke's paper with the following modification. The curves in Figure 1 have been extrapolated from the original curves from an error probability of 10^{-5} to 10^{-6}. The curves compare the performance of an FSK system having a modulation index of 0.7 and simple noncoherent detection, with a PSK system using 180° peak-to-peak deviation and completely coherent detection with zero phase error. The band-pass filters have been assumed to be rectangular for this comparison. A modulation index of 0.7 gives optimum performance for an FSK system. The curves demonstrate that for a time-bandwidth product, BT, of 1.0, the FSK system is better than the PSK system by about 1.5 dB. However, for BT $\geq$ 1.2, the PSK system is better than the optimum FSK system. Clearly, for BT $\geq$ 1.2, PSK modulation should be used. The choice of the time-bandwidth product, BT, is not so clear. The transmission energy required per bit when BT = 1.0 is at least 4.5 dB greater than the energy required per bit when BT = ∞ for a probability of error, $P(\varepsilon) = 1 \times 10^{-6}$. When BT = 1.2, the energy required per bit is about 3 dB less than the energy required when BT = 1. Thus, increasing the bandwidth of the channel by 20 per cent over the bit rate, reduces the power required by about 3 dB. Increasing the bandwidth further until it is unrestricted reduces the power requirements by only about 1.5 dB. Thus, it appears an increase in bandwidth of 20 per cent is a good bandwidth-power trade-off for a coherent PSK system. Consequently, the bandwidth used to transmit and receive the data in the telemetry system being considered in this report will be taken to be 1.2 times the bit rate, R.

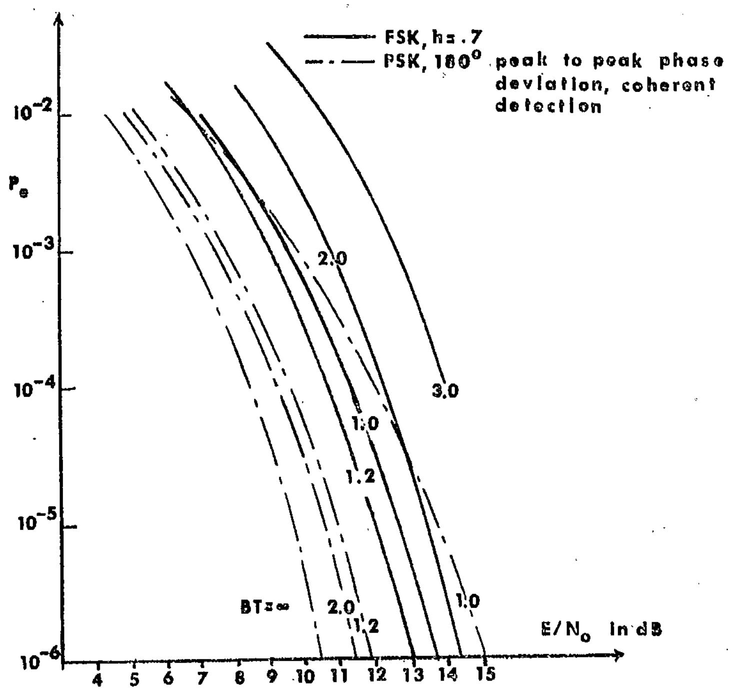

Fig. 1. (Energy per bit)/(noise density) required versus probability of error for FSK and PSK systems as indicated.

4.3 MULTIPLE-ACCESS METHODS

As will be seen in Section 4.6 it is advantageous to multiplex remote station transmissions into the transponder data channel to reduce station transmitter power and total readout time.

4.3.1 FDMA

Advantages

a) No network timing is required.

b) Use can be made of existing hardware and technology to a greater extent than with other techniques.

Disadvantages

a) Intermodulation products occur if the transponder is nonlinear.

b) All signals must be of equal power at the input of a nonlinear transponder to prevent higher power signals from suppressing the weaker signals.

The problem of producing equipower signals at the input of the transponder may require some form of carrier power control.

Under the assumption of a linear transponder, there would be no intermodulation products. If, however, the transponder is nonlinear, the carrier to intermodulation noise ratio of the signal from the transponder decreases as the degree of nonlinearity increases until it reaches a limiting value of 8 dB for 100 per cent usage of a hardlimiting transponder. After the design parameters of the transponder have been fixed, this problem may have to be considered further.

4.3.2 TDMA

Advantages

a) Performance is not degraded by a nonlinear transponder.

b) Signals at the input to the transponder need not be of equal power.

Disadvantages

a) Accurate network timing is required.

b) It is more costly than FDMA.

c) Since a signal from only one telemetry station occupies the transponder at a time, the rf transmitter power must be sufficient to maintain adequate CNR. If the transmitter is peak power limited, then TDMA may not be possible.

TDMA is unsuitable for a telemetry system in which the readout times from the RUT stations are controlled by a local clock since there is no means of system time synchronization. TDMA is possible with an interrograted system but the equipment would be complex and costly compared to the simpler FDMA system.

TDMA also requires each station to use the entire data channel. Since it is desired to keep the costs of these stations to a minimum, the rf transmitter power should be kept as low as possible. For example, 20.4 watts of rf power are required for a bandwidth of 50 kHz at 2.5 GHz and only 0.53 watts are required for a bandwidth of 1300 Hz. The higher power requirement adds nearly 50 per cent to the cost of the lower power station. Of course, a data bandwidth of 1300 Hz could be used, but the readout time would greatly increase.

4.3.3 SSMA

Advantages

a) Random access with frequency and time overlap of signals is possible.

b) SSMA has inherent anti-jamming and anti-interference qualities.

Disadvantages

a) Signals must be orthogonal or there is mutual interference.

b) The system is costly and complex.

SSMA is, in general, too costly and complex for an application where its specific advantages are not essential.

4.3.4 Conclusions

Under the assumption of a linear transponder, FDMA is the easiest and cheapest to implement. If the transponder is nonlinear, this problem will have to be reconsidered. Under these conditions, it may be desirable to evaluate the use of error correcting codes or TDMA to achieve the desired error rate. For the purposes of this report, however, FDMA will be used.

4.4 FREQUENCY AND TIMING CONSIDERATIONS

The width of the frequency guard bands around each data subchannel and, consequently, the number of subchannels that can be frequency division multiplexed into the data channel depends on the stability of the reference oscillator in each remote station. In the case of clocked stations the length of the time guard band required between successive transmissions in a particular data subchannel also depends on the stability of this oscillator. Consequently, the stability of the reference oscillator has a large effect on the total readout time for a group of RUT stations.

Very stable oven controlled crystal oscillators are available but the oven consumes 5-7 watts of power, which is excessive for use in RUT stations. Temperature compensated crystal oscillators (TCXO) are somewhat less stable but consume much less power (50-70 mW).

Using some of the best TCXO's commercially available, time quard bands as long as 29 seconds per year between successive transmissions in a data subchannel may be required and frequency guard bands of as much as ±1800 Hz for the 2500 MHz case and ±288 Hz for the 400 MHz case may be required if the transmitter carrier frequency is derived from multiplication of the TCXO frequency. It may be possible to reduce the time guard bands if some data overlap is allowed and aging and stability statistics are available for the TCXO. However, only the worst case situation is considered in the sample calculations in this report.

4.5 READOUT OPERATING MODES

4.5.1 Clock Controlled Stations

Under this system, the local oscillator in each RUT station would provide a timing signal. A counter would turn the transmitter on at the proper time and shut it off after the data has been read out. Stations could be programmed to read out sequentially such that they each use the entire data channel or to read out in groups with several stations multiplexed into the data channel. Note that a group could contain only one station in a limiting case.

The carrier frequency is obtained by multiplication of the local reference oscillator frequency and consequently, a wide frequency guard band is required due to the local oscillator instability. Since the timing signal is also derived from the local oscillator, and the oscillator must run for an entire year without adjustment, the time guard bands required to prevent stations which readout successively in the same transponder data sub-channel, from overlapping are as much as 29 seconds. A block diagram of a clocked station appears later in Figure 4.

Advantages

a) The stations are cheaper (see Section 6).

Disadvantages

a) If a clock fails, unwanted transmissions cannot be stopped remotely.

b) Transmissions are at regular intervals and cannot be altered or suppressed if a need arises.

c) A long readout time is required (see Section 4.6) due to wide time and frequency guard bands.

4.5.2 Coherent Transceiver Interrogated System

In this system, each station has a transceiver in which the transmit frequency is derived from the received carrier frequency by phase lock techniques. Each group of stations would also have a unique address. The CCS station commands a group of stations to read out their data by transmitting a coherent bi-phase, PSK signal over the interrogation subchannel (of the data channel) which contains the address of the group of stations it wants to read out. Upon decoding its own address, the interrogated station transmits its data and awaits another command signal.

The incoming interrogation signal consists of pure carrier followed by necessary synchronization and addressing bits and then the carrier modulated by a suitable data pattern to keep the demodulator in the RUT station synchronized. The carrier is down converted to a lower frequency, modulated with the data to be transmitted, and then up converted to the transmit frequency. With the appropriate phase lock loop, the stability of the transmit carrier frequency is the same as the receiver carrier frequency and the frequency guard bands formerly required because of the local oscillator instability are not required. The only instabilities in the carrier frequencies are due to doppler shift and oscillator instabilities in the satellite transponder. The effect of these instabilities can be reduced if the doppler shift and the long term local oscillator instability in the transponder are taken into account and the CCS alters its carrier frequency (of the interrogation signal) appropriately.

The power density assumed in the 2.5 GHz transponder was 1 watt in a 50 kHz band. Consider, for simplicity, a channelized transponder for the 2.5 GHz case in which each 50 kHz channel has its own power amplifier which is capable of producing 1 watt. Recall that the data channel is to be used for both data transmission from the remote stations and the interrogation signal. For example, the bandwidth required for the interrogation signal is 4800 Hz for a bit rate of 1000 bps (bandwidth = 1.2 times bit rate ± 1800 Hz guard bands). If the interrogation signal is the only signal present in the channel, then it is transmitted at a level of 1 watt. Link calculations show that if the interrogation signal were transmitted at this 1 watt level in a 4800 Hz band, the resultant error rate would be 1×10^{-6} with a margin of 3.9 dB. However, as soon as the data from the remote stations is received at the transponder, the power is divided between the data and the interrogation signal. The power level of the interrogation signal drops and the error rate of 1×10^{-6} is no longer maintained due to the decrease in CNR. Consequently, this type of system is applicable only for burst type transmissions. The length of the burst of data would be equal to the two way transit time from the transponder to the nearest remote station in each group minus the CCS signal acquisition time. This system is referred to in the rest of this report as the 'short burst coherent transceiver interrogated system' or SBCTI system.

Advantages

a) The system is very flexible since transmissions can be suppressed or their schedule altered to suit the needs of the entire telemetry system, e.g., high priority or emergency use.

b) Readout time is faster due to the elimination of the time and frequency guard bands.

c) Readout can only occur when the interrogation signal is present and thus unwanted transmissions due to spurious signals which trigger the station are eliminated.

Disadvantages

a) The stations are more expensive.

b) The system requires an exclusive frequency allocation of 2.5 GHz since the interrogation signal exceeds CCIR flux density limits established for this band.

c) An interrogation subchannel is required.

If, however, the 1 watt level in the interrogation signal could be maintained even when the data was occupying the data subchannel (e.g., wide-band transponder or separately powered interrogation subchannel), then the data could be relayed as long as the interrogation signal was being transmitted. Also, the interrogation signal would not have to be interrupted for each group of stations that was to report. Instead, the interrogation signals could be made into one long uninterrupted interrogation signal. Consequently, all remote stations would lock on to the interrogation signal initially and since the interrogation signal between address messages is modulated in order to maintain the bit synchronizer in the address decoder in synchronization, all stations would acquire bit synchronization initially as well. This eliminates the need for both carrier and bit synchronization times when each group of stations is commanded to read out, thus resulting in overall shorter readout times. This system is referred to as the 'continuous transmission coherent transceiver interrogated system' or CTCTI system.

4.6 READOUT TIMES

4.6.1 Introduction

In this section, the total time required to read out 200 RUT stations for a clock controlled system, a short burst coherent transceiver interrogated system and a continuous transmission coherent transceiver interrogated system is considered.

The total number of stations ultimately to be read out cannot be predicted at this time. The estimate of 200 stations is probably a reasonable upper limit on the number of stations participating in an experiment. This number of stations, also, is large enough to illustrate the optimum number of stations to multiplex into the transponder data channel. The results appear in Figures 2 and 3, and are obtained from the following equations.

4.6.2 Clocked System

Consider the problem of reading out N stations with a transponder data channel bandwidth of B Hz. The readout time for the clocked stations is

$$T_r = \frac{N}{n}\left[T_g + T_A + \frac{D}{R}\right], \qquad \text{.....(1)}$$

where

T_r = readout time in seconds for all N stations,

N = total number of stations to be read out,

n = number of stations frequency division multiplexed into data channel,

T_A = access time for the CCS, i.e., search and lock-on time and bit synchronization time,

T_g = time guard band required between successive group readouts,

D = number of data bits to be read out,

R = bit rate in bps.

Equation (1) above is really only valid for integer values of N/n with fractional values rounded off to the next highest integer. For the purpose of illustration, Equation (1) will be regarded as having continuous values since actual values of N are unknown and will probably vary as growth (or decline) in the telemetry system takes place.

$$B = n[b_g + 1.2R] , \qquad \text{.....(2)}$$

where

B = bandwidth of the data channel in Hz,

b_g = total frequency guard band required for the data subchannels in Hz.

Therefore,

$$T_r = \frac{N}{n}\left[T_g + T_A + \frac{1.2D}{\left[\frac{B}{n} - b_g\right]}\right] . \qquad \text{.....(3)}$$

Equation (3) shows that the time guard band and the frequency guard band should be as small as possible to reduce the total readout time. Curves (a) and (b) of Figures 2 and 3 illustrate the readout times for 200 stations for which the number per data channel varies from n = 1 to B/b_g. The parameters used for curves (a) and (b) are:

T_A = 0.01 seconds

N = 200

n = 1 to B/b_g

T_g = 29 seconds

D = 50 (curve (a)) and 256 (curve (b)) bits

b_g = 1800 Hz

B = 50,000 Hz for Figure 2 and 25,000 Hz for Figure 3.

Consider curves (a) and (b) of Figure 2 (2.5 GHz case). The maximum number of stations that can be multiplexed into 50 kHz is 13 due to the rather wide frequency guard bands. Also it may be shown that for 13 stations multiplexed into the 50 kHz band, the data rate is only 246 bps which means that 256 bits of data would require about 1 second for transmission. Clearly the time guard band of 29 seconds is the predominant factor in the readout time. Thus, many RUT stations should be multiplexed into the data channel in order to reduce the total readout time. Also, there is an additional advantage since the power required in each RUT station decreases as the number of stations multiplexed into the data channel increases thus reducing station cost, especially in the 2.5 GHz case where high power amplifiers are still expensive and inefficient.

Curves (a) and (b) of Figure 3 (400 MHz case) illustrate also that the time guard band is the predominant factor in the readout time except for the case in which many RUT stations are multiplexed into the channel (i.e., low data rates). The maximum number of stations that can be multiplexed into the 25 kHz band is 43, which is about three times the number of stations possible in the 2.5 GHz case. Also, the 43 stations occupy only half the bandwidth used in the 2.5 GHz case.

It is evident in the 400 MHz case that there is an optimum number (i.e., to produce minimum total readout time) of stations to multiplex into the data channel and that the total readout time is about one third that required in the 2.5 GHz case and with only half the bandwidth. This dramatically demonstrates the effect large frequency guard bands has on the system.

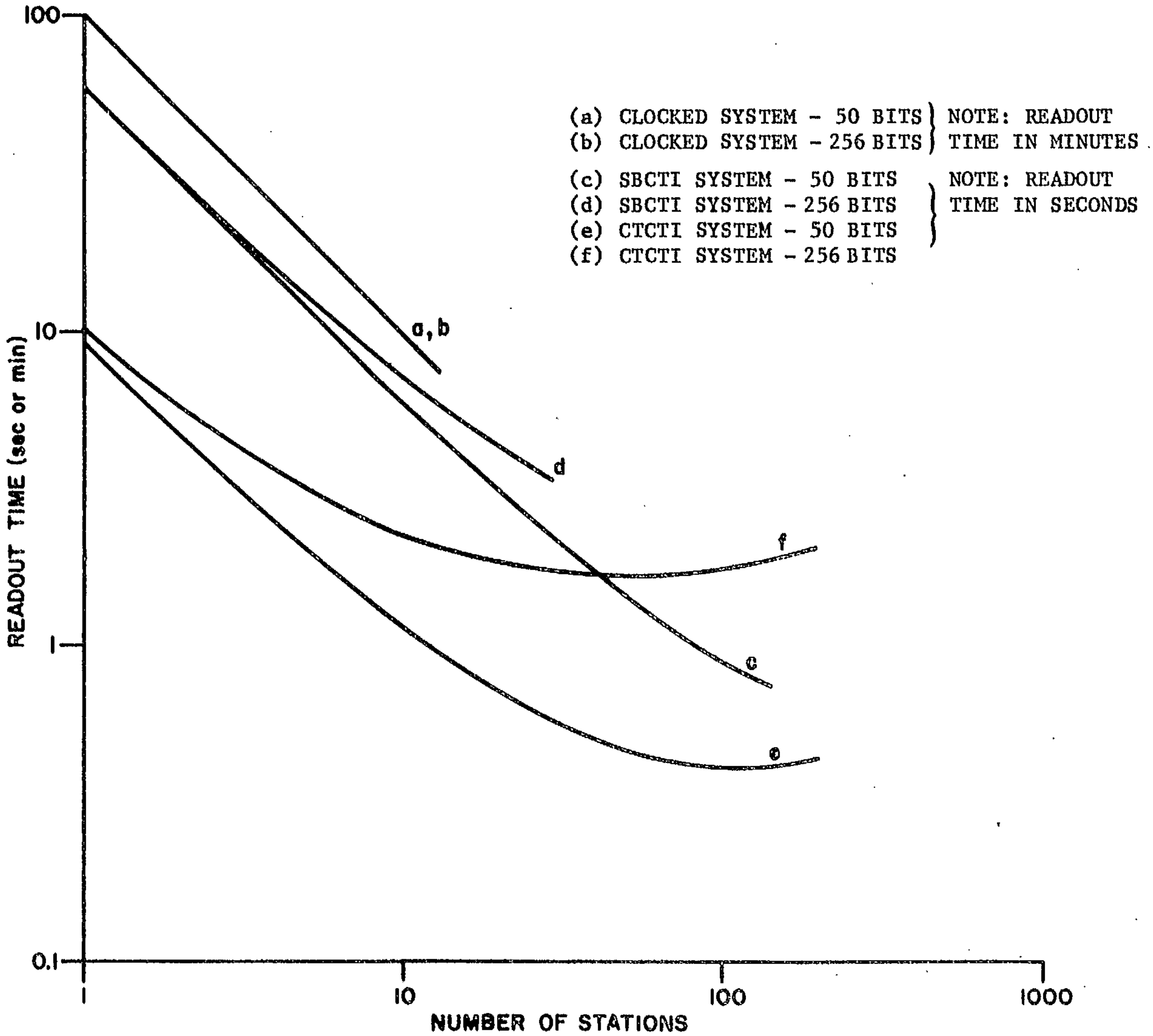

Fig. 2. Time required to read out 200 stations versus number of stations multiplexed into a 50 kHz data channel for the 2.5 GHz case.

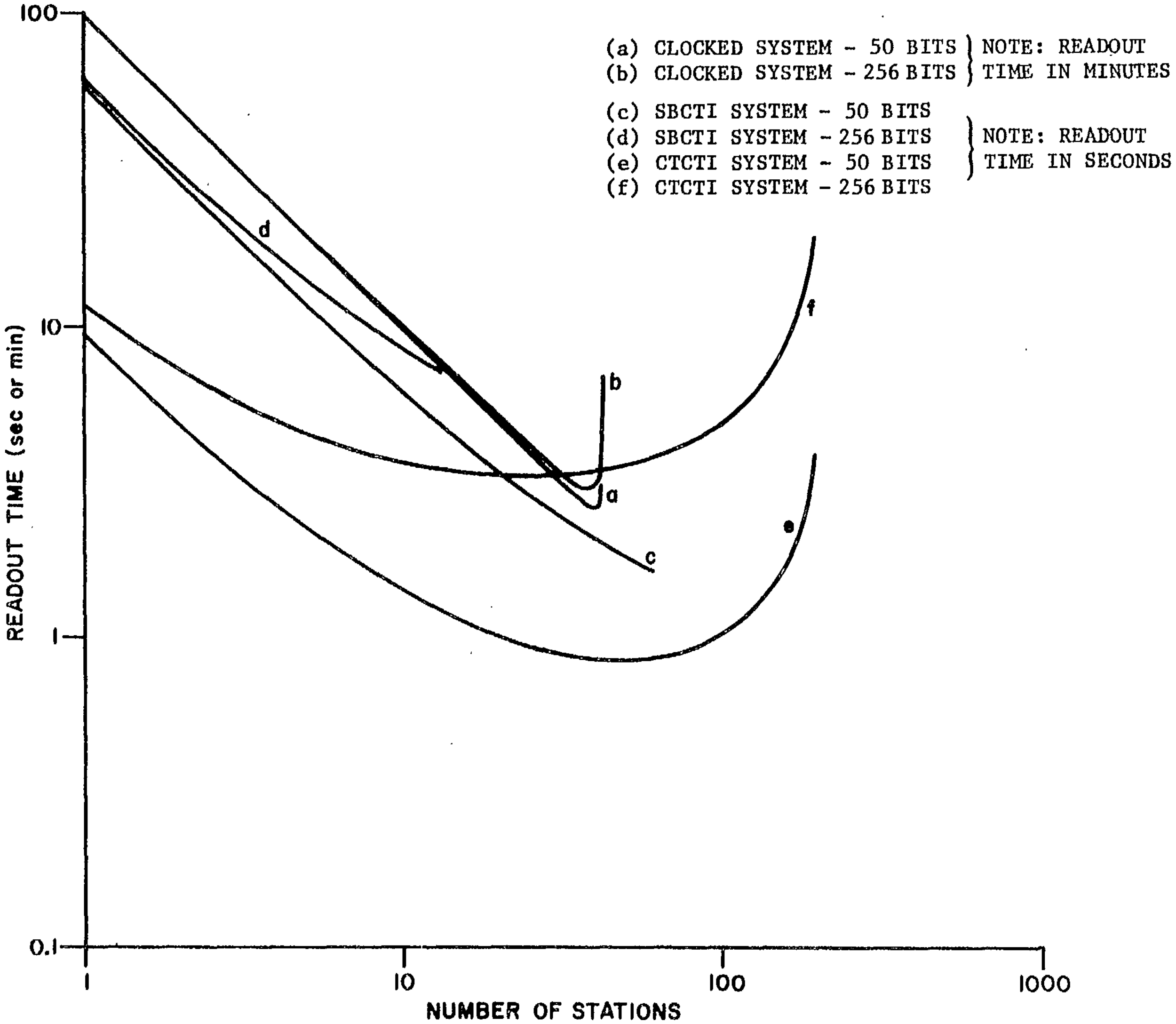

Fig. 3. Time required to read out 200 stations versus number of stations multiplexed into a 25 kHz data channel for the 400 MHz case.

4.6.3 Short Burst Coherent Transceiver Interrogated System

The minimum two-way transit time from an earth terminal in Canada to the satellite is 236 msec and the maximum two-way time is 260 msec. Assume each remote station receiver requires a maximum of 20 msec for search and lock-on time (SLT), bit synchronization time (BST) and address decoding time (ADT). These times are collectively known as the access time, T_a, in this report. The CCS requires a similar access time, T_A which consists of SLT and BST. No address bits are required in the transmission from remote stations to CCS since each remote station is assigned a carrier frequency which identifies it. T_A is assumed to be 10 msec. Recall that the power level of the interrogation signal will drop as soon as the data from the nearest remote station reaches the transponder and will not return to its full value until the data from the furthest station has been relayed from the transponder. Therefore, the interrogation signals transmitted from the CCS have a maximum duration of 236 + T_a msec with a 260 msec interval between interrogation signals. It is planned that the remote station sends pure carrier and synchronization bits in order that the CCS receiver can lock-on and synchronize to the signal. The remaining 236-T_A msec are available for data readout from the RUT stations.

The readout time for N stations is given by

$$T_r = \frac{N}{n}\left[T_a + T_A + \hat{T}_p + \frac{1.2D}{\left[\frac{B}{n} - b_g\right]}\right] \quad \text{.....(4)}$$

where N, n, D and b_g have been previously defined and,

T_a = The SLT for the RUT station receiver plus the BST, and the ADT taken as 20 msec.

T_A = The SLT and BST for the CCS is taken as 10 msec. No decoding time is required since the frequency at which the transmission is made plus the order in the group transmissions addresses each RUT station.

$\hat{T}_p$ Maximum transit time of signal from transponder to RUT station and back which equals 260 msec. It is assumed that at least one station per group is at the farthest distance from the satellite and at least one is at the closest distance.

The parameters used to calculate curves (c) and (d) in Figures 2 and 3 are:

N = 200,

T_a = 20 msec,

T_A = 10 msec,

$\hat{T}_p$ = 260 msec,

D = 50 and 256,

$B = 50,000 - 4,800 = 45,200$ Hz for Fig. 2 and $25,000 - 1,776 = 23,224$ Hz for Fig. 3,

$b_g = 100$ Hz

where, in the expression for B, 4800 Hz is used for the interrogation sub-channel.

Curves (c) and (d) in Figures 2 and 3 demonstrate that the readout times achievable are considerably smaller than those for a clocked system. The maximum number of stations that can be multiplexed into the data channel is 144 for 50 information bits and 31 for 256 bits in the 2.5 GHz case and 63 for 50 bits and 15 for 256 bits for the 400 MHz case. This is due to the fact that the data readout must be completed in $236-T_A$ msec. If more stations are multiplexed into the data channel, then the data rate is too slow. In general, the data rate would be selected so that the available number of data bits can be transmitted in the $236-T_A$ msec. The curves show that as many stations as possible should be multiplexed into each data channel to reduce RUT station transmitter power, but the optimum number to multiplex into the data channel in order to obtain minimum readout time depends on their number.

4.6.4 Continuous Transmission Coherent Transceiver Interrogated System

In the case of this system, the readout time is not limited by the transit time between the RUT station and the satellite. However, the difference between the maximum and the minimum transit time does affect the readout time. Data from the nearest station(s) will reach the transponder 24 msec ahead of the data from the farthest station(s). Consequently, the nearest station(s) will appear to have completed its readout 24 msec ahead of the farthest station(s), and therefore a time guard band of 24 msec must be left between successive interrogation signals.

$$\begin{aligned} T_d &= \text{maximum transit time} - \text{minimum transit time} \\ &= 260 - 236 \\ &= 24 \text{ msec} \\ &= \text{time guard band.} \end{aligned}$$

Therefore, the readout time for N stations is given by

$$T_r = \frac{N}{n}\left[T_d + T_A + T_a + \frac{1.2D}{\left[\frac{B}{n} - b_g\right]}\right] \qquad \ldots\ldots(5)$$

where all symbols have been previously defined.

The time guard band can be accomplished in two ways. First, no signal can be transmitted. Second, the interrogation signal can be extended for an additional 24 msec. Thus, the interrogation signal would be transmitted continuously and only one SLT would be required at the beginning of the N station readout sequence for each station. Thus a saving of about 10 milliseconds in T_a could be achieved per group readout. Consequently, T_a is taken to be 0.01 sec in the calculation of the readout time. The parameters used are,

$N = 200,$

$T_d = 24$ msec,

$T_A = 10$ msec,

$T_a = 10$ msec,

$D = 50$ and 256,

$b_g = 100$ Hz,

$B = 50{,}000 - 4{,}800 = 45{,}200$ Hz for Figure 2, and
$25{,}000 - 1{,}776 = 23{,}244$ Hz for Figure 3.

Curves (e) and (f) of Figures 2 and 3 show the readout times for such a system and demonstrate that further reductions in readout times are achievable for this system over the SBCTI system. Although the reduction in readout times is not very significant for the number of bits considered in the example, the main advantage of this system is that continuous data readout is possible while in the SBCTI system data may only be read in bursts. This feature becomes more significant as the number of data bits increase.

The curves of Figures 2 and 3 also demonstrate that there is an optimum number of stations to multiplex into the data channel to minimize readout time. However, this optimum depends on the total number of stations. The required transmitter power in each RUT station will be less when the maximum number of RUT stations are multiplexed into the data channel. The maximum number that can be multiplexed into the data channel will depend on the number and bandwidth of bandpass filters that is practical in the CCS, and the width of the guard bands around each data subchannel (645 stations is the maximum for the 2.5 GHz example in this paper).

The optimum number of stations to multiplex into the data channel varies for each of the above cases. However, a convenient rate of 1000 bps is fairly close to the rate which would be employed if the optimum number of stations were used in each of the above cases, and will be used for illustrative purposes in this report. The frequency guard bands quoted earlier in Section 4.4 will also be used in the example calculations which follow.

4.7 LINK CALCULATIONS

4.7.1 Uplink Data Transmission

	SYSTEM 1	SYSTEM 2
Uplink frequency	2660 MHz	400 MHz
Gain of transmitting antenna, G_t	22.0 dB	12 dB
Gain of satellite receiving antenna, G_r	26.0 dB	15 dB
Freespace path loss, L_p	193.2 dB	176.8 dB
Cumulative margin for ionospheric fading, ellipticity loss, reflection loss, and mechanical misalignment, L_x for 99% propagation reliability	3.5 dB	6.0 dB
System noise temperature, T	800°K	800°K
Required CNR at transponder to overcome front-end noise	20 dB	20 dB
Data rate, R	1000 bps	1000 bps
Data subchannel bandwidth for clocked system, B_c	4800 Hz	1776 Hz
Data subchannel bandwidth for interrogated system, B_i	1300 Hz	1300 Hz
Required transmitter power for clocked system, P_{tc}	3.93 w	7.45 w
Required transmitter power for interrogated system, P_{ti}	1.06 w	5.5 w

4.7.2 Downlink Data Transmission

	SYSTEM 1	SYSTEM 2
Downlink frequency	2505 MHz	300 MHz
Gain of satellite transmitting antenna, G_t	25.5 dB	15 dB
Gain of central control station receiving antenna, G_r	45.0 dB	26.6 dB
Free space path loss, L_p	192.5 dB	174.2 dB
Cumulative margin, L_x	3.5 dB	7.5 dB
Transmitted power density	0 dBw/50,000 Hz	5 dBw/25,000 Hz
Noise bandwidth	50 kHz	25 kHz
System noise temperature	800°K	800°K
CNR at receiver input	27.2 dB	20.5 dB
Effective CNR at receiver input considering uplink signal CNR of 20 dB	19.2 dB	17.2 dB
Receiver margin, M	7.8 dB	5.8 dB

4.7.3 Downlink Interrogation

	SYSTEM 1	SYSTEM 2
Downlink frequency	2505 MHz	300 MHz
Gain of satellite transmitting antenna, G_t	25.5 dB	15 dB
Gain of remote station receiving antenna, G_r	25.0 dB	12 dB
Free space path loss, L_p	192.5 dB	174.2 dB
Cumulative margin, L_x	3.5 dB	7.5 dB
Transmitted power density	0 dBw/4800 Hz	5 dBw/1776 Hz
Noise bandwidth	4800 Hz	1776 Hz
System Noise Temperature	1000°K	1000°K
CNR at receiver input	17.3 dB	17.1 dB
Effective CNR at receiver input considering uplink signal CNR of 20 dB	15.4 dB	15.3 dB
Receiver margin, M	3.9 dB	3.8 dB

4.8 REMOTE STATION CONSIDERATIONS

4.8.1 RUT Stations

As previously stated, RUT stations could be of two types; clocked and interrogated. The clocked stations are cheaper than the interrogated ones but are potentially more wasteful of transponder bandwidth and time. The cost (see Section 6) of the interrogated stations is about 80 per cent (on a per 1000 station basis) more than that of the clocked stations but many more per hour can be read out (422,000 versus 1600 for System 1 and 211,000 versus 4100 for System 2). If interrogated stations were used, RAT stations would have greater access to the transponder and it may even be possible to use the data channel for voice communications between RUT station transmissions. In addition to the above, an interrogated system offers more flexibility than a clocked system.

4.8.2 RAT Stations

Since these stations are attended, they can be serviced as necessary and need not have a power supply that can operate without maintenance for a year. Consequently, the power supply for these stations will be cheaper than power supplies for RUT stations of equal performance capabilities. RAT stations would be free to use the transponder whenever it was not being used by RUT stations. They could also be clocked or interrogated.

If clocked, a prescheduled transmission time would have to be negotiated and strictly observed to prevent interference between users. Since the clock would be periodically corrected, very accurate timing of RAT station transmissions could occur.

If interrogated, stations would notify the CCS well in advance that a readout was desired and give the approximate readout time. The CCS would interrogate the stations in advance of the estimated readout time to confirm the scheduled readout and thus update the readout schedule. Then, at a time convenient to the CCS, it would transmit a readout command on the interrogation subchannel. This command signal could also be used to trigger the measurement apparatus of the scientific personnel operating these stations. Since it is expected that the number of RAT stations will be much less than the number of RUT stations and also transmit much less frequently, interrogating the RAT stations as to their status would probably not overload the telemetry system. The interrogation mode is again preferred over the clocked system since the possibility of overlap with other various users in the telemetry system is eliminated. Also, the most efficient use of the time between RUT station transmissions can be made.

5. POWER SOURCES

5.1 TYPES

In remote areas, the choices for the power supply are limited to battery packs and self-contained generators.

Nickel cadmium cell battery packs are capable of operation in the temperature range -40°C to 70°C. The self discharge rate is low enough to permit operation for a year without recharging.

Conventional lead acid cells are unsuitable for two reasons. First, their self-discharge rate is too high to permit operation for a year without recharging. Second, they cannot operate at low temperatures.

Nickel cadmium cells require careful recharging to maintain their performance. Consequently, nickel cadmium packs should not be recharged at the remote site. Rather, they should be replaced with a fully charged one and the used one should be returned to facilities which can recharge them correctly. Nickel cadmium cells also suffer from reduced output at low temperatures (but not nearly as badly as lead acid cells) and thus the best time to replace batteries would be in the late fall so that a fully charged battery would be available in the winter when the output is lower. Nickel cadmium cells are heavy and consequently, weather stations mounted on poles to protect them from 'predators' must be suitably constructed. The battery weight, if they were mounted high above ground, would make battery replacement awkward at best. If possible, they should be buried in the ground (or perma-frost). Burying them would also help reduce the temperature fluctuation and the resultant voltage fluctuation. Also, the minimum ground temperature expected (0°F) is much higher than the lowest expected air temperatures. It may be advantageous to bury the electronics package as well.

Self contained generators such as diesel generators, thermo-electric generators, fuel cells and thermo-nuclear generators may also be used but must be capable of continuous operation for one year. Servicing must be simple and require no skilled personnel or special parts.

Diesel generators are reasonably reliable but a year's fuel supply would have to be transported to the site. It is doubtful if a diesel generator could operate for an entire year without maintenance. Servicing must be done by fairly skilled personnel whose services in remote northern areas is expensive. Consequently, generators of this type are considered unsuitable.

Thermo-nuclear generators are attractive due to the long time periods between refuelling. However, lead shielding is very heavy and costly to transport into remote northern areas and refuelling would require highly skilled personnel using special procedures. In addition their minimum power output is several times that required by the RUT stations, although lower power units are the subject of much research. Consequently, such generators are not considered suitable at this time and should only be considered for experimental purposes.

Thermo-electric generators which use propane as a fuel are available in low power models suitable for powering RUT stations. It is possible to use the heat generated to warm the station but at reduced efficiency. There are some major drawbacks to these power supplies. There is the possibility of a flame-out. Consequently, unless a reliable wind shield is provided, the inclusion of a re-light facility is essential. These features would have to be designed and built at extra cost. Thermo-electric generators of this type are not 'demand regulated', i.e., they must be operated near their rated power output at constant load in order not to damage the generator. Consequently, for applications such as the RUT stations which have fluctuating loads, either a great deal of power must be wasted on low load or a battery pack must supply the peak load power requirement. If the battery were recharged between peak loads, the charging circuits would have to be built at extra cost.

Cold temperatures pose a problem to these generators as well. First, the pressure in the propane tanks can become so low that the generator will stop due to a lack of fuel. One method of overcoming this problem is to pressurize the system with another gas such as nitrogen. A detailed description of this system is contained in Reference 4. Second, one of the products of combustion is water vapor. If the temperature is low enough, icing occurs and the generator shuts down. Consequently, the generator must be housed in a shelter with thermostatically controlled louvres which let the excess heat out. The added cost and complexity of the housing and the other extra costs render therm-electric generators of this type unsuitable except in high power applications. However, self-contained thermo-electric generators incorporating the above mentioned features required for far North operation are currently being marketed.

Fuel cells have an attractive feature in that fuel is consumed in proportion to the power demanded. However, no suitable fuel cell (hydrazine-air) have demonstrated a reliability of one year of uninterrupted service. This situation may change in the next few years but at present they cannot be considered reliable enough to power the RUT stations.

5.2 COSTS

Nickel cadmium cell cost is about five to ten dollars per ampere-hour* (depending on capacity) and the cost of recharging a nickel cadmium cell is negligible (excluding recharging equipment).

Propane fuelled thermo-electric generators cost about $1500 for low wattage units but the additional equipment necessary to ensure reliable operation will cost extra and probably equal or exceed the cost of the generator itself.

Prices are not available for hydrazine-air fuel cells and thermo-nuclear generators since they are still under test and development.

6. COST AND POWER ESTIMATES OF CLOCKED CONTROLLED AND INTERROGATED RUT STATIONS

The proposed stations shown in Figures 4 and 5 include off-the-shelf components which were not designed with low power consumption in mind. Consequently, the power consumption of these stations may be considered to be worst case. This is especially true in the case of the interrogated station which uses a 24 v supply and 6 watts of standby power. Work currently being carried out indicates that this power may possibly be reduced to between 250 and 500 milliwatts. For purposes of comparison, an idling power consumption of 250 milliwatts is assumed. This allows the relative cost comparison between a projected 'low power' interrogated station and a clocked station to be made. It is assumed that the component costs for the 'low power' interrogated station are the same as those in this report.

Table 1 gives a summary of the power requirements, and costs of the two types of stations. The component costs of each station are given both with and without a power supply. The quantity figures were arrived at by doubling the component cost for one station (exclusive of battery) to give a single station cost and employing a 'production learning factor' of 85 per cent, i.e., the unit cost of N stations is $N^{-0.2345}$ times the cost of only one station[5]. The battery cost was then added to the result. The batteries were not subjected to the 'learning factor' reduction since these items are currently manufactured in large quantities. Some quantity reduction is possible but would probably be fairly small.

One possible way of reducing the idling power of the interrogated stations would be to have the station under the control of a crude clock and have it turned on for a short period of time prior to the expected interrogation. For maximum timing accuracy, the clock would only have to provide timing for the time interval between interrogations and the interrogation signal would be used to reset the clock each time. Calculations have shown that such a scheme would indeed reduce the power consumed in the interrogated station by a considerable amount. However, the flexibility of the interrogated system is lost.

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* Pocket plate type cells

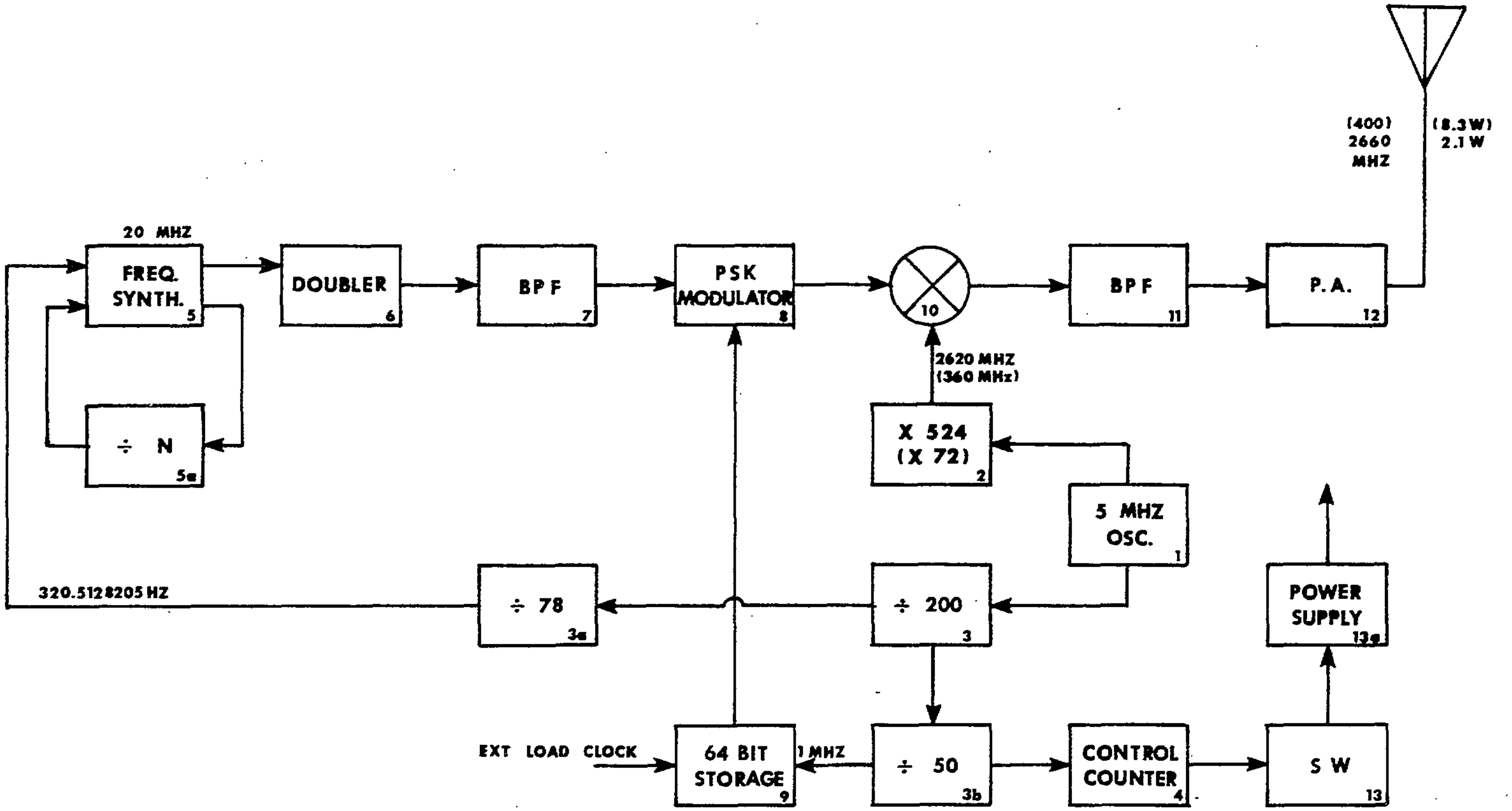

Fig. 4. Clock controlled telemetry station.

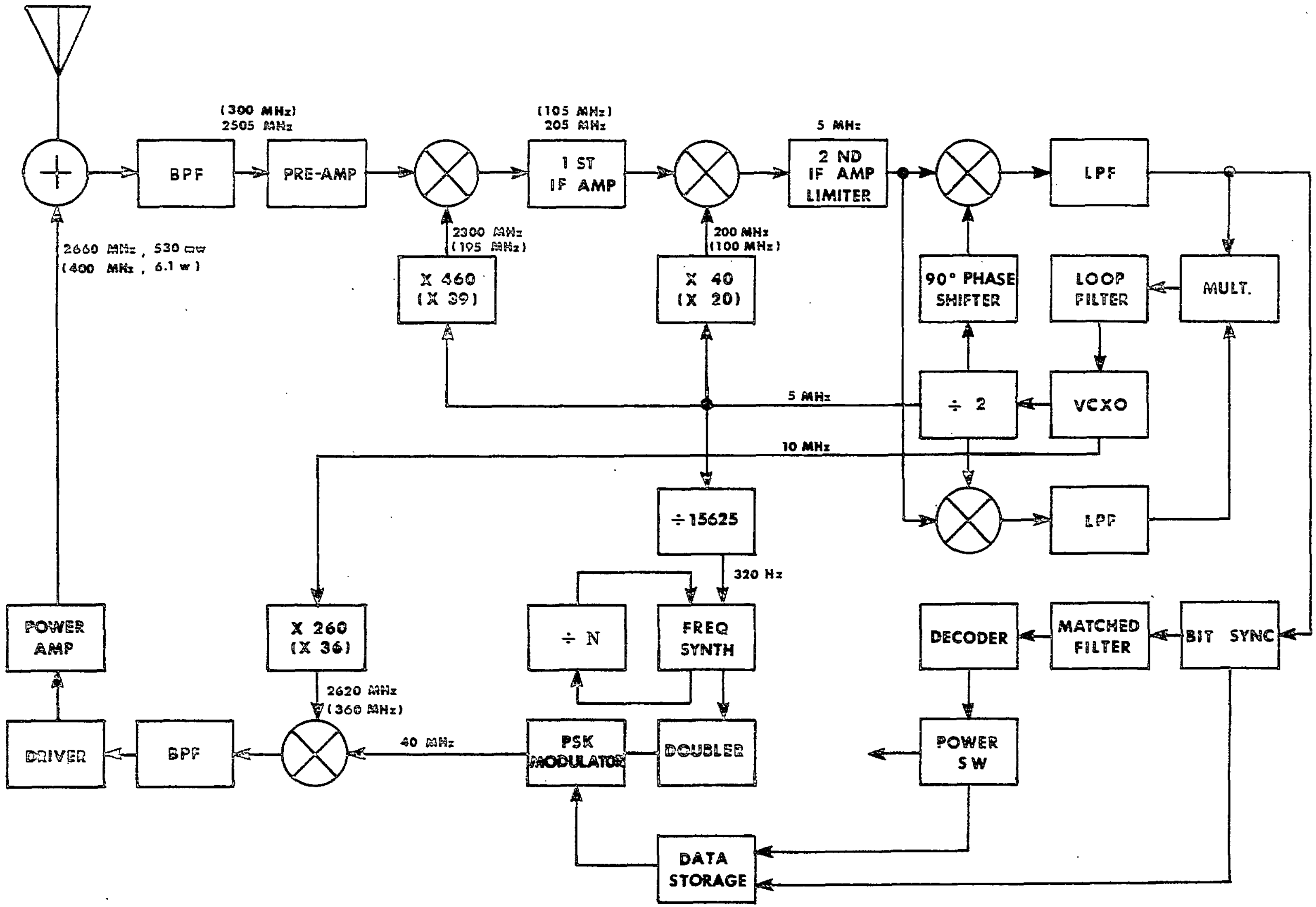

Fig. 5. Coherent telemetry transceiver.

TABLE 1

System	Idling Power (W)	Peak Power (W)	Battery Capacity (AH)	Battery Cost ($)	Single Station Cost No Battery ($)	Total Single Station Cost ($)	Unit Cost of 200 Stations ($)	Unit Cost of 1000 Stations ($)
2.5 GHz interrogated system best TCXO	6.00 (0.25)*	10.4 (4.65)	2200 (91)	11,000 (720)	19,000 (19,000)	30,000 (20,000)	16,500 (6200)	15,000 (4500)
2.5 GHz clocked system best TCXO	0.15	11.5	55	480	10,000	10,500	3400	2500
400 MHz interrogated system best TCXO	5.5 (0.25)	22.5 (17.25)	2000 (92)	10,000 (720)	13,000 (13,000)	23,000 (14,000)	14,000 (4,500)	13,000 (3,300)
400 MHz clocked system best TCXO	0.15	21.8	55	480	7,500	8,000	2,700	2,000

* Quantities in brackets are for projects low power stations.

7. CONCLUSIONS

A general study of the factors affecting the feasibility of using a UHF communications satellite for telemetry from remote stations has been made. It has been shown that, for the constraints imposed and the assumptions made, such a telemetry system is capable of relaying data from a great many stations in very little time with a low bit error rate. The telemetry system can easily be included in a UHF communications satellite experiment by assigning one (simplex) voice channel for telemetry. If the continuous transmission coherent transceiver interrogated system can be implemented, no change in the formatting section of meteorological RUT stations is necessary.

A summary of the proposed telemetry system appears below. The numerical values are based on automatic weather station requirements with no data formatting changes, i.e., 256 bits of information. The stations are interrogated using the continuous transmission coherent transceiver interrogated system and the interrogation signal uses part of the transponder data channel.

	SYSTEM 1	SYSTEM 2
Modulation	bi-phase PSK	bi-phase PSK
Multiplexing technique	FDMA	FDMA
Data subchannel bandwidth including guard bands	1300 Hz	1300 Hz
Transmitter Power	1.06 W	5.5 W
Data Rate	1000 bps	1000 bps
Telemetry system capacity at 1000 bps	410,000	210,000 stations per hour
P(ε) (per bit)	$\leq 1\times10^{-6}$	$\leq 1\times10^{-6}$
Clocked RUT station cost including power supply (per 1000 stations basis)	$2500	$2000
Interrogated RUT station cost including power supply (per 1000 station basis for low power stations)	$4500	$3300
RUT station power supply	ni-cad batteries	ni-cad batteries

Two assumptions have been made which may not be valid for an actual telemetry system. It was assumed that the satellite is in perfect geostationary orbit and thus that there would be no doppler shift in the carrier frequencies. The effect of any doppler shift will be to increase the width of the frequency guard bands around each data subchannel. This effect can be minimized in the coherent transceiver interrogated systems by offsetting the frequency of the interrogation signal to account for the doppler shift. It is expected that this effect will have a small effect on the total readout times in Figures 2 and 3.

It was also assumed that the transponder is linear in order to eliminate any intermodulation products. The degree of nonlinearity which is finally achieved will govern the error probability in the data transmission. However, error correcting codes may be implemented to maintain the desired error rate. It is expected that, even without error correcting codes, the error probability will be better than that encountered by potential users currently using common carrier transmission.

8. ACKNOWLEDGEMENT

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