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A CODE PHASE DIVISION MULTIPLE ACCESS (CPDMA) TECHNIQUE FOR VSAT SATELLITE COMMUNICATIONS

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Abstract

This paper describes a reference concept and implementation relevant to the application of Code Phase Division Multiple Access (CPDMA) to a high capacity satellite communication system providing 16 Kbps single hop channels between Very Small Aperture Terminals (VSATs). The description includes a potential implementation of an on-board CPDMA bulk demodulator/converter utilizing programmable CCD technology projected to be available in the early 90's. Also provided are a high level description of the system architecture and operations, identification of key functional and performance requirements of the system elements, and analysis results of end-to-end system performance relative to key figures of merit such as spectral efficiency.

I. Introduction

In recent years, a great deal of effort has gone into developing advanced communications satellite architectures and concepts that are suited to providing single hop service between Very Small Aperture Terminals (VSATs) at user premise locations. Satellite transponders work most efficiently in a Time Division Multiple Access (TDMA) mode whereby a satellite transponder is time-shared by a number of users and each user is served via dedicated short duration bursts at high data rates. From a consideration of the satellite alone, TDMA allocation among the user population is the most efficient operating mode for both uplink and downlink channels. However, high burst rate TDMA on the uplink is incompatible with VSAT cost constraints. In recognition of the need for low cost VSATs, many studies of advanced satellite communications systems serving VSATs have converged on a concept of Frequency Division Multiple Access (FDMA) Single Channel Per Carrier (SCPC) on the uplinks and burst TDMA on the downlinks. The FDMA/SCPC scheme on the uplink supports the concept of a low cost VSAT, but the FDMA/TDMA conversion required at the satellite represents a significant processing burden. The Code Phase Division Multiple Access (CPDMA) concept was developed as an alternative to FDMA/TDMA to support future commercial communications from VSATs. The CPDMA techniques for separation of distinct uplink channels from VSATs meshes particularly well with TDMA downlinks in that the required on-board CPDMA/TDMA demodulation and conversion is easily accomplished with little computational complexity.

II. The CPDMA Concept

Figure 1 conceptually illustrates the CPDMA data baud structure at baseband. The N VSAT users transmit continuously using an identical maximal length PN code of length L and fixed PN chip duration T_c. The user symbol duration is fixed at one period of the PN code:

$$T_s = LT_c \tag{1}$$

At the satellite front-end, all symbol epoches are aligned in time and the required signal bandwidth is approximately $2/T_c$. The individual VSAT users are distinguished by distinct PN code epoches (equivalently, code phases). In the figure, a code phase separation between adjacent VSAT users of one chip is illustrated but, more generally, the code phase separation can be ≥ one chip.

Figure 2 is a high level diagram of a satellite CPDMA demodulator implementation based on binary DPSK modulation. The demodulator begins with generation of baseband in-phase and quadrature signal waveforms via downconversion by a non-coherent local oscillator. These baseband waveforms are then input into chip matched filters whose outputs are sampled and fed into PN Matched Filters (PNMFs). A simple hardware implementation of the PNMFs using CCDs is described in Section 3 below.

The role of each PNMF is to sequentially correlate the input chip samples over one symbol period with each code phase of the original PN code sequence. At each code phase position, the PNMF reference will match one and only one user

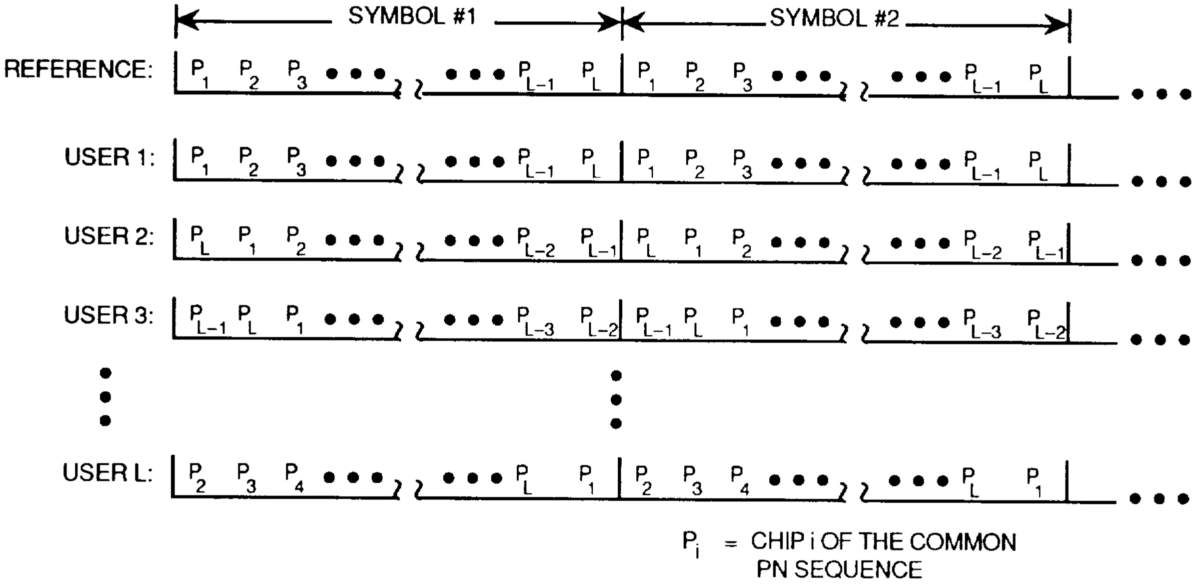

FIGURE 1 CPDMA DATA BAUD STRUCTURE FOR A USER CODE PHASE SEPARATION OF ONE PN CHIP

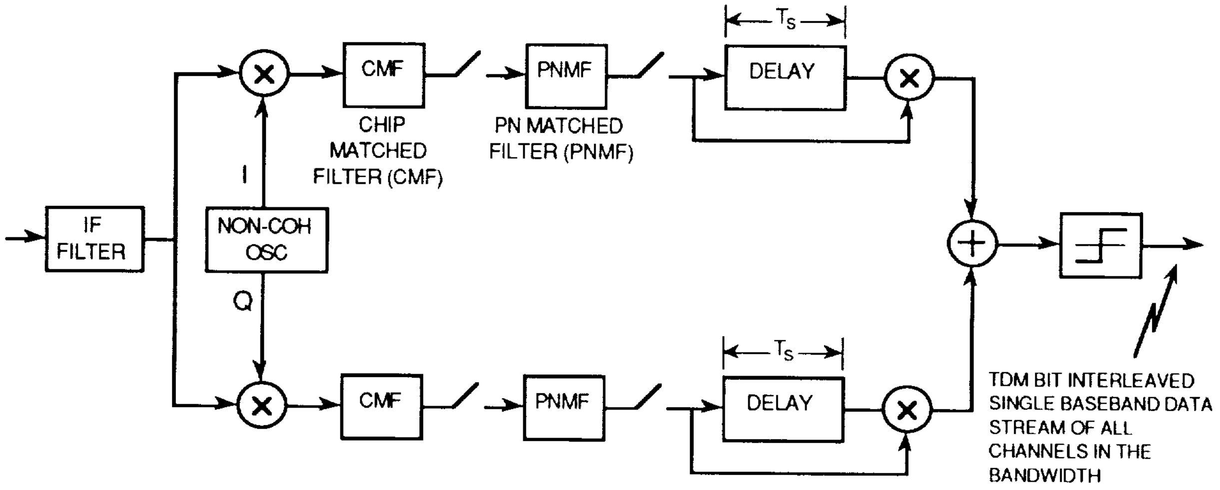

FIGURE 2. CHARGE COUPLED DEVICE (CCD) DEMODULATOR/CONVERTER — BINARY DPSK

code phase with all other users producing minimum correlation. The sequence of correlations within the PNMF thus produce a sequence of despread samples corresponding to each user's data symbol in turn. These samples are then processed using conventional DBPSK methods to yield a single Time Division Multiplexed (TDM) baseband data stream consisting of all symbols from all users.

Because the user symbol boundaries are aligned in time and each symbol consists of one full period of the code sequence, the correlation properties of the Maximal Length PN sequences are not disrupted by the presence of user data. Under ideal conditions (e.g., no user signal time or frequency errors) the cross correlation between one user signal and any other user signal is 1/L in magnitude. With a total of N users, each with signal energy E, there will be N-1 users interfering with the desired signal, producing a composite interference signal at the PNMF output having zero mean and variance KE/L^2. Treating the composite interference signal as additive gaussian noise, an effective E/No ratio due to user-to-user interference can be computed for the CPDMA system:

$$\text{CPDMA: } (E/N_o)_{eff} = \frac{E/N_o}{1 + \left(\frac{N-1}{L^2}\right)(E/N_o)} \qquad (2)$$

Compare this result to conventional Code Division Multiple Access (CDMA) in which user PN codes are not synchronized with transmitted symbols. In this case, the composite of the N-1 other users supplies an interference energy of (N - 1)E over the user bandwidth for an effective E/N_o of:

$$\text{CDMA: } (E/N_o)_{eff} = \frac{E/N_o}{1 + \left(\frac{N-1}{L}\right)(E/N_o)} \qquad (3)$$

Equation 2 implies that, for a code length L sufficiently large, the CPDMA system can support up to L users spaced one chip apart in code phase without significant degradation to effective E/N_o. Under ideal conditions, CPDMA represents a significant improvement over conventional CDMA.

The above results assume ideal conditions of no user time and frequency errors relative to the satellite references. In a practical system, the VSAT users will not have perfect knowledge of time and frequency, and time errors may be significant relative to the duration of a code chip. For this reason, it is desirable to separate VSAT users by more than one code chip in phase — at the expense of fewer users per CPDMA group and reduced bandwidth efficiency. To date, our studies have focused on a user code phase separation of 1.5 chips.

Section 3 describes a CPDMA bulk demodulator implementation using Charge Coupled Devices (CCDs). While the description is based on a 1.5 chip user separation, the fundamental architecture is applicable to other code phase separations. Section 4 describes system performance for the baseline 1.5 chip separation while taking into account less than ideal user conditions.

III. CPDMA Bulk Demodulator Implementation

As described above, the PNMF must sequentially correlate the received composite signal samples output from the chip matched filter with each phase of the code sequence and output a time division multiplexed stream of samples representing the stream of I or Q symbols for all users. A potential CPDMA implementation of the PNMF based on CCD shift registers has been defined and is illustrated in Figure 3 for a user code phase separation of 1.5 chips. Input to the PNMF are analog samples of the chip matched filter (CMF) output waveform which contains a composite of all user signals. The sample rate is twice the PN chip rate, so a CCD register of length 4L holds two symbols worth of samples. Note, however, only one of the symbols will be processed, so two such PNMFs on each of the I and Q channels are required. Every other stage of the signal register is tapped — resulting in 2L total taps. The second shift register holds two complete sequences of the PN code which remain fixed as the user signal samples pass through their register. Finally, a third shift register contains a block of L one's which are shifted right one position for every two CCD sample times.

Because the PN code register is fixed, movement of the CMF output samples through the CCD register will cause multiplication of the signal samples by a different phase of the PN code each sample time. Since the user code phases are separated by 1.5 chips (or three samples), the stored tap weights will match a different user's PN code phase every third CCD sample.

The role of the mask word is to limit accumulation to samples within a single symbol interval. The

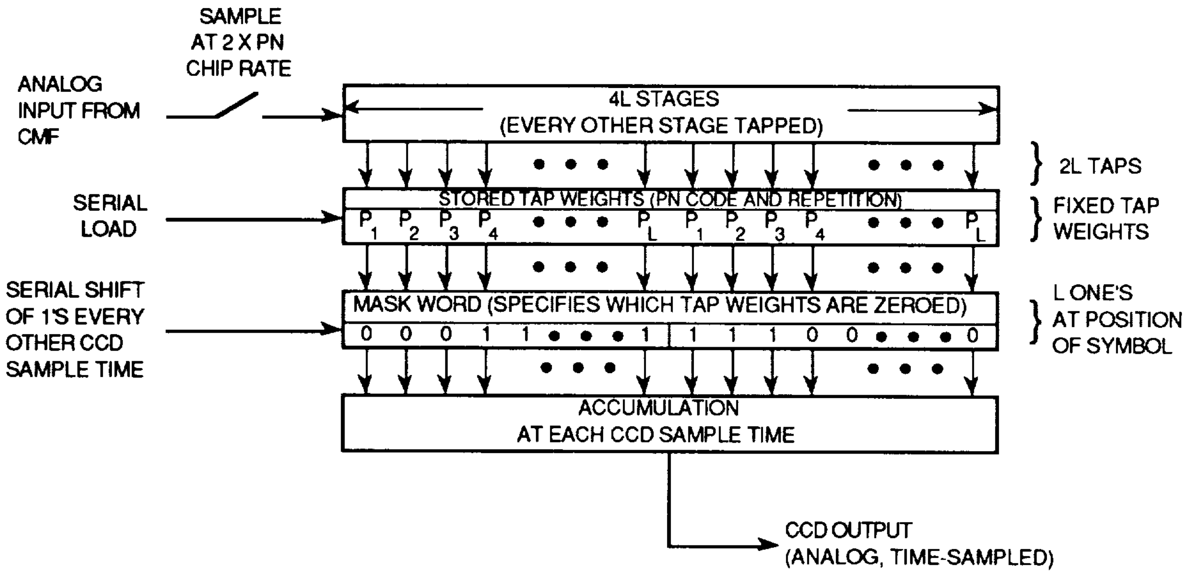

FIGURE 3. CANDIDATE CCD IMPLEMENTATION OF PN MATCHED FILTER FOR USER CODE PHASE SEPARATION OF 1.5 CHIPS

mask word (consisting of L one's) moves down its shift register at a location and rate which match the symbol interval within the signal sample register. As time progresses, the non-zero samples input into the accumulator will correspond to one symbol's worth of the composite samples output from the CMF multiplied by each phase of the PN code in turn. The output from the accumulator is a correlation over one symbol time of the received composite waveform of all user signals with each phase of the PN code.

As stated above, the stored tap weights match a different user's PN code phase every third signal sample. The accumulator output sequence contains the on-time I or Q channel symbol sample for a different user every third sample. However, the intermediate samples are not wasted. At each sample time, the relative phases between the received signal samples and reference PN code shift by one-half chip. The intermediate samples represent correlations of each user's symbol with a reference either one-half chip early or one-half chip late from the ideal user symbol/PN epoch required. The satellite uses these samples to derive an uplink timing error measurement for each VSAT user which is then sent to the users via the downlink. It is the user's responsibility to use this information to maintain required uplink timing accuracy.

For a user code phase separation of 1.5 PN chips and a code length L, the number of CPDMA user channels which can be processed is L/1.5 channels per demodulator. With sampling at twice the PN chip rate, the CCD sample rate required is $2L/T_C$ samples per second. For example, in a rate 1/2 encoded DBPSK implementation providing user services at 16 Kbps, a length 255 PN code could be used to permit simultaneous demodulation of 170 CPDMA user channels with a CCD sample rate of 16.32 MHz. If the code length is increased to 1023 chips, 682 channels are provided but the CCD sample rate required increases to ~65 MHz. Technology limitations on achievable CCD sample rate are one factor limiting the maximum number of user channels which can be demodulated by a single CPDMA bulk demodulator.

IV. A CPDMA Reference Architecture

Figure 4 illustrates one potential implementation of a satellite providing connectivity among a large number of VSAT users. On the uplink, eight fixed antenna beams are used to receive VSAT transmissions. Each antenna beam is divided into M CPDMA user groups with individual groups having distinct carrier frequencies and PN codes. On the downlink, TDMA is used on four hopping beams each having a single downlink carrier.

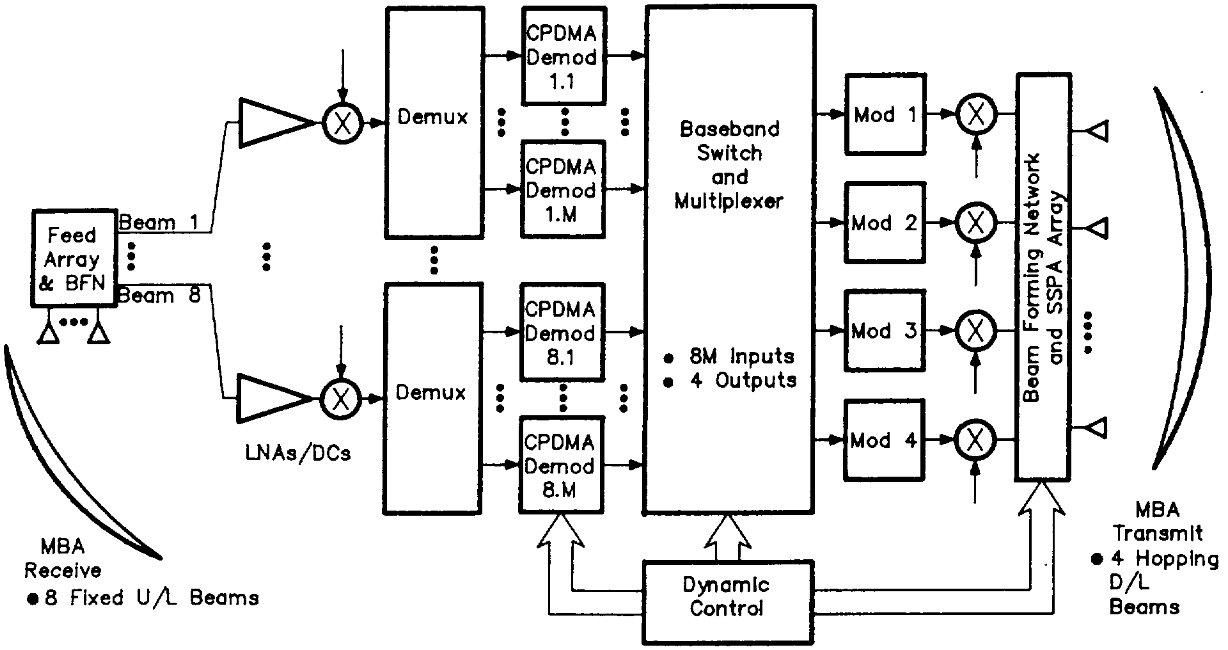

FIGURE 4. SAMPLE CPDMA/SATELLITE SWITCHED/TDMA APPLICATION

Continuing the rate 1/2 encoded DBPSK example from above, for a code length of 255 chips, there are 170 users per CPDMA group and, if M=33 bulk demodulators per beam are used, there will be 33 * 170 or 5610 user channels per beam or 44,880 total user channels. At a data rate of 16 Kbps, the total throughput available is ~718 Mbps and each downlink beam must operate at ~180 Mbps. If the PN code length is increased to L=1023 chips, then only 8 to 9 CPDMA bulk demodulators per beam are required to provide this level of service.

In addition to demodulation of all VSAT transmissions, the satellite also provides data buffering and routing to the appropriate downlink beam, relay of channel control and channel status messages between the VSAT and network controller, and support for the uplink acquisition process executed by the VSAT users. The uplink acquisition process is described in some detail below.

VSAT responsibilities include acquisition and tracking of the satellite provided TDMA downlink, uplink acquisition and maintenance, generation and reception of service control messages to and from the network controller, and communication service implementation and monitoring. Because accurate uplink timing is essential for operation of the CPDMA system, the VSAT must reduce local time errors by acquiring and tracking the satellite downlink before attempting uplink acquisition. Following acquisition, the VSAT must still maintain accurate uplink timing by compensating for satellite motion using satellite ephemerides provided by the network controller, and by adjusting uplink timing in response to uplink tracking measurement reports provided by the satellite.

Even with tracking of the satellite downlink, VSAT uplink timing errors are expected to be too large to permit direct access of a specified CPDMA channel within the group used for VSAT-to-VSAT communications. Instead, an uplink acquisition procedure must be executed by the VSAT using a separate set of CPDMA channels provided by the satellite. The acquisition channel group needs to have enough CPDMA phase channels both to cover the uplink time uncertainty (or equivalently PN phase uncertainty) region of the VSAT uplink signal and to make contention between VSAT users attempting uplink acquisition unlikely.

The acquisition process starts with the VSAT sending uplink probes into the acquisition channel group. These probes can be modulated with information and need to contain at least enough information to identify the VSAT user attempting acquisition. Assuming no contention with another VSAT user at the same code phase, the satellite demodulates the received acquisition probe to identify the user and, additionally, measures the PN phase of the probe. This phase information is sent to the VSAT in order to allow the VSAT to make appropriate uplink clock adjustments. The probe/response cycle may need to be repeated several times before the VSAT clock uncertainty is reduced sufficiently to permit assignment of a communications channel.

A network controller is also required in the reference architecture. The network controller is responsible for assignment and control of all satellite communications resources as well as monitoring of both satellite performance and service operations. Additionally, the network controller must perform satellite tracking and generate satellite ephemerides for distribution to the VSAT users.

V. CPDMA Performance Issues/Evaluations

Initial CPDMA uplink performance examinations have been conducted for the reference architecture using a code length of L=255 chips. Of particular concern were the overall bandwidth efficiency obtainable in the CPDMA architecture as well as oscillator stability and tracking accuracy requirements imposed on the VSATs by the implementation.

Noise sources impacting the VSAT transmitted signal include: Additive white gaussian noise, interference from other user signals within the user's CPDMA group, and interference from users in other CPDMA user groups. The signal transmitted by a VSAT user is subject to time and frequency errors which reduce the signal correlations detected at the satellite. Additionally, channel filtering used to limit interference between CPDMA user groups also reduces the detected signal level. Note, however, that these signal degrading effects are not unique to a CPDMA implementation, but are similar for an ordinary PN spread communications link. For this reason, the current discussion is limited to the interference sources only (although bandwidth efficiency results presented below include all degrading factors).

Of greatest interest is the interference contribution from users within the desired user's CPDMA group. Users within a common CPDMA group are separated only by PN code phase. VSAT uplink signal time errors must be kept small to prevent significant cross-correlation between users that are adjacent in phase. Additionally, factors which could disrupt the ideal correlation properties of the maximal length PN sequences used must also be considered.

Our analyses have indicated that the interference between users adjacent in code phase is small as long as user uplink timing errors are held below 10 to 20 percent of a chip duration. While channel filtering to limit required bandwidth does increase interference among users within a common CPDMA group, the 1.5 chip phase separation between adjacent users keeps the impact small. For the reference architecture, with a length 255 PN code and 16 Kbps data rate, the 0.1 to 0.2 chip accuracy requirement translates into an absolute time error of 12 to 25 ns. To maintain this timing the VSATs must use the timing error measurements periodically reported on the satellite downlink.

Under ideal conditions of zero time and frequency error, the correlation between a user signal and any other user's signal within a CPDMA group is 1/L. For users separated significantly in PN code phase from a desired user, time errors do not alter this result. However, uplink signal carrier frequency errors can significantly raise the correlation magnitude. Our analyses have indicated that maintenance of low signal correlations among users within a common CPDMA group is the driving factor behind user requirements on carrier frequency stability. To maintain the correlation minimums of the maximal length PN sequence the user signal frequency error (Δf) relative to the satellite reference needs to be kept below:

$$\frac{\Delta f}{f_c} < 10^{-8} \qquad (4)$$

where

f_c = Nominal Carrier Frequency

To maintain this carrier frequency accuracy the VSAT must track the frequency of the satellite downlink and compensate for satellite motion using ephemeris predictions. Additionally, the satellite will need to maintain a stable local reference. This reference could be obtained by tracking a stable reference provided by the network control station.

Also included in our evaluations were the degradations due to interference from users in other CPDMA groups. Users in other CPDMA groups are separated from the desired user by both PN code and frequency. It is assumed that users would provide uplink channel filtering to limit the spectral occupancy of their transmissions. Of key importance is the frequency spacing required between CPDMA groups since this spacing determines the overall bandwidth efficiency achievable for the reference architecture.

The current study has been limited to examination of channel spacing and channel filter trades for Butterworth type filters only. Using computations of uplink bit error rate which included all of the degrading factors mentioned thus far, we explored performance as transmission filter bandwidth and user group frequency were varied. The results of this analysis indicate that a center-to-center frequency spacing equal to 0.75 times the null-to-null PN spread signal bandwidth of $2/T_c$ Hz can be readily achieved. Based on this frequency separation between CPDMA channel groups, Table 1 summarizes bandwidth efficiencies for the CPDMA reference architecture under a variety of modulation and coding options. We believe that the current CPDMA implementation, having a code phase separation of 1.5 chips between CPDMA users, provides a bandwidth efficiency that is competitive with FDMA bulk demodulator implementations. Also note that no attempt to optimize all of the parameters of the reference architecture has yet been performed. In particular, it may be possible to significantly reduce the current 1.5 chip user phase separation without sacrificing performance. A reduced phase separation permits more users within a CPDMA user group and raises bandwidth efficiency.

VI. Conclusions

A reference concept and implementation of a communications architecture using code phase division multiple access for single hop satellite communications between VSAT terminals has been described. The architecture includes use of bulk demodulators based on CCD technology projected to be available in the early 90's. Additionally, performance evaluations have been conducted in order to define key VSAT and satellite functional requirements as well as achievable spectral efficiency.

Table 1. CPDMA Achievable Spectral Efficiency

Modulation Format	Coding Rate	Spectral Efficiency (bps/Hz)
QPSK	Uncoded	8/9
QPSK	Rate 3/4	2/3
BPSK	Uncoded	4/9
BPSK	Rate 3/4	1/3

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