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ADAPTIVE BEAMFORMING IN A CDMA MOBILE SATELLITE COMMUNICATIONS SYSTEM

Samuel G. Muñoz-García
Communications Satellites Department
ESA-ESTEC 2200AG Noordwijk, The Netherlands

1 INTRODUCTION

Over the next few years, Mobile Satellite Communications systems will experience a rapid evolution towards providing Global Personal Communication services to hand-held terminals. To meet the challenge, a number of innovative satellite systems have been recently proposed. In terms of payload technology, the use of advanced on-board digital processing techniques is currently being investigated in order to enhance the satellite performance. The functions to be implemented on board include digital beamforming, multiplexing and demultiplexing, signal regeneration and switching.

Code-Division Multiple-Access (CDMA) stands out as a strong contender for the choice of multiple access scheme in these future mobile communication systems [1]. This is due to a variety of reasons such as the excellent performance in multipath environments, high scope for frequency reuse and graceful degradation near saturation. However, the capacity of CDMA is limited by the self-inteference between the transmissions of the different users in the network. Moreover, the disparity between the received power levels gives rise to the near-far problem, this is, weak signals are severely degraded by the transmissions from other users.

In this paper, the use of time-reference adaptive digital beamforming on board the satellite is proposed as a means to overcome the problems associated with CDMA. This technique enables a high number of independently steered beams to be generated from a single phased array antenna, which automatically track the desired user signal and null the unwanted interference sources. Since CDMA is interference limited, the interference protection provided by the antenna converts directly and linearly into an increase in capacity. Furthermore, the proposed concept allows the near-far effect to be mitigated without requiring a tight coordination of the users in terms of power control.

A payload architecture will be presented that illustrates the practical implementation of this concept. This digital payload architecture shows that with the advent of high performance CMOS digital processing, the on-board implementation of complex DSP techniques –in particular digital beamforming– has become possible, being most attractive for Mobile Satellite Communications.

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2 THE COMMUNICATIONS SYSTEM MODEL

Let us consider a communications system in which M mobile users are communicating with a fixed Hub station through a satellite. An *On-board Processing* (OBP) type satellite will be considered which is able to regenerate and apply on-board routing to the uplink signals for its subsequent transmission to the ground. Among other features, the OBP satellite enables the different links to be decoupled and independently optimized; particularly, different modulation and access schemes can be employed for the mobile and the feeder link. As mentioned above, CDMA offers a number of advantages which make it most interesting for the mobile environment. This paper focuses on the study of the mobile link, for which a *Direct-Sequence Code-Division Multiple-Access* (DS-CDMA) scheme will be considered.

In a CDMA system, all the users transmit over the same frequency band. Let R_s be the basic user *information rate*. A different Pseudo-Noise (PN) sequence of length L is assigned to each user, which is employed to spread the basic user information stream to form a transmitted signal at *chip rate*, $R_c = L \cdot R_s$. The spreading factor, R_c/R_s, is hence equal to the length of the PN sequence, L. At the receiver, the desired user's transmission is discriminated by using a conventional correlation scheme, in which the received signal is multiplied by a synchronized replica of the desired user's PN sequence and integrated over a symbol period. The PN sequences considered here belong to a family of *Preferentially phased Gold codes*. Gold PN sequences present optimum cross-correlation properties at the origin, this is, synchronized PN sequences are quasi-orthogonal. In the forward direction, the signals transmitted to the different users are spread with synchronized PN sequences. The signals are quasi-orthogonal and, therefore, the mutual interference between them is negligible. This is referred to as a *Synchronous CDMA* (S-CDMA) link. Conversely, the signals transmitted in the return link are not synchronized, and hence, they are not orthogonal at the satellite transponder input. The non-orthogonality of the PN sequences employed in an *Asynchronous CDMA* (A-CDMA) link gives rise to the problem of *self-jamming*, this is, nonzero interference contributions arise from the transmissions of the other users in the network. Associated to the self-jamming is the so-called *near-far* problem.

We concentrate on the asynchronous return link, for which the use of adaptive digital beam-forming on board the satellite is proposed in order to overcome the problems associated with CDMA. The effect of the adaptive antenna in an A-CDMA system is illustrated in figure 1, which has been obtained by computer simulation. This figure compares the bit error rate (BER) versus the E_s/N_o for S-CDMA, A-CDMA and A-CDMA with adaptive beamforming. The self-interference, which strongly degrades the performance of A-CDMA, is drastically cancelled by the antenna in such a way that the performance of A-CDMA with adaptive beamforming is comparable to –or even better than– that of S-CDMA.

We assume that the available bandwith is occupied by a frequency multiplex of N_c contiguous CDMA carriers. The satellite antenna generates one independent beam per user which is automaticaly steered to point the maximum gain in the direction of the mobile terminal while nulling the co-channel interferences arriving from other users. The adaptation of the radiation pattern is illustrated in figure 2. Users allocated to the same CDMA carrier should be as spread as possible over the satellite coverage, in order for the satellite antenna to have sufficient resolution to point the beam to one user while nulling the others. Nevertheless, a limited number of co-channel interferers can be tolerated within the desired user's main-beam coverage which are discriminated by the PN code. A low spreading factor will be considered, so that the CDMA carriers are relatively narrowband. This will have important implications in the implementation.

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3 INTEGRATION OF ADAPTIVE BEAMFORMING IN A DS-CDMA SYSTEM

The objective of an adaptive array antenna is to improve the reception of a certain desired signal in the presence of undesired interfering signals. The antenna radiation pattern must be conformed in such a way that the main lobe is pointed in the direction of the desired signal, while the nulls are steered in the direction of the interferences. In this way, the signal-to-interference-plus-noise-ratio (SINR) at the array output is maximized.

The achievable performance in an adaptive array has two basic limitations: these are associated with the *degrees of freedom* and the *resolution* of the array. An N-element array has only N-1 degrees of freedom in its pattern. Requiring a beam maximum at a given angle uses up one degree of freedom, the same as requiring a null. Thus, the array is able to point the main beam to the desired user direction and still null up to N-2 interferences. Another limitation the designer must be aware of is the fact that a given array has only a certain ability to resolve signals in space. If the arrival angle of the desired and interfering signals are too close, the array cannot simultaneously null the interference and form a beam on the desired signal. The minimum angular separation between a maximum and a null in the radiation pattern depends primarily on the array aperture size but also to a lesser extent on the element patterns and the number of elements.

In order to apply adaptive beamforming, the desired signal must be different from the interfering signals in some respect. Two different classes of adaptive techniques can be distinguished: *time reference* beamforming and *spatial reference* beamforming. Time reference beamforming can be applied when a time *reference signal* is available which is correlated with the desired signal and uncorrelated with the interferences. Instead, if the *direction of arrival* of the desired signal is known, a spatial reference technique is to be utilized.

Due to the *a priori* knowledge of the desired user PN sequence, a DS-CDMA system lends itself very easily to the generation of an adequate time reference signal. Therefore, we will mainly concentrate here on a time reference beamforming technique, namely, the well-known LMS (least-mean-square) algorithm. After introducing the LMS algorithm, we will describe the way to generate the reference signal. The hardware implementation of this algorithm in a CDMA system will be presented later. Finally, the adaptive algorithms *with main-beam constraints* will be introduced which overcome the problems associated with the limited resolution of the antenna.

3.1 The LMS Algorithm

The *Least Mean Square* (LMS) algorithm is a gradient-based algorithm that minimizes the mean-squared value of the *error signal* $\epsilon(t)$, which is the difference between a locally generated reference signal $r(t)$ and the array output $y(t)$. The (discrete) LMS algorithm is given by the following equations:

$$W(n+1) = W(n) + \gamma \cdot \epsilon(n) \cdot X^*(n) \tag{1}$$

$$\epsilon(n) = r(n) - y(n) = r(n) - X^T(n) \cdot W(n) \tag{2}$$

where $W(n)$ and $X(n)$ are complex vectors of samples at instant n of the antenna weights and the signals in the antenna elements respectively, $\epsilon(n)$ is the corresponding sample of the

instantaneous error. The parameter γ is called the *step-size*. In order for the LMS algorithm to converge, the step size γ must meet the following stability condition:

$$0 < \gamma < \frac{1}{P_t} \tag{3}$$

where P_t is the total power received by the array. The speed of convergence of the algorithm increases with the step-size γ; once in steady-state the weights oscillate with a variance which is also proportional to γ.

As explained in [2], the depth of the null created in the direction of arrival of the interference increases with the interference power; strong interferences are deeply cancelled by the antenna. In our system, this performance characteristic provides an excellent robustness in the presence of the near-far problem.

3.2 Reference signal generation

In order to apply a time-reference adaptive algorithm, the main challenge is to find a way to obtain a suitable reference signal which is highly correlated with the desired signal and uncorrelated with the interferences. In a CDMA system, the reference signal can be derived from the array output as shown in the reference signal generation loop illustrated in figure 3. The reference signal generation comprises the despreading and demodulation[1] of the desired user signal using a conventional correlation receiver, and subsequent re-spreading of the demodulated data with the same PN sequence. The generated reference is an almost perfect replica of the desired user signal: the desired signal component at the array output passes through this loop unchanged –except for the amplitude adjustment and a certain delay–, while the interference signal waveform is drastically altered and its correlation with the reference signal is essentially destroyed by the loop.

The reference signal generation loop has a certain delay which is mainly determined by the integrator contained in the spread-spectrum demodulator. If a full demodulation is performed, the delay is equal to one information symbol period T_s. Instead, partial demodulation can be used, this is, the integration time can be reduced and the decision on the transmitted symbol can be taken on the basis of a fraction of the received symbol waveform.

3.3 Hardware Implementation

The delay incurred in the generation of the reference signal has important implications in the hardware implementation, calling for some modifications in the basic LMS algorithm. The block diagram illustrated in figure 4 represents the implementation of an adaptive array antenna using the *delayed LMS algorithm* in a DS-CDMA system. Let us assume that the reference signal generation circuit introduces a delay equal to D samples. Both the signals in the array elements and the signal at the array output are stored during D samples to properly obtain the (delayed) error signal. Then, these signals are applied to the so-called *delayed LMS algorithm* which is given by the following equations:

$$W(n+1) = W(n) + \gamma \cdot \epsilon(n - D) \cdot X^*(n - D) \tag{4}$$

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[1] Attention should be drawn to the fact that the amplitude of the reference signal must be constant. For this purpose, a hard limiter (detector) has also been included in the reference generation loop.

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$$\epsilon(n - D) = r(n - D) - X^T(n - D) \cdot W(n - D) \qquad (5)$$

As a consequence of the delay, the step-size γ has to be contrained to a much more restrictive range. The stability condition for the delayed LMS algorithm is given by:

$$0 < \gamma < \frac{1}{D \cdot P_t} \qquad (6)$$

Therefore, the delay in the generation of the reference has two major implications. At hardware level, the signals in the array elements and the array output need to be stored. As far as the performance is concerned, the speed of convergence of the algorithm is severely reduced. The acceptability of the reduced speed of convergence will depend on the application; for slowly varying scenarios the delayed LMS algorithm will exhibit in general a satisfactory performance.

3.4 Adaptive algorithms with main-beam constraints

Due to the limited resolution of the antenna, when the directions of arrival of the desired and the interfering signals are too close, nulling the interference may cause the gain in the direction of the desired signal to drop. In order to avoid the problem of signal cancellation in the main beam, linear constraints can be placed in the adaptive algorithm [3]. The processor will then maintain a constant gain in the desired direction and the shape of the pattern will be controlled in the vicinity of that direction (derivative constraint) without responding to interference signals in the main lobe.

These techniques require the information on the direction of arrival of the desired signal, this is, the *steering vector*. In essence, they constitute spatial-reference rather than time-reference beamforming techniques; in practice, however, the steering vector can be estimated by averaging the correlation of the time reference signal with the signals in the array elements over a certain number of samples.

4   PAYLOAD CONFIGURATION

Digital beamforming techniques are currently being considered for future mobile satellite communication payloads. The payload implementation presented here relies upon the use of some technologies currently under development by ESA [4] [5]. In particular, SAW-chirp Fourier transform (CFT) techniques and Digital Signal Processing employing CMOS ASIC technologies are considered. SAW-CFT devices are used to demultiplex the various CDMA carriers. The extensive use of CMOS ASIC technology enables the size and power consumption of the DSP circuitry to be reduced so that the implementation of very complex functions –such as digital beamforming or demodulation– becomes feasible.

As mentioned above, an On-Board Processing (OBP) satellite is considered. By using OBP, the uplinks and downlinks are decoupled and, in consequence, the configuration of the different payload sections becomes fairly independent. Here, we focus on the receive section of the return link, in which the adaptive beamforming concept proposed in this paper is implemented.

The payload configuration for the receive section of the return transponder is illustrated in figure 5. The funcional performance is as follows. A single large mobile-link array antenna is

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used which consists of N antenna elements. The signals in the antenna elements are applied to receiver chains which perform the filtering, LNA amplification and downconversion to an intermediate frequency. The N_c contiguous CDMA carriers are demultiplexed by the SAW-CFT processors. The principle of the CFT is to slide a slot filter characteristic across the input band during the course of a given chirp frame. Then, by critically sampling at the output, a single CFT device can operate as a bank of fixed filters. The CFT output is analog-to-digital converted, and the signals corresponding to the different CDMA carriers are separated by means of commutators and applied to separate beamformers.

A low spreading factor is considered, so that the CDMA carriers are relatively narrowband. This has a two-fold effect in reducing the payload complexity. First, the bandwidth of the beamformers is decreased, along with their power consumption. Moreover, the number of users allocated to a particular CDMA carrier is relatively small, therefore requiring a small number of degrees of freedom in the antenna; this reduces the number of antenna elements required, further simplifying the beamformer.

Let us consider that up to N_u users can be allocated to each CDMA carrier. A bank of N_u parallell beamformers –one per user– is then associated to each CDMA carrier. Each beamformer is connected to a particular user's CDMA receiver and controlled by an adaptive processor. The weights calculated by the adaptive algorithm can also be utilized in the Tx forward link, assuming a digital beamforming antenna is used there. The outputs of the CDMA receivers are connected to a baseband switch for on-board routing of the channels. The mobile-to-mobile communication channels can be directly connected to the forward link.

5   SYSTEM CAPACITY. NUMERICAL EXAMPLE

To conclude this paper, we will assess the capacity of the proposed system by means of a numerical example. Let us consider a basic user information rate of 6.4 Kbps, a spreading factor $L=31$ and let us assume that the signal is QPSK modulated and filtered with 50% roll-off. The bandwidth occupied by a CDMA carrier is then equal to 148.8 KHz. Assuming that 10 MHz of bandwith are available, the number of CDMA carriers is equal to $N_c=67$. In our case, the number of users N_u that can be supported by a CDMA carrier is no longer limited by the self-interference –since this is drastically cancelled by the beamformer– but by the number of degrees of freedom of the antenna which approximately equals the number of antenna elements N. If we consider a 100 element antenna, the number of users per CDMA carrier is equal to $N_u \simeq N=100$. Hence, the total system capacity is given by $N_c \cdot N_u \simeq 6700$ channels.

This capacity value can be compared with that obtained for a conventional CDMA satellite system utilizing a (fixed) multiple-beam antenna. In such a system, capacity can be increased by reusing the whole frequency band in all the beams [6]. For a BER objective of 10^{-4}, using uncoded QPSK, the number of 6.4 Kbps channels supported in 10 MHz available bandwidth by a 91-beam satellite system is approximately equal to 3800. (This value has been obtained in the assumption of uniform traffic distribution, without considering the near-far effect.)

In conclusion, the adaptive beamforming CDMA payload presented in this paper enables the capacity to be sensibly increased with respect to a more conventional system. Moreover, the system is robust to the near-far problem and the capacity is fairly independent of the traffic distribution.

Contact the Author for References and Figures.