Spread Spectrum in a Four-Phase Communication System Employing Adaptive Antennas

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Abstract—**This paper discusses the use of spread spectrum in a four-phase communicaton system employing adaptive antennas. A system is described that provides protection against both conventional (i.e., noise and CW) and smart (in particular, repeat) jamming with rapid acquisition of the signal at the receiver. A method is shown for generating reference signals required by the adaptive array through the use of spread spectrum. With these reference signals, the received antenna pattern can be adapted to maximize desired signal to interference and noise power ratio at the receiver. The signal acquisition technique is also described and analyzed. Analytical and experimental results demonstrate both the rapid acquisition and protection against jamming with this system.**

I. INTRODUCTION

An ADAPTIVE antenna is an array of antenna elements whose pattern is automatically controlled [1], [2]. The signal from each element of the array is multiplied by a controllable weight, which adjusts the amplitude and phase of that signal. The pattern of an adaptive antenna is automatically changed to null interfering signals and optimized desired signal reception.

Adaptive antennas can be combined with spread-spectrum communication techniques to yield even greater interference rejection capabilities than either one alone. A system combining the temporal processing of spread spectrum with the spatial processing of adaptive antennas can provide protection against a wide variety of jamming techniques.

The weights in an adaptive array may be controlled by several techniques [1], [2]. In particular, the technique used in the LMS array [1] is considered here. In the LMS array, the weights are adjusted to obtain the least mean-square error between the array output and a reference signal. This reference signal is a locally generated signal that allows the array feedback to differentiate between the desired signal and interference. It must be a signal correlated with the desired signal and uncorrelated with any interference.

The major problem in the development of a communication system using an adaptive array is the generation of the reference signal. A method must be developed for the acquisition of the signal by the receiver. This method includes the code timing acquisition, if the timing of the pseudonoise code used to spread the signal spectrum must be acquired by the receiver.

A reference signal generation technique has been previously described for spread-spectrum signals using biphase modulation [3]. The timing of the pseudonoise code used in the system is acquired at the receiver by a slewing method. To determine the correct code timing, the code generated at the receiver is correlated with the received signal for all possible timing offsets [4]. The reference signal generation technique for the biphase system works well, but does have two shortcomings. First, it is vulnerable to repeat jammers with biphase remodulation. Second, short codes must be used to achieve reasonable acquisition times, and short codes may not provide adequate security for many applications.

This paper presents a four-phase communication system that may be used with an LMS adaptive antenna. The system is a spread-spectrum communication system. It is assumed that the location of the desired transmitter is not known at the receiver and that system code timing must be acquired by the receiver. A four-phase system has been developed that overcomes the shortcomings of the previous biphase system [3], without sacrificing the system's rapid acquisition and conventional (i.e., noise and CW) jamming protection capabilities. This four-phase system will now be described.

The four-phase signal consists of two orthogonal biphase signals. One signal contains a short code for rapid acquisition. The other contains a long code to be used for protection against smart jammers (jammers that the biphase system is vulnerable to). The reference signal generation technique and signal acquisition technique are described. Both rapid acquisition and protection against conventional and smart jamming are demonstrated by analytical and experimental results.

We first describe in Section II the four-phase signal and the LMS adaptive array used in the system. We then discuss in Section III reference signal generation for the array. Next, in Section IV the code timing acquisition process is discussed. Finally, in Section V we describe an experimental system, discuss experimental results, and compare them to theoretical results.

II. SYSTEM DESCRIPTION

The transmitted carrier is modulated by two codes plus data. The one code is a pseudonoise code, i.e., a maximal length linear shift register sequence. This code has a short length (on the order of 1000 symbols) to permit its timing to be rapidly acquired by the receiver. The other code has a very long length (e.g., greater than 10^9 symbols). The code may be either a pseudonoise (linear) or a nonlinear code [5], i.e., it is generated from a shift register with nonlinear feedback logic. This code is used to provide greater communication security in the system as shown later.

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The codes plus data modulate the carrier in the following way. Let the mth short code symbol and long code symbol be labeled a_m and b_m (equal to 0 or 1), respectively, and have a duration of Δ seconds. The ith data, or useful information, symbol is labeled d_i (equal to 0 or 1) and has a duration of T_b seconds. The data symbol duration is greater than the code symbol duration by an integer multiple k, the spreading ratio. With these symbols differentially encoded, the transmitted signal is given by

$$s(t) = \frac{A}{\sqrt{2}} \sin(\omega_1 t + \zeta(t)) + \frac{A}{\sqrt{2}} \cos(\omega_1 t + \phi(t)) \tag{1}$$

where

$$\zeta(t) = \theta(t) + \gamma(t), \tag{2}$$

$$\phi(t) = \phi_m = \phi_{m-1} + \pi b_m \quad \text{for } (m-1)\Delta \leqslant t < m\Delta \tag{3}$$

and

$$\theta(t) = \theta_m = \theta_{m-1} + \pi a_m \quad \text{for } (m-1)\Delta \leqslant t < m\Delta, \tag{4}$$

$$\gamma(t) = \gamma_i = \gamma_{i-1} + \pi d_i \quad (i-1)T_b \leqslant t < iT_b. \tag{5}$$

In the above equations, A is an amplitude constant, ω_1 is the carrier frequency, and γ_0, θ_0, and ϕ_0 are equal to 0. The data symbol transitions coincide with the code symbol transitions. Thus, the signal is a four-phase differential phase shift keyed (DPSK) signal consisting of two orthogonal binary DPSK signals. One binary signal contains a short code plus data (as in the biphase system), and the other contains a long code.

A block diagram of an N element LMS adaptive array [1] is shown in Fig. 1. The signal received by the ith element $y_i(t)$ is split with a quadrature hybrid into an in-phase signal $x_{I_i}(t)$ and a quadrature signal $x_{Q_i}(t)$. These signals are then multiplied by a controllable weight w_{I_i} or w_{Q_i}. The weighted signals are then summed to form the array output $s_0(t)$. The array output is subtracted from a reference signal (described below) $r(t)$ to form the error signal $e(t)$. The element weights are generated from the error signal and the $x_{I_i}(t)$ and $x_{Q_i}(t)$ signals by using the correlation feedback loops as shown in Fig. 2.

The purpose of the reference signal is to make the array track the desired signal. The reference signal must be a signal correlated with the desired signal and uncorrelated with any interference. Generation of a reference signal from a four-phase signal is described below.

Two different reference signals can be generated from the four-phase signal. These two signals are the two binary DPSK signal components of the four-phase signal. Thus, one reference signal contains a short code, and the other a long code.

A reference signal can be generated from the four-phase signal using the loop shown in Fig. 3. This is the same loop

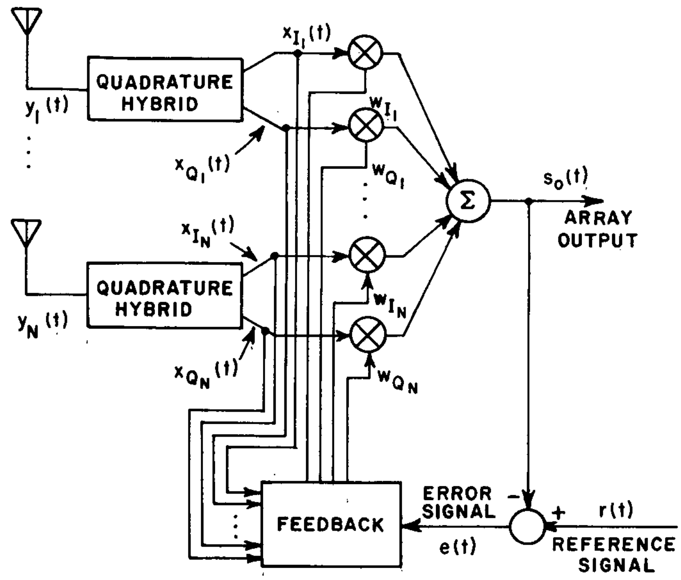

Fig. 1. Block diagram of an N element LMS adaptive array.

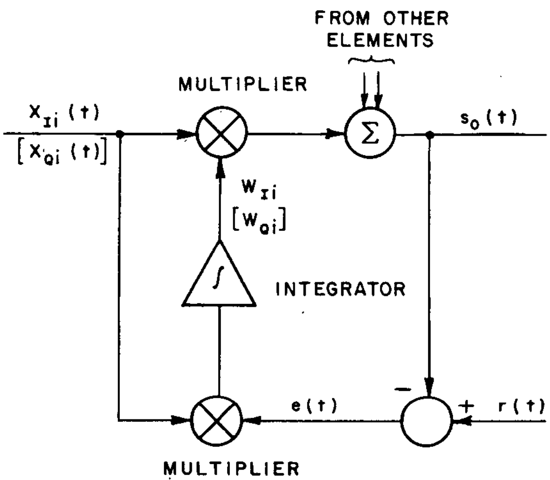

Fig. 2. Correlation feedback loop for the adaptive array.

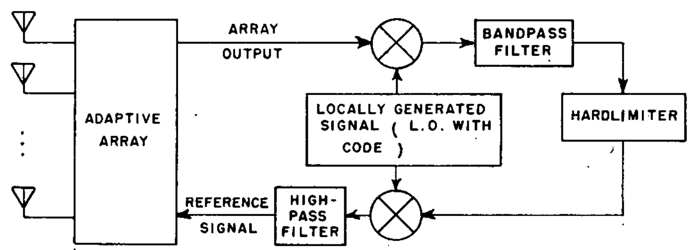

Fig. 3. Reference signal generation loop with the adaptive array.

that was used with the biphase system [3]. The array output is first mixed with a locally generated signal modulated by either the short or long code. When the codes of the locally generated signal and the array output signal are synchronized, the array output signal's spectrum is collapsed. It is collapsed to the data bandwidth when the locally generated signal is modulated by the short code and a single frequency component when the locally generated signal is modulated by the long code. The mixed output is then passed through a filter with either the data bandwidth or a very narrow bandwidth

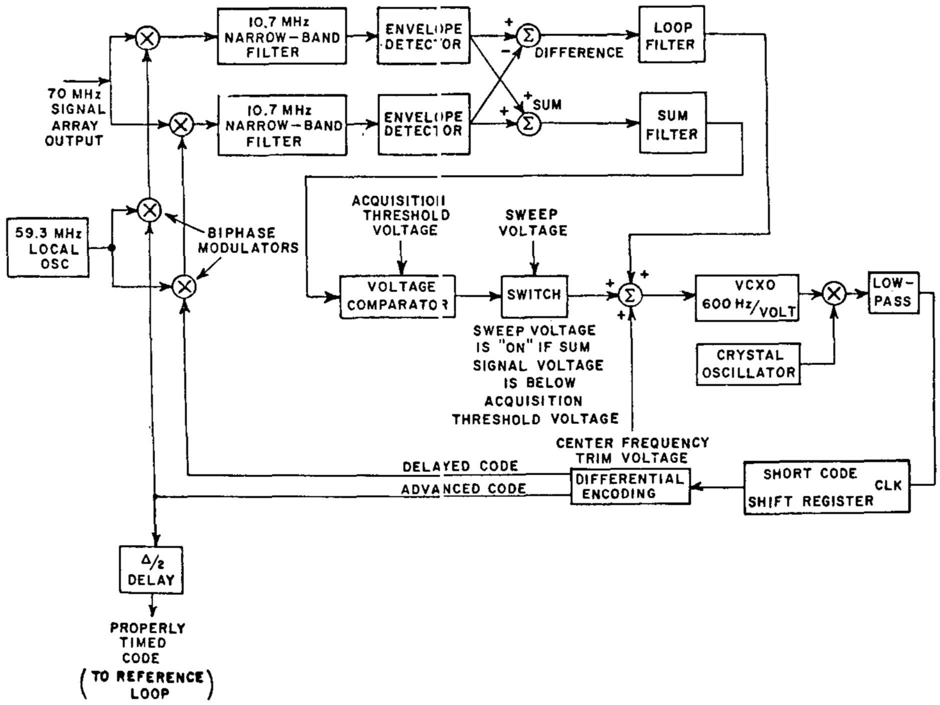

Fig. 4. Block diagram of the delay lock loop.

depending on the code involved. The biphase desired signal component is, therefore, unchanged by the filter. The filter output is then hard limited so that the reference signal will have constant amplitude. The hard-limiter output is mixed with the locally generated signal to produce a biphase reference signal. The reference signal is, therefore, an amplitude scaled replica of one of the biphase components of the four-phase desired signal.

Any interference signal without the proper code has its waveform drastically altered by the reference loop. When the coded locally generated signal is mixed with the interference, the interference spectrum is spread by the code bandwidth. The bandpass filter further changes the interference component out of the mixer. As a result, the interference at the array output is uncorrelated with the reference signal.

III. ACQUISITION OF THE SIGNAL

The acquisition of the signal by the receiver will now be described. In particular, we describe the method for obtaining the timing of the codes by the receiver. The method presented here combines a sequential search method and the rapid acquisition by sequential estimation (RASE) [6] method for code timing acquisition with the use of an adaptive array.

The acquisition method consists of several steps. The first step is the acquisition of the short code timing. The short code timing is acquired and then tracked by the delay lock loop shown in Fig. 4. In the delay lock loop the difference voltage from the two envelope detectors is used to track the code timing [3], and the sum voltage is used for timing acquisition. The sum voltage is used for timing acquisition because it indicates the alignment (maximum correlation) of the received and locally generated codes.

The acquisition method for the short code timing is similar to that used in the biphase system [3], i.e., a sequential search (slewing) method is used. To acquire the short code timing, the code generator at the receiver is run faster than the received signal's code. When the two codes begin to align, the sum voltage increases. When the sum voltage exceeds the acquisition threshold, the sweep voltage is turned off, and code tracking begins. Also, during the short code acquisition process, the short code is used to generate the reference signal in the adaptive array. Thus, the reference code is also slewed. Before acquisition, the array nulls interference and the desired signal. When the codes begin to align, the array pulls the desired signal out of the noise. The desired signal power into the delay lock loop, therefore, also increases when the codes align. This process is described further in [3].

With this slewing method, the code generated at the receiver is correlated with the received signal for as many as all possible timing offsets. Thus, the acquisition time is proportional to the code length, and the code length must be short for reasonable acquisition times.

The second step in the acquisition method is the acquisition of the long code timing. During this step the short code is used to generate the reference signal in the array. Because the array has nulled all signals except the signal acquired (including CW and noise jammers), the array output consists mainly of the desired signal. Therefore, the RASE [6] method can be used to quickly acquire the long code timing. In the RASE method the timing for a code generated from an n stage feedback shift register is obtained by detecting and loading n consecutive code symbols into a similar shift register at the receiver.

Fig. 5 shows how the RASE method can be used to determine the long code timing in the four-phase system. The array output containing the desired four-phase signal is differentially

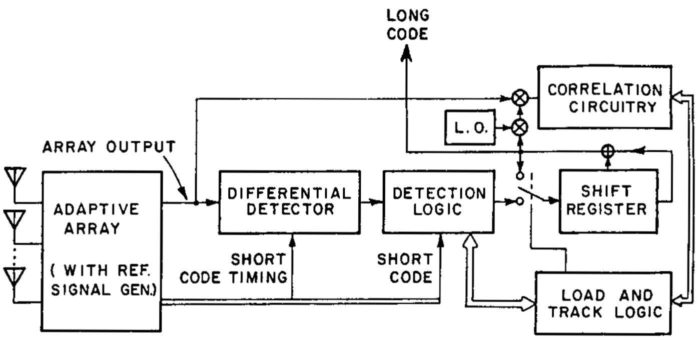

Fig. 5. RASE with an adaptive array for four-phase modulated signal.

detected using the symbol transition timing from the tracking of the short code. The differential detector output (relating to the phase transitions in the signal) is then processed by the detection logic. These phase transitions depend on the long code, the short code, and the data symbols. Since the short code symbols are known, the detection logic can determine the long code symbols and, in some cases, also determine if errors have been made by the differential detector. If no errors are detected, the long code symbols are loaded into the shift register. The feedback loop in the shift register is then connected and the output of the shift register correlated for a short time with the array output to verify code timing. If the correlation of the two signals exceeds a threshold value, the output of the shift register is used to generate the reference signal for the array. Otherwise, the shift register is reloaded and the process repeated until code synchronization is obtained.

It should be noted that with the long code acquisition method the only requirement for the shift register network generating the code is that the only feedback connection must be to the first shift register stage. Thus, the timing for nonlinear codes (which are more secure than linear codes [7]) that are generated in this way [5] can also be obtained by the RASE method.

Fig. 6 shows the results of a simulation study of the long code acquisition process. This simulation study and additional analytical results are discussed in [8]. The Appendix presents a summary of some of these analytical results. In Fig. 6, the required energy per chip (code symbol interval) to noise density ratio E_Δ/N_0 at the processor input (array output) is plotted versus the long code shift register length for various acquisition times. The results show that very long codes can be quickly acquired if E_Δ/N_0 is greater than about 3. For example, with a 10 Mbit/s code modulation frequency, a 10^{12} length code (n equal to 40) can be acquired in less than 0.001 s if E_Δ/N_0 is greater than 3. In general, E_Δ/N_0 at the array output will be at least 3 because of two factors. First, the energy per data bit to noise density ratio at the array output must be fairly high (usually greater than 15) for low bit error rates. Second, the spreading ratio is usually as small as possible to minimize the signal bandwidth and can be as small as 5 [3]. Thus, with these two conditions, the E_Δ/N_0 at the array output will be greater than 3.

The four-phase system as described so far provides the same protection against conventional (i.e., noise and CW) jamming

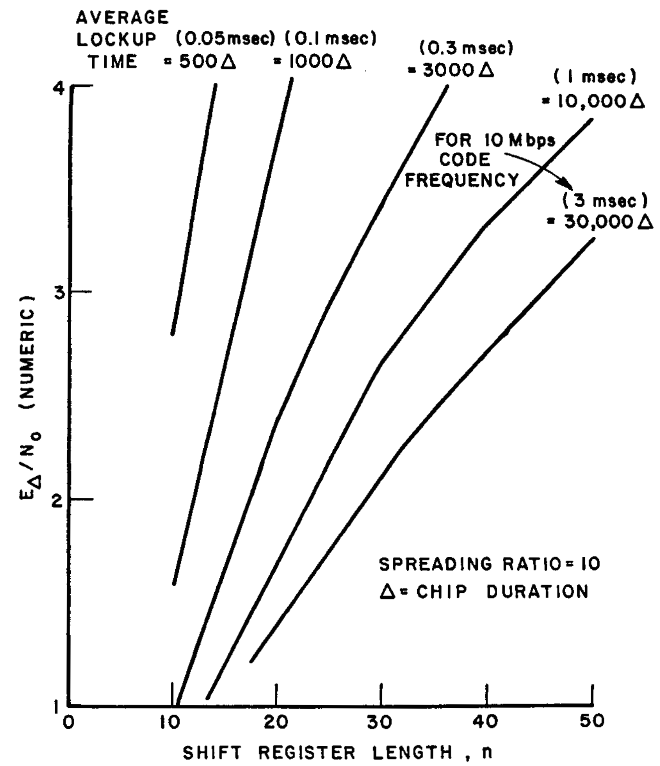

Fig. 6. Required E_Δ/N_0 versus shift register length for given average lockup times, with a long code correlation time of $20\,n\Delta$.

as the biphase system [3]. With the biphase system, as much as a 35 dB improvement in signal-to-interference ratio can be achieved with a spreading ratio of only 5.

An additional step in the acquisition method provides protection against smart jammers (i.e., jammers using only the short code or repeat jammers with remodulation). If the long code timing is not acquired in a short period of time, the short code timing is changed and the acquisition procedure is repeated. The reason this provides smart jammer protection is described below.

IV. SMART JAMMER PROTECTION

The long code is present to add greater security to the system. In the previous biphase system [3], the signal contained no long code, only a biphase signal with a short code plus data. Therefore, this system had the two shortcomings listed below.

First, in the biphase system data are modulated on the transmitted signal by the introduction of additional 180° phase shifts. Therefore, the signal from a jammer that repeats and adds 180° phase shifts (at a rate equal to or less than the data rate) to the desired signal cannot be distinguished from the desired signal by the array. The array may acquire the jammer's signal and null the desired signal. To overcome this problem, the data modulation must be different than biphase.

Second, short codes must be used for reasonable acquisition times. Short codes, however, may not provide adequate security for many applications. The short code repeats often during transmission of the signal, and, therefore, the code can easily be determined and used by a jammer. When the jamming signal contains the code, the receiver is unable to distinguish the jamming signal from the desired signal. To overcome this problem, codes with very long periods are required.

Because the four-phase signal contains an orthogonal biphase signal with the long code, the biphase system shortcomings are overcome. First, the data modulation technique is no longer biphase. Examination of (1) shows that the additional phase transition due to the data bit "1" is either +90° or −90°. Also, the phase transition depends upon both the short and long code symbols. Thus, the data modulation method cannot be easily duplicated by a jammer. Furthermore, biphase remodulation by the jammer changes the long code symbols and, thus, can be detected. Second, a long code for communication security has been combined with the short code for rapid acquisition. Since both codes are acquired by the receiver, a jammer must use both codes to jam effectively. However, because the long code does not repeat for a long time and may even be nonlinear, it is very difficult for a jammer to determine and use this code [7].

Although there are other jamming strategies, the above two examples point out that for a smart jammer to effectively jam the four-phase system, it needs to determine the long code. In particular, the jammer must determine the length and feedback connections of the shift register generating the long code. With this system, protection against smart jamming depends on the security of the long code. Since very long (and nonlinear [5]) codes can be used, the codes can be very secure (i.e., it can be almost impossible for a jammer to determine the code feedback shift register from the signal). Thus, the system can provide significant protection against smart jamming.

We will now describe the process through which protection is provided against smart jammers. To begin, we will assume, that the short code timing on a jammer signal is different from that of the desired signal.[1] Thus, during the first step in the acquisition method, the short code timing of either the desired signal or a jammer may be acquired by the receiver. If the desired signal's short code is acquired, then the jammer will be nulled and the acquisition process can be completed. If the jammer's short code is acquired, however, the long code timing will not be acquired in a short time, because the long code symbols are either not present or changed due to remodulation by the jammer. The short code timing at the receiver will then be changed, and the acquisition process repeated. Since the receiver's code timing is slewed sequentially during acquisition, all possible code timing offsets will be examined before the smart jammer's short code is acquired again. Thus, if the desired signal is present it will be acquired before acquisition of the smart jammer is attempted again. Thus, with smart jamming the acquisition time may be increased, but acquisition of the desired signal cannot be prevented.

V. AN EXPERIMENTAL SYSTEM

An experimental system was developed to verify analytical results and demonstrate conventional and smart jamming protection with rapid acquisition. A block diagram of the system is shown in Fig. 7. The transmitted four-phase signal is received by the adaptive array through a channel and interference simulator. This simulator was used to generate the received signals for each antenna element. The signals correspond to those received with a desired signal and interference arriving at the receiving array from different angles.[2] From the desired signal in the array output the short code timing is determined and tracked by the delay lock loop. Long code timing is acquired by the long code acquisition circuitry. The control logic manages the acquisition procedure steps, including which codes are used in the reference loop to generate the reference signal.

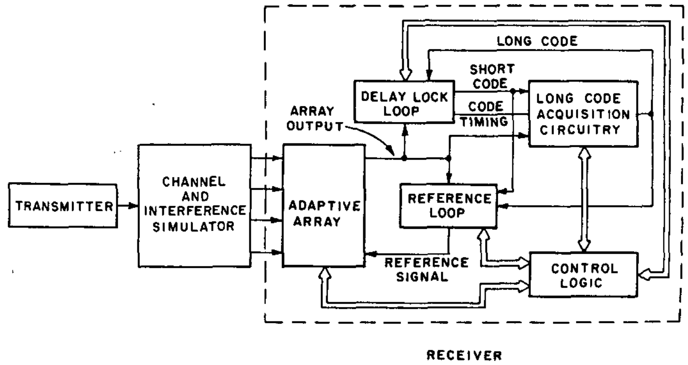

Fig. 7. Block diagram of the experimental four-phase communication system with an adaptive array at the receiver.

Some of the parameters for the system are listed in Table I. The code modulation frequency and the spreading ratio were chosen to be compatible with an existing four-element array [9]. The maximum allowed acquisition time is the time allowed for acquisition of the long code. If the long code is not acquired in this time, the short code timing is changed and the acquisition process repeated.

We will now consider the acquisition time as a function of the received E_Δ/N_0 (array input), $E_\Delta/N_0|_{IN}$. Fig. 8 shows the average total acquisition time versus $E_\Delta/N_0|_{IN}$ for the system (see the Appendix for analytical results). The figure shows that the signal can be rapidly acquired even when $E_\Delta/N_0|_{IN}$ is near 0 dB. It should be noted that with a four-element adaptive array the array output E_Δ/N_0 will be 6 dB higher than $E_\Delta/N_0|_{IN}$.

Figs. 9 and 10 show the CW interference suppression of the four-phase system. The CW signal is 20 dB stronger than the desired signal at the array input, yet very little interference power can be seen in the output. For the experimental system, this was the maximum jammer-to-signal ratio (J/S) for which acquisition could occur. However, the experimental system was designed to show concept feasibility, and not necessarily a large jammer rejection. Systems can be designed with a maximum J/S of 40 dB or more. The reason for this limit in the experimental system is described below.

The maximum J/S is dependent on the code modulation

[1] This is a reasonable assumption. For a repeat jammer with remodulation, the signal will be delayed by the jammer. If the jammer is using only the short code, it is unlikely that the jamming signal would arrive at the receiver with the same code timing as the desired signal.

[2] For the experimental results, the desired signal arrives from broadside and the interference has a 60° element-to-element phase shift, corresponding to an angle of arrival of 19.5° from broadside for half wavelength element spacing.

TABLE I
EXPERIMENTAL FOUR-PHASE SYSTEM PARAMETERS

LMS Adaptive Array	4 antenna elements
Code Modulation Frequency	175.2 kbits/s
Spreading Ratio	16
Data Rate	10.95 kbits/s
Minimum Received E_Δ/N_o	0 dB
Average Acquisition Time	0.23 s
Maximum Allowed Acquisition Time	0.55 s
Short Code Length	255 symbols
Long Code Length	1.72 * 10 ** 10 symbols (n = 34)

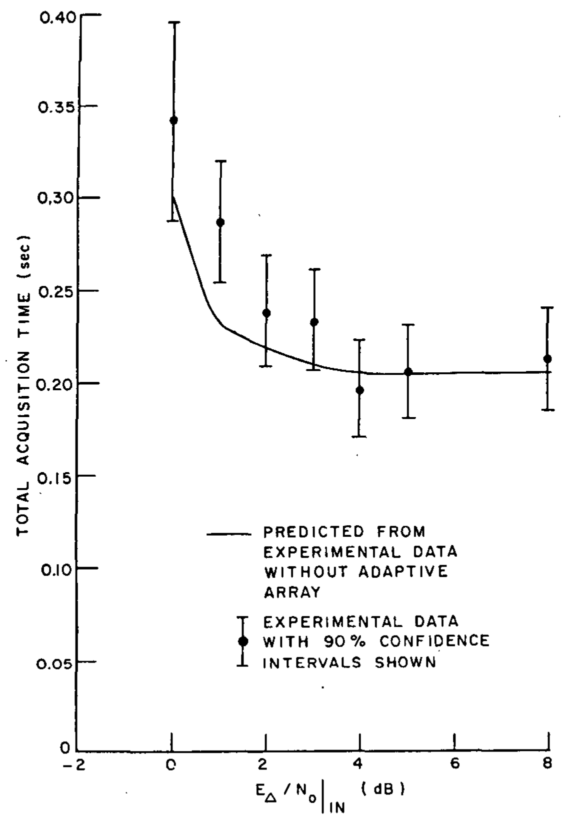

Fig. 8. Total acquisition time versus received energy per chip to noise density ratio $E_\Delta/N_0|_{IN}$.

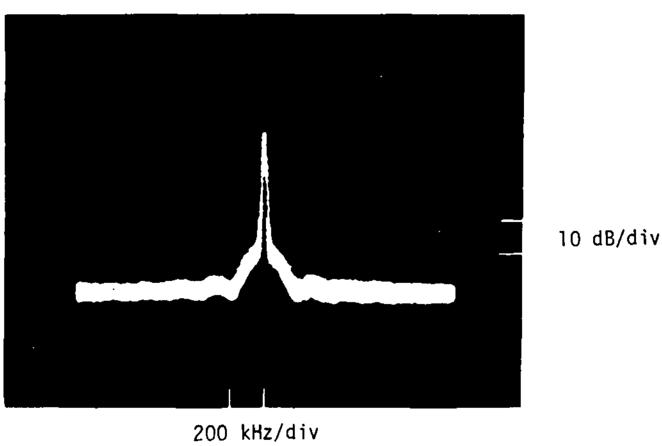

Fig. 9. Received power density spectrum at array input, $E_\Delta/N_0|_{IN}$ equal to 8 dB and J/S equal to 20 dB.

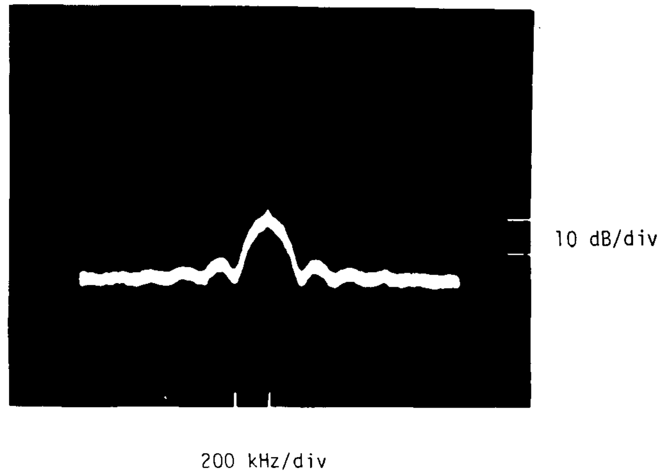

Fig. 10. Array output power density spectrum for input as shown in Fig. 9.

frequency and the acquisition time. The reason is that the rate of response of the array weights is proportional to the signal strength (in the LMS array). For the strongest interfering signal, the weights must respond slower than 0.2 times the code modulation frequency [10]. Otherwise, the weights will begin to modulate the interference to look like the reference signal. For the weakest desired signal, the weights must respond faster than the slewing speed during acquisition. Otherwise, during acquisition the desired signal will not be pulled out of the noise and the acquisition threshold in the delay lock loop exceeded. For the experimental system the ratio of 0.2 times the code modulation frequency to the sweep speed was approximately 20 dB (see the Appendix), as shown experimentally. It should be noted that a much higher maximum J/S can be achieved with higher code modulation frequency. Furthermore, adaptive array algorithms are currently being studied [11] to eliminate the weight response problem.

Fig. 11 shows the average acquisition time with the four-phase system when a repeat jammer with biphase remodulation is present at the receiver. As seen in the figure, when J/S is greater than -1 dB, the jammer signal's short code can be acquired by the receiver for a brief time, and, therefore, the average acquisition time for the desired signal is increased (see the Appendix). However, acquisition of the desired signal is not prevented until J/S is greater than 20 dB. Thus, the smart jammer is no more effective in preventing acquisition than a CW jammer.

VI. CONCLUSIONS

In this paper we have described a four-phase spread-spectrum communication system with an adaptive antenna. Reference signal generation for the adaptive array and a signal acquisition procedure were described. The system was shown to provide protection against both conventional and smart jammers (in particular, repeat jammers) with rapid acquisition of the signal at the receiver.

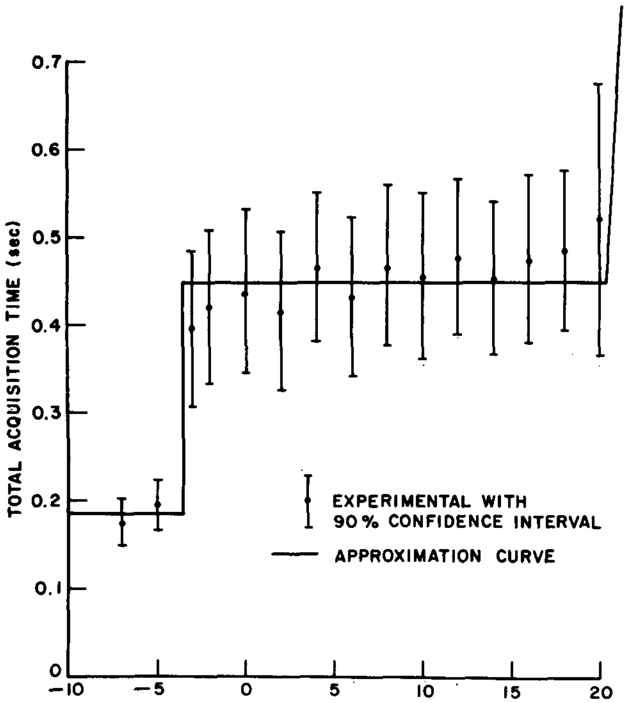

Fig. 11. Total acquisition time versus jammer to signal power ratio for repeat jammer with biphase remodulation.

APPENDIX
SUMMARY OF SOME THEORETICAL RESULTS FROM [8]

Average Long Code Acquisition Time

The average long code acquisition time T_{avg} can be determined theoretically if we make the following approximations for the acquisition process.

1) The long code can be differentially detected by itself (without the short code plus data).

2) The bit error probability for each code symbol is independent of other symbols.

3) The bit error probability is given by

$$P_E = \tfrac{1}{2} \exp\left[-E_\Delta/2N_0\right] \quad (\text{for } 0 \leqslant E_\Delta/N_0 \leqslant 4). \tag{A1}$$

These approximations are shown to be reasonably accurate in [8].

The long code acquisition scheme involves the loading of a shift register with the detected code symbols followed by the correlation of the output of the shift register with the received signal. With the approximations described previously, the probability of fully loading an n stage shift register with error-free code symbols is given by

$$P_n = (1 - P_E)^n \tag{A2}$$

where P_E is given in (A1). The trials of fully loading the shift register are independent Bernoulli trials. Thus, the number of trials required for an error-free loading (i.e., for acquisition) has a geometrical distribution. The probability of success on the Xth trial is then given by

$$P_r(x = X) = P_n(1 - P_n)^{X-1} \tag{A3}$$

and the average number of trials required is the reciprocal of P_n.

For each loading of the shift register, the output of the shift register is correlated with the received signal over a multiple M of the number of bits in the shift register n. The average long code acquisition time is, therefore, given by

$$T_{\text{avg}} = \frac{Mn\Delta}{(1 - P_E)^n}. \tag{A4}$$

For M equal to 20, as in Fig. 6, theoretical results [from (A4)] show about 1 dB less E_Δ/N_0 for the same T_{avg} as compared to computer simulation results.

Maximum Acquisition Time

For the short code acquisition the acquisition time has a uniform probability density with the maximum acquisition time equal to twice the average. However, for the long code, the acquisition time has a geometrical distribution as shown in (A3). Thus, the probability of more than X trials being required to achieve lockup can easily be shown to be given by [6]

$$P_r(x > X) = (1 - P_n)^X. \tag{A5}$$

Therefore, there is no maximum lockup time and a probability of acquisition P_{acq} within a specified number of trials must be considered. From (A5) the probability of acquisition in X trials is given by

$$P_{\text{acq}} = 1 - (1 - P_n)^X. \tag{A6}$$

Since P_n is, in general, small (for large P_n the long code acquisition time is negligible compared to the short code acquisition time), (A6) may be approximated by

$$P_{\text{acq}} \doteq 1 - e^{-XP_n} \tag{A7}$$

From the above equations we can determine the probability of long code acquisition in a given time (a multiple of the average acquisition time). For example, from (A7), there is a 99 percent probability of acquisition in 4.6 times the average long code acquisition time.

Acquisition Time for the Experimental System

For the experimental system, the maximum allowed acquisition time was chosen to be 0.55 s (see Table I) for a received E_Δ/N_0 equal to 0 dB. We arbitrarily allow 0.4 s for short code acquisition and 0.15 s for long code acquisition.

Thus, for a 99 percent probability of acquisition, the average long code acquisition time is given by [from (A7)]

$$T_{avg} = \frac{0.15}{4.6} \doteq 0.033 \text{ s.} \tag{A8}$$

The average short code acquisition time t_{avg} is half the maximum or 0.2 s. Thus, the total average acquisition time is given by

$$T_{tot} = T_{avg} + t_{avg} \doteq 0.23 \text{ s} \tag{A9}$$

as shown in Table I.

We can determine the average acquisition time for other received E_Δ/N_0 values from (A4). Thus, for the experimental system,

$$T_{tot} \doteq \frac{20 \times 34/(175.2 \times 10^3)}{(1 - \exp(-E_\Delta/(2N_0)))^{34}} + 0.2 \text{ (s).} \tag{A10}$$

Theoretical results [from (A10)] show about 1 dB greater E_Δ/N_0 for the same T_{avg} as compared to experimental results (Fig. 8; note that E_Δ/N_0 in (A10) is four times $E_\Delta/N_0|_{IN}$).

Maximum Jammer to Signal Power Ratio

As discussed in the text, the maximum jammer to signal power ratio for acquisition is given by the ratio of 0.2 times the code modulation rate to the slewing speed. Since the code at the receiver must slew past an entire code cycle in the maximum short code acquisition time t_{max} the slewing speed is simply the short code length N divided by t_{max}. Thus,

$$J/S|_{max} = \frac{0.2/\Delta}{N/t_{max}} = \frac{0.2 t_{max}}{N\Delta}. \tag{A11}$$

For the experimental system,

$$J/S|_{max} = \frac{0.2 \times 0.4}{255/(175.2 \times 10^3)} \tag{A12}$$

$$\doteq 55 \text{ (17 dB).} \tag{A13}$$

The weight response speed with the weakest desired signal can be somewhat less than the sweep speed, although the probability of not acquiring the short code in the maximum time P_{miss} is increased. In the experimental system, the response speed for the weakest signal was about one-half the sweep speed. In this case P_{miss} is still very small and $J/S|_{max}$ is increased to 20 dB (as shown in Figs. 9 and 10). Note that $J/S|_{max}$ is increased further with higher code rates, longer acquisition times, and shorter length short codes.

Acquisition Time with Smart Jamming (Experimental System)

With a smart jammer present, the receiver will first acquire either the smart jammer's signal or the desired signal. If the jammer's signal is acquired first, 0.55 s will elapse before the receiver nulls the jammer and searches for the desired signal. The receiver then takes an average of about 0.2 s to acquire the desired signal. If the desired signal is acquired first, the average acquisition time is also about 0.2 s. Thus, with a smart jammer present, the average total acquisition time is given by

$$T_{tot} \doteq \tfrac{1}{2}(0.55 + 0.2) + \tfrac{1}{2}(0.2) = 0.475 \text{ s} \tag{A14}$$

as shown in Fig. 11.

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