Chaotic Pulse Position Modulation: A Robust Method of Communicating with Chaos

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***Abstract*—In this letter we investigate a communication strategy for digital ultra-wide bandwidth impulse radio, where the separation between the adjacent pulses is chaotic arising from a dynamical system with irregular behavior. A pulse position method is used to modulate binary information onto the carrier. The receiver is synchronized to the chaotic pulse train, thus providing the time reference for information extraction. We characterize the performance of this scheme in terms of error probability versus E_b/N_0 by numerically simulating its operation in the presence of noise and filtering.**

***Index Terms*—Chaos, impulse radio, spread spectrum.**

IN RECENT years, a personal wireless communication device has found enormous commercial and military applications. The desirable attributes of such a device share all of the desired features of a conventional communication system, such as meeting requirements on data transmission rate, BER, bandwidth, complexity, and cost. However, due to its portable operation in hostile environments (e.g., multipath propagation; interferences from other such devices), additional desirable features of such a device may include secure communication, low probability of intercept, spread spectrum/wide-band spectrum utilization with low spectral density feature resulting in no licensing operation, and an overall efficient battery powered system. We propose a novel chaotic pulse position modulation method applied to the ultra-wide-band based impulse communication system (UWB-ICS) that possesses many of these desired attributes. Some basic features and advantages of an UWB-ICS as compared to a conventional spread spectrum (SS) system have been reported [1]. Furthermore, since the final high power amplifier (HPA) of a conventional SS system needs to operate in a quite linear region, the overall DC-RF efficiency of such a device is low (10%–20%). However, since the HPA associated with an UWB-ICS can operate more in the nonlinear region, the overall DC–RF efficiency of such a device can be much higher (60%–80%). This efficiency factor can play a significant role on the practicality of a UWB-ICS, and motivates our effort in enhancing its operation using special properties of chaotic signals.

Since chaotic signals are generated by deterministic dynamical systems, two coupled chaotic systems can be synchronized to produce identical chaotic oscillations. This provides the key to the recovery of information that is modulated onto a chaotic carrier [2]. A number of chaos-based communication schemes have been suggested [3], but many of these systems are very sensitive to distortions, filtering, and noise. Chaos-based communication systems and ICS appear to form excellent partners, with each contributing important features. A chaotic system, as a part of an ICS, can improve the communication privacy since chaotic sequences, unlike pseudorandom sequences can be made completely nonperiodic. Without a matched chaotic receiver extracting the information from a mixture of information and chaotic signals can be an uneasy task. A chaos-based ICS may have a lower probability of intercept compared to a conventional ICS using periodic sequences. The negative effects of filtering and channel distortions, which typically severely impair the ability of chaotic systems to synchronize are substantially reduced by using impulse signals. In our proposed system, each pulse has identical shape but the time delay between them varies chaotically. Since the information about the state of the chaotic system is contained *entirely* in the timing between pulses, channel distortions that affect the pulse shape will not significantly influence the ability of the chaotic pulse generators to synchronize. Finally, chaotic impulse signals are easier to multiplex than continuous chaotic signals [4].

The particular chaotic encoding method that we propose—Chaotic Pulse Position Modulation (CPPM)— is related to the dynamical feedback modulation method [5]. The communication scheme is built around a chaotic pulse regenerator (CPRG) as shown in Fig. 1. When a CPRG has a pulse train with interpulse intervals T_i as its input, for the nth incoming pulse in this train it produces at its output a new pulse after a delay time ΔT_n. The delay time depends on the interpulse intervals of k previous input pulses: $\Delta T_n = F(T_n, \cdots, T_{n-(k-2)})$. $F(\bullet)$ is such that when the CPRG output is applied directly to its input, forming a feedback loop, the system generates a pulse train with chaotic interpulse intervals. In the simple case when $k = 2$ and $F(\bullet)$ is a function of only one argument, the operation of CPRG is illustrated in Fig. 1. The linearly increasing signal generator is reset to zero by the input pulse. The value of the signal right before the reset instance is applied to the input of the nonlinear transformer, whose output is

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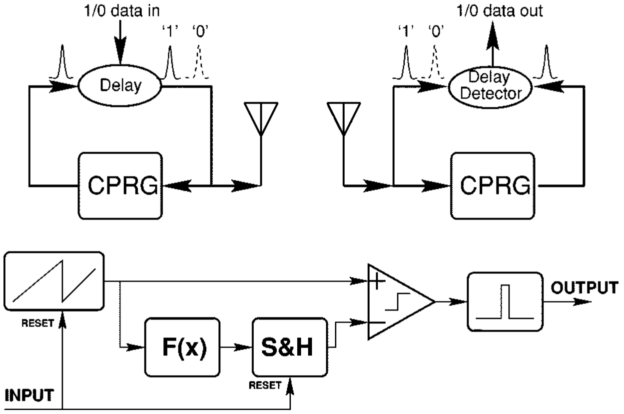

Fig. 1. Illustration of the basics of CPPM schemes and CPRG operation.

stored in the sample-and-hold circuit. When the output of the linearly increasing signal generator reaches the value stored in the sample-and-hold circuit, a pulse is produced at the output of the CPRG. With a proper choice of $F(\bullet)$ the system will spontaneously generate chaotic pulse trains, when the CPRG output is applied to its input. An example of such chaotic system can be found in [4].

In our scheme the binary information is applied to the pulse train at the output of the CPRG by adding a block in the feedback loop that leaves the signal unchanged, if "0" is being transmitted, or delays the pulse by a fixed time if "1" is being transmitted. This modulated pulse sequence is the transmitted signal. If an unauthorized receiver has no information on the spacing between the pulses leaving the CPRG, it cannot determine whether a particular received pulse was delayed, and thus whether "0" or "1" was transmitted. At the receiver side, the signal is applied to the input of an identical CPRG, so the outputs from the CPRG's in the transmitter and the receiver are identical. Thus the signal at the output of the receiver CPRG is identical to the signal in the *channel*, except some pulses in the transmitted signal are delayed by the information modulation. By evaluating the relative pulse timings in the received signal and in the signal at the output of the CPRG, the receiver can recover the digital message. When the CPRG's are not matched with sufficient precision, a large decoding error results. Thus the parameters of the CPRG's act like a privacy key.

When synchronized, the receiver "knows" the time interval or a window where it can expect a pulse corresponding to "1" or "0." This allows the input to be blocked at all times except when a pulse is expected. The time intervals when the input to a particular receiver is blocked can be utilized by other users. To decode a bit of information we must determine whether a pulse from the transmitter falls into the window corresponding to "0" or that corresponding to "1," which can be done by integrating the input signal within the windows around the expected locations of pulses corresponding to "0" and to "1." Under the ideal condition of perfect time and polarity synchronizations, P_E performance of the CPPM system (denoted by the "Ideal PPM" curve) is known to be 3 dB worse than the BPSK system [6] as shown in Fig. 2. This performance is achieved with the window size equal to the pulse duration. In the case of imperfect synchronization the window cannot be so narrow, and with the larger window size and the same detection method we shall have an additional performance loss equal to $10 \log T/\tau$ dB where T is the window size and τ is the pulse duration. The ideal noncoherent binary FSK system performance is also shown in Fig. 2 for comparison.

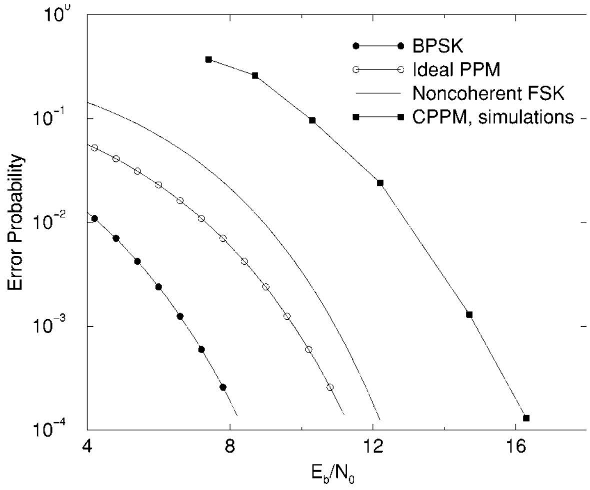

Fig. 2. Error probabilities of ideal BPSK, PPM, and noncoherent FSK systems compared to the simulated proposed CPPM systems.

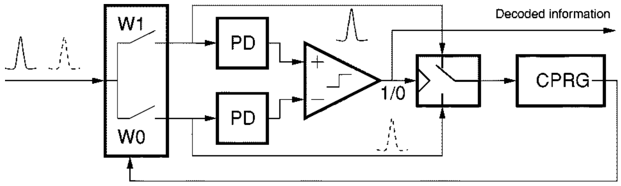

Fig. 3. Diagram of the receiver.

We evaluated the performance of CPPM by numerically simulating its real-time implementation. The transmitter generates the pulse train with separation between the pulses proportional to x_n. The sequence x_n is generated by the modulated tent map, $x_{n+1} = \alpha|0.5 - |0.5 - x_n|| + s_n$ with $\alpha = 1.3$, where s_n is the binary information signal.

The proposed CPPM receiver block diagram is shown in Fig. 3.[1] Based on the state of the synchronized CPRG, the input is blocked at all times except the time windows around the expected locations of the pulses corresponding to "1" and "0." The signals within these windows are applied to two peak detectors (PD). Based on which window contained the peak of the maximum height, we decide whether "1" or "0" was transmitted and the signal within the corresponding time window is passed to the receiver CPRG. Details concerning the real-time implementation of this scheme will be described elsewhere.

The channel and transmitter and receiver operations are modeled by adding WGN to the output of the transmitter and then LP-filtering the signal with a FIR filter. We measure SNR and find E_b/N_0 using the following formula [7]: $E_b/N_0 = S/N(W/R)$, where S/N is the SNR, W is the channel bandwidth and R is the bit rate.

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[1] We have considered a few receiver designs. The design presented here contains an extra feedback loop, which improves the performance.

In our simulations we used the following parameters: the pulse duration was 100 ps, the modulation amplitude, 400 ps, and the window size ∼400 ps. The filter cut-off was at 5 GHz. The threshold was set at half the pulse peak voltage. The average bit rate was ∼0.5 Gb/s with the average inter-pulse distance ∼2 ns. The distance between the pulses would vary by as much as 50% from the average.

The performance curve corresponding to these parameters is shown in Fig. 2. One can see that CPPM performs in simulations 5 dB worse than the ideal PPM system. This is primarily due to the fact that it is difficult to maintain perfect synchronization for chaotic systems. In particular, to use convolution detection, the synchronization error should be less than the pulse duration. We found that with the synchronization errors that we typically encountered in our system, decoding based on peak detectors performs better.

Although the CPPM performance is not as good as that of noncoherent FSK and BPSK, the power efficiency of HPA's used in impulse transmission makes this system competitive and places it well within the range that is acceptable in practical applications. At the expense of the performance loss, CPPM improves communication privacy, spectral characteristics and detection resistance compared to conventional impulse communications. From the electronics design point of view, incorporating these features using chaos does not lead to a significant increase in design complexity or power consumption. As a number of improvements to CPPM are currently being studied, to the best of our knowledge, CPPM already performs extremely well, compared to other chaos-based communication systems. This makes CPPM a prime candidate for the development of practical chaos-based covert spread spectrum systems.

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