Application of Convolutional Error Correcting Codes in Ultrawideband M-ary PPM Signaling

Amir R. Forouzan and Mohammad Abtahi

***Abstract*—The interference issues related to ultrawideband (UWB) radio pose tight restrictions on the maximum data rate of UWB radio telecommunication systems. A possible solution is to reduce the required signal to interference ratio (SIR) that gives satisfactory performance to the UWB system. In this letter, we propose coded M-ary UWB radio communication systems. Two classes of convolutional codes, namely, low-rate superorthogonal codes and high-rate punctured codes are considered for this purpose. Simulation results on the bit error rate of the proposed system indicates that the system is capable to work in lower SIR's and therefore supports higher data transmission rates in a real interference environment compared to the previously proposed UWB communication systems.**

***Index Terms*—High-rate punctured codes, low-rate superorthogonal codes, M-ary pulse position modulation (PPM), ultrawideband (UWB) radio, Viterbi decoding.**

I. Introduction

ULTRAWIDEBAND (UWB) radio (or impulse radio) has attracted much interest for indoor high rate communications in recent years. In this system data is transmitted using sub-nanosecond baseband pulses, and the occupied frequency band is from near DC to several gigahertzes. Because of this extremely large bandwidth the system presents a considerably high capacity and robustness to multipath fading. However when the mutual interference of the system with conventional systems being taken into account the maximum data rate of the system is constrained by a number much smaller than the numbers obtained without considering it [1]. A possible solution is to use modulation schemes and/or receiver structures that are capable to work in lower signal to noise ratios (SNR) at the same data transmission rate and probability of bit error.

In [2] the use of M-ary Pulse Position Modulated (PPM) UWB communication systems is proposed and it is shown that this method reduces the required SNR to achieve a desired performance. In [3] a coding scheme on binary PPM (BPPM) UWB systems is proposed that outperforms the uncoded scheme without any increase in the required bandwidth. In this article, however, we consider coded M-ary PPM UWB systems. These systems can be considered as the combination of M-ary PPM modulation [2] and coded BPPM UWB systems [3]. The bit error rate (BER) of the proposed scheme is presented vs. SNR and the results are compared with the BER of the previously proposed schemes. The results show that despite the relatively low complexity of the proposed scheme the system is capable to work in lower SNR's at the same BER thus supporting higher data transmission rates in a real interference environment.

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II. System Description

The transmitted signal of a coded M-ary PPM UWB system can be written as follows;

$$s_{tr}(t) = \sum_{j=-\infty}^{+\infty} w_{tr}(t - jT_f - m_j T_c), \qquad (1)$$

where j indicates the frame number, $w_{tr}(\cdot)$ is the transmitted pulse, T_f is the frame duration, T_c is the chip duration and m_j is the data symbol that conveys the transmitted information in some form. Usually, frame duration, T_f is in the order of one hundred nanoseconds, and chip duration, T_c, is in the order of one nanosecond or less. T_c is considered to be greater than the received pulse duration at the output of the receiver's antenna.

The transmitted symbol m_j is an integer number in the interval [0, M), where $M = 2^L$ is the number of possible PPM symbols. m_j is computed from the transmitted binary sequence, $\{d_j\}$, as follows;

$$m_j = \sum_{\ell=0}^{L-1} 2^\ell d_{jL+\ell} = (\overline{d_{jL+L-1} \cdots d_{jL+1} d_{jL}})_2, \qquad (2)$$

where $L = \log_2 M$. To guaranty the transmission of exactly one pulse in each frame we have $MT_c \le T_f$ or $M \le T_f/T_c$. In an uncoded M-ary PPM UWB system the data symbol m_j is considered constant during N_s frames, and the transmitted binary sequence is N_s repetitions of the binary data sequence $\{D_i\}$ (see [2] and [4] for some other possible M-ary modulation schemes). In this case the transmission rate R_s will be $R_s = L/(N_s T_f)$. In a coded M-ary system, the transmitted binary sequence, $\{d_j\}$, is the output of a convolutional encoder. The input to the convolutional encoder is the binary data sequence, $\{D_i\}$. In this article we consider low-rate and high-rate convolutional codes.

As a low-rate convolutional encoder, we consider a low-rate superorthogonal convolutional encoder that can be implemented with a low complexity [5]. The rate of a superorthogonal code with constraint length K is $r = 1/2^{K-2}$. For each incoming bit to the convolutional encoder $N_s = 2^{K-2}/L$ M-ary symbols are generated and transmitted in N_s successive frame times. As a high-rate convolutional encoder, we consider high-rate punctured convolutional codes with short constraint lengths proposed in [6]. The rate of these codes is $r = (n-1)/n$, where $n = L$ is the number of output bits, and $n-1$ is the number of input bits (D_i) to the encoder in each frame. In this case, N_s is considered to be one (See [6]).

We assume an Additive White Gaussian Noise (AWGN) channel. In this case the received signal can be written as

$$r(t) = A \sum_j w_{rec}(t - jT_f - m_j T_c - \tau) + n(t), \quad (3)$$

where A and τ are the attenuation factor and delay of the received signal, respectively, and $n(t)$ is the total noise and interference from any existent interference source including other UWB radiators, conventional transmitters and receiver noise. $w_{rec}(\cdot)$ is the received pulse with duration T_w. To ensure orthogonal signalling, we assume $T_w < T_c$, and for the purpose of performance analysis, we assume that $n(t)$ is white and Gaussian.

III. Receiver Structure

The receiver employs Viterbi algorithm to decode the transmitted data sequence. Since Viterbi algorithm is a well-known algorithm, in the following we only describe the procedure of computing branch metrics, which is somewhat special to our proposed system.

Primarily, a branch metric is defined as the power of noise assuming that the transmitted bit stream is the output bit stream associated to this branch. The output bit stream associated to a branch can be evaluated easily using the origin and destination states of the branch.

Assume that the associated bit stream to branch number i in the time interval $[0, T_b)$ is $S_B^{(i)} = (b_0^{(i)}, b_1^{(i)}, \ldots, b_{N_s'-1}^{(i)})$, where $N_s' = LN_s$ (For the considered high rate codes we have $N_s = 1$). The associated M-ary symbol stream to this branch is $S_M^{(i)} = (m_0^{(i)}, m_1^{(i)}, \ldots, m_{N_s-1}^{(i)})$, where $m_j^{(i)} = \sum_{\ell=0}^{L-1} 2^\ell b_{jL+\ell}^{(i)}$. Then the power of noise conditioned on the transmitted symbol stream being the associated symbol stream to branch i can be computed as:

$$d_{(i)} = \int_\tau^{\tau+T_b} (r(t) - u_{(i)}(t))^2 dt, \quad (4)$$

where $T_b = N_s T_f$ and

$$u_{(i)}(t) = A \sum_{j=0}^{N_s-1} w_{rec}(t - jT_f - m_j^{(i)} T_c - \tau) \quad (5)$$

is the desired received signal assuming the branch i bit stream. Assuming the metric defined in (4) the survivor path in each state is the path with the minimum metric. As it can be seen in (5) the receiver should know the attenuation factor A to evaluate the branch metric. However, the above metric can be simplified to the following metric, which does not depend on the attenuation factor A (see [5]):

$$d'_{(i)} = \int_\tau^{\tau+T_b} r(t) \sum_{j=0}^{N_s-1} w_{rec}(t - jT_f - m_j^{(i)} T_c - \tau) dt. \quad (6)$$

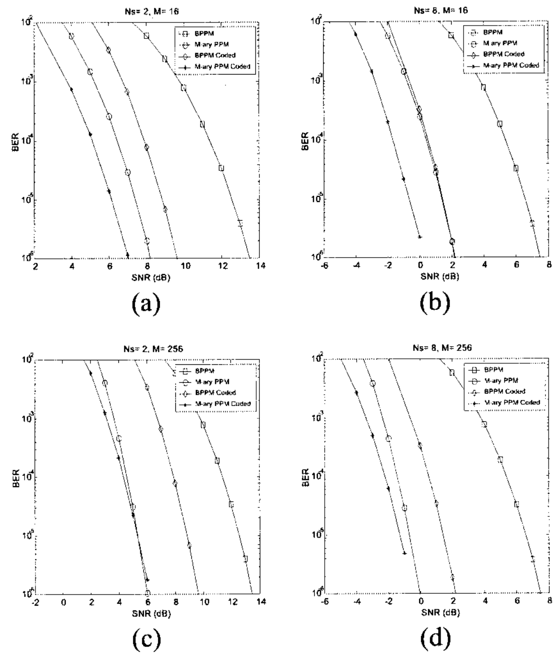

Fig. 1. BER vs. the required SNR for BPPM, M-ary PPM, coded BPPM, and low-rate coded M-ary systems at several system parameters (a) $M = 16; R_s = 5$ Mbps (b) $M = 16; R_s = 1.25$ Mbps (c) $M = 256; R_s = 5$ Mbps (d) $M = 256; R_s = 1.25$ Mbps.

In this case the survivor path in each state is the path with the *maximum* metric.

For the considered high-rate convolutional codes where $N_s = 1$, (6) reduces to,

$$d'_{(i)} = \int_\tau^{\tau+T_b} r(t) w_{rec}(t - m_j^{(i)} T_c - \tau) dt. \quad (7)$$

where $T_b = T_f$.

IV. Simulation Results

In this section we present the results of simulations on the Bit Error Rate (BER) of the proposed coded systems and we compare the results with the BER of the three previously proposed systems. These systems are Uncoded BPPM-TH-UWB system [7], Coded BPPM-TH-UWB system [3], and Uncoded M-ary-TH-UWB system [2]. We employ the results in [7], [3], and [2] to obtain the BER of the above systems, respectively. In the following; we consider the entire ultrawideband related parameters equal for the systems under consideration. For example the received pulse signal shape $w_{rec}(t)$ and pulse repetition rate $(1/T_f)$ are the same in the following figures. In the following figures, we assume $T_f = 100$ ns and $T_c = 0.39$ ns.

Fig. 1 shows the minimum required Signal to Interference Ratio (SIR) to achieve a desired limit of performance (BER) for the M-ary low-rate convolutionally encoded system and other currently proposed systems in several conditions. In addition to ultrawideband related parameters, in each subplot system parameters for each scheme are set for the same data transmission rate in order to have a fair comparison among the schemes. As it can be seen, the low-rate convolutionally encoded M-ary system achieves the same BER as other previously proposed systems in about 2 dB lower SIR's for number of symbols M less than or

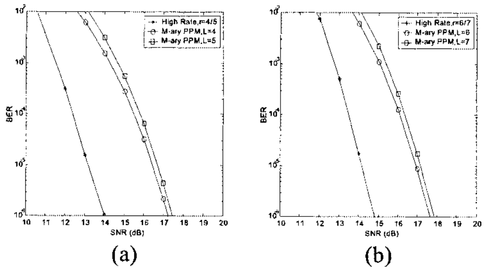

Fig. 2. BER vs. SNR of a high-rate convolutionally encoded M-ary UWB system and two uncoded M-ary UWB systems with the same I) date rate (circle) and II) complexity (square) (a) $M = 32$; $R_s = 40$ Mbps (b) $M = 128$; $R_s = 60$ Mbps.

equal to 16. However when the number of symbols M is high ($M = 256$), the system performance is approximately the same as for the uncoded M-ary systems. This is because the low-rate superorthogonal encoder is designed for binary signaling and moving from binary signaling toward M-ary orthogonal signaling decreases the effective free distance of the code.

Fig. 2 illustrates the performance of M-ary coded system using high-rate convolutional codes, and compares it with the performance of two uncoded M-ary systems. As it can be seen the proposed high-rate encoded system outperforms the uncoded systems by 3 dB in the required SIR in the same probability of bit error and data transmission rate using encoders with low excess complexity, even when the number of symbols M gets large.

V. Conclusion

In this letter, we considered the application of convolutional codes on M-ary ultrawideband TH systems. Two classes of convolutional codes, namely, low-rate superorthogonal codes and high-rate punctured codes were considered and the probability of bit error for the systems vs. SIR was obtained by simulation considering an AWGN channel. The results show that the proposed systems are capable to work in lower SIR's compared to previously proposed systems including the uncoded M-ary system, coded binary system and uncoded binary system. Since one of the most challenging problem in the development of ultrawideband radio communication systems is their mutual interference with conventional systems, the result is important in the sense that it allows the system to work with higher data transmission rates at the same BER and interference on conventional communication systems with a little increase in implementation complexity.

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