Design and Simulation of Bit-interleaved SCCPM with Physical-layer Network Coding

Nan Sha, Yuanyuan Gao, Mingxi Guo* and Shijie Wang

Army Engineering University of PLA, Nanjing 210007, China
Email: njshanan@163.com; njyygao@sina.com; gogomx@sina.com; world900214@gmail.com

Abstract. Serially concatenated continuous phase modulation (SCCPM) is bandwidth and power efficient in point-to-point communication systems. The physical-layer network coding (PNC) protocol proposed in 2006 can boost the throughput of a two-way relay channel (TWRC). In this paper, we integrate SCCPM with bit interleavers into PNC, i.e., SCCPM-PNC, which inherits the advantages of the both, in wireless TWRC. The decoding structure of the relay for the superimposed SCCPM signals is designed. Furthermore, the influences of various parameters such as the constraint length of convolutional code (CC), the interleaver size and the number of iterations, on the performance of SCCPM-PNC are simulated and discussed.

1. Introduction

Continuous phase modulation (CPM) is a power and bandwidth efficient modulation scheme which has constant envelope. Because of the continuous and smooth nature of the phase modulation, CPM has attractive spectral efficiency which depends on a number of parameters including the modulation index $h$, the pulse shape $g(t)$, the cardinality $M$, and the memory length $L$. Due to its constant envelope, it enables the transmission with energy efficient and inexpensive nonlinear power amplifiers. These characteristics make it widely used in various systems including deep-space communications, satellite communications, telemetry, DVB and fiber-optical communications [1].

For wireless communications, channel coding is an effective method to further improve the error performance of the system. Compared with turbo codes, serially concatenated codes (SCCs) are suitable for iterative decoding and might gain even better performance. When SCCs are combined with CPM, the spectrum efficiency can be more improved than that of SCC with PSK. On the other hand, Rimoldi showed that a CPM scheme can be seen as a continuous phase encoder which can be taken as a convolutional code (CC), and a memoryless modulator [2]. Thus, CPM can be combined with an external CC to obtain further improvement in power efficiency. Taking advantage of the inherent coding property in CPM, serially concatenated CPM (SCCPM) which inherits the technical advantage of CPM and SCCs was proposed [3]. A conventional SCCPM scheme consists of an outer code (binary CC), a bit-wise interleaver and an inner code (CPM). When $M > 2$, a symbol mapper is adopted between the bit-wise interleaver and the $M$-ary CPM ($M$-CPM). Soft input soft output (SISO) iterative methods are used for decoding.

Suppose two users out of radio range exchange information through a relay in range of both users which is a typical two-way relay channel (TWRC). With the conventional relay strategy, four time
slots are needed: two time slots for transmission to the relay and two more for the relay to transmit to each user. Physical-layer network coding (PNC) protocol proposed in [4] reduces the requirement to two time slots by allowing the users to transmit to the relay simultaneously. In the first time slot, i.e., the multiple access (MA) stage, two users transmit their messages to the relay at the same time, and the relay decodes a network-coded message (the bit-wise XOR of the two messages) based on the superimposed signals received from the two users. In the second time slot, i.e., the broadcast (BC) stage, the relay broadcasts the network-coded message to both users, and then each user obtains the other’s message from the received network-coded information and its previously transmitted information by using XOR operation. Obviously, PNC can boost the throughput of TWRC significantly. In order to improve the spectrum efficiency in TWRC, the application of High-order modulation and CPM for PNC were discussed in [5-8]. Meanwhile, channel-coded PNC systems were proposed to guarantee communication reliability [9-11].

In this work, we integrate the point-to-point SCCPM scheme into PNC, i.e., SCCPM-PNC, which is considered as an attractive solution to obtain high bandwidth efficiency, power efficiency and throughput in TWRC. As the links in the BC stage are typical point-to-point links, we focus on the MAC stage issues. The system model of SCCPM-PNC with bit interleavers for the MAC stage is designed and the corresponding bit error rate (BER) performance is discussed.

2. **System Model**

Consider a TWRC where two users exchange their own messages through a relay using the PNC protocol. All nodes employ the same SCCPM scheme which includes a binary CC, a bit interleaver, an $M$-ary symbol mapper, and an $M$-CPM modulator. The users transmit to the relay simultaneously during the MAC phase, and the relay then broadcasts to the users during the BC phase. We assume the symbol-level synchronization at the relay and the average powers of all nodes are equal. Since the links in the BC phase are point-to-point SCCPM issues and correlative researches about the detection at the user can be found in [3], we mainly focus on the MAC phase issues. The system model of SCCPM-PNC with bit interleavers for the MAC phase is shown in Fig. 1.

![System model for the MAC phase.](image)

2.1 **Transmission by users**
The user $S_i, i \in \{1,2\}$, generates binary information sequence $b_i = \{b_{i,0}, b_{i,1}, ..., b_{i,L}\}$ where $b_{i,n} \in \{0,1\}$ with equal probability. Each $b_i$ is encoded by the binary CC which generates an output codeword sequence $c_i$. The binary sequence $c_i$ is passed through the bit interleaver and then sent to the $M$-ary symbol mapper, yielding a symbol sequence $u_i = \{u_{i,0}, u_{i,1}, ..., u_{i,L}\}$, $u_{i,n} \in \{0,1,2, ..., M-1\}$. After $M$-CPM-modulation, the signal transmitted by user $S_i$ during the interval $nT \leq t \leq (n+1)T$ can be expressed by

$$s_i(t,u_i) = \sqrt{E/T} \exp\{j\psi_i(t,u_i)\}$$

where $E = E_b \log_2 M$ is the symbol energy and $E_b$ is the bit energy, $T$ is the symbol interval duration, and $\psi_i(t,u_i)$ is the titled-phase which can be expressed by

$$\psi_i(t,u_i) = \left[2\pi h v_{\pi} + 4\pi h \sum_{k} u_{i,k}q(t+kT)+W_i(t)\right] \mod 2\pi$$

where $0 \leq t < T$, $q(t)$ is the integral of pulse shape $g(t)$, $h = K/P$, $v_{\pi} = \left(\sum_{k} u_{i,k}\right) \mod P$ is the phase state, and $W_i(t)$ is a data independent term [2]. Hence, the titled-phase state at time $t = nT$ of the CPM signal $s_i(t,u_i)$ can be expressed by $v_{i,n} = [u_{i,n-1,L}, u_{i,n-L+1}, v_{i,n}]$.

2.2 Relay Reception

Suppose that the transmissions are performed over additive white Gaussian noise (AWGN) channels, the received signal $r(t)$ at relay $R$ can be expressed by

$$r(t) = s_1(t,u_1) + s_2(t,u_2) + n(t)$$

where $n(t)$ is the AWGN term with one-sided power spectral density $N_0$. By employing PNC protocol, $R$ decodes the XORed codeword sequence of the two users, i.e., $b_1 \oplus b_2 = \{b_{1,0} \oplus b_{2,0}, b_{1,1} \oplus b_{2,1}, ..., b_{1,L} \oplus b_{2,L}\}$. The detection version of $b_1 \oplus b_2$ is denoted by $b_1 \oplus b_2$. 


Figure 2: A superimposed signal path through the combined titled-phase state trellis.

In order to decoding $b_i \oplus b_i$ from the superimposed signal, an SISO iterative decoding scheme at the relay is adopted as shown in the lower part of Fig. 1 which includes two a posteriori probability decoders, inner decoder (“SISO for CPM+PNC”) and outer decoder (“SISO for CC”), and $\Lambda(g; g)$ denotes the log likelihood ratio (LLR) function in which “T” or “O” denotes the input or output of the block.

Iterations are performed on extrinsic LLR between the inner decoder and the outer decoder. Based on the combined titled-phase state trellis of the two CPM signals $s_i(t, u_i)$ and $s_j(t, u_j)$, the maximum a posteriori probability (MAP) decoding can be applied for the inner decoder. A path through the combined titled-phase state trellis of $s_i(t, u_i)$ and $s_j(t, u_j)$ corresponding to the combined input sequence $(u_i, u_j) = \{(1,0), (1,1), (1,2), (1,3), (2,0), (2,1), (2,2), (2,3)\}$ is illustrated in Fig. 2 where the parameters of CPM are $M = 4$, $h = 1/4$ and $L = 1$. For the outer decoder, the same is true. Both are based on the BCJR algorithm. The “bit-to-symbol” and “symbol-to-bit” blocks refer to the transformation from bit-wise LLR to symbol-wise LLR and from symbol-wise LLR to bit-wise LLR, respectively. Note that, the symbol priori information $\Lambda(u_i \oplus u_j; i)$ which is sent to the inner decoder is set to be zero during the first iteration and the input $\Lambda(b_i \oplus b_j; i)$ of the outer decoder is always set to be zero. After the final iteration, $\Lambda(b_i \oplus b_j; O)$ is passed through a “hard decision” block to obtain $b_i \oplus b_j$.

3. Simulation Results And Discussion

In this section, the detection performance of the proposed SCCPM-PNC with bit interleavers is evaluated by Monte Carlo simulations. In the following simulations, we assume the transmissions are performed over AWGN channels. Pseudo random interleavers and 4-CPM with $h = 1/4$, $L = 1$ and raised cosine (RC) pulse shapes are employed.
Simulation 1: In order to assess the BER performance of SCCPM-PNC, a comparison of BER is made between SCCPM-PNC and convolutional coded CPM-PNC (CC-CPM-PNC). In CC-CPM-PNC, there are no interleavers and iterative decoding, the relay only needs to detect the XORed symbol sequence $u \oplus u_1$, which is then passed through the “symbol-to-bit” block and sent to the CC decoder to obtain $b \oplus b_1$. (5,7) CC is adopted for both SCCPM-PNC and CC-CPM-PNC, and the interleaver size $N = 2048$ and the number of iterations $V = 5$ are set for SCCPM-PNC. The BER performance of the two schemes is shown in Fig. 3. It can be seen that SCCPM-PNC outperforms CC-CPM-PNC and the BER of SCCPM-PNC decreases quickly as $E_b/N_0$ increases when $E_b/N_0 > 1dB$.

Simulation 2: In order to assess the influence of CC on the BER performance of SCCPM-PNC, we investigate three rate-1/2 CCs with different constraint length which are (5,7), (13,17), (20,35) with constraint length 3, 4, 5, respectively. We also set the interleaver size $N = 2048$ and the number of iterations $V = 5$. The corresponding BER curves are shown in Fig. 4. We observe that the performance of small constraint length is better than that of large constraint length. The reason is that in the low $E_b/N_0$ region, outer codes with more states suffer from the convergence problem [3].

Simulation 3: In order to assess the influence of interleaver size on the BER performance of SCCPM-PNC, Fig. 5 illustrates BER curves for $N = 512$, $N = 1024$ and $N = 2048$ where (5,7) CC is used and the number of iterations is set to be 5 for each case. It can be seen that considerable improvements can be achieved by increasing the interleaver size especially in the mid-to-high $E_b/N_0$ region. It proves that the interleaver gain is proportional to the interleaver size, and this phenomenon is same as that of point-to-point SCCPM.

![Figure 3: BER performance comparison of SCCPM-PNC and CC-CPM-PNC.](image1)

![Figure 4: Simulation results for three different CCs (N = 2048, V = 5).](image2)

![Figure 5: Simulation results for different interleaver sizes ((5,7) CC, V = 5).](image3)
Simulation 4: For the purpose of studying how number of iterations affects the performance of SCCPM-PNC, the BER performance with different numbers of iterations are shown in Fig. 6 in which (5,7) CC is used and the interleaver size is set to be 2048 for each case. Obviously, the BER performance improves by increasing the number of iterations, and this phenomenon is same as that of point-to-point SCCPM.

4. Conclusions
This paper presents our study on bit-interleaved SCCPM with PNC in TWRC. The system model of SCCPM-PNC is designed and the corresponding signal processing procedure is discussed. Moreover, the influences of various parameters on the performance of SCCPM-PNC are simulated and discussed. It is shown that the proposed scheme exhibits superior performance and considerable improvements can be achieved by increasing the interleaver size or number of iterations.

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6. References
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