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Redundant residue number system based space-time block codes

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ABSTRACT

In this paper, we propose a novel application of Redundant Residue Number System (RRNS) codes to Space-Time Block Codes (STBCs) design. Based on the so-called "Direct Mapping" and "Indirect Mapping" schemes, the link between residues and complex signal constellations is optimized. We derive upper bounds on the codeword error probability of RRNS–STBC and characterize its achievable diversity gain assuming maximum likelihood decoding (MLD). The knowledge of apriori probabilities of residues is utilized to implement a probability based Distance-Aware Direct Mapping scheme. Using simulation results, we demonstrate that the Distance-Aware Direct Mapping scheme provides performance gain, relative to a traditional direct mapping scheme, that increases with decreasing code rate.

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1. Introduction

Residue number system (RNS) is a non-weighted, carry-free number system which represents any given integer as a tuple of residues [1] obtained the modulo dividing the given integer by a set of relatively prime integers called moduli. The representation of the integer in the residue field defines an RNS encoding. RNS finds applications in high-speed parallel signal processing and digital hardware implementations [1–6]. The carry-free property of RNS ensures that operations related to the different residue digits are independent. The errors during multiplication, addition and subtraction operations, or due to transmission or processing noise do not propagate and remain confined to their original residue digits. Other residue digits are not contaminated as carry-forward is absent [5–9]. Thus RNS arithmetic simplifies computations by decomposing a problem into a set of parallel residue computations.

These desirable properties of RNS motivate the use of redundant residue number system (RRNS) for robust self-checking, error detection and error correction. The lack of ordered significance among the residues implies that some redundant residue digits can be discarded without affecting the result, as long as a sufficiently high dynamic range is maintained by the retained residues of the reduced RNS so that the information symbols can be unambiguously described. The use of RRNS as an error correcting code was initially proposed by [3,4,7]. But prior efforts in application of RRNS as a channel coding scheme have been limited due to the complexity of decoding. But with recent advances in computing, RRNS has been used as a channel code to improve error detection and correction [1,5,8–16]. The theoretic framework of RRNS as a channel coding scheme and its error detection and correction capabilities has been investigated in detail by [5,8–10]. The application of RRNS based codes in OFDM based communication systems has been discussed in [11,16], while its application and performance in DS-CDMA systems have been studied

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in [12]. An adaptive RRNS based multi-carrier modulation scheme for combating effects of frequency selective fading channels has been discussed in [13]. The performance of systematic and non-systematic RRNS codes and near-optimal decoding algorithms for soft decision decoding has been proposed in [15]. The similarities and advantages of RRNS over other non-binary codes like Reed–Solomon (RS) codes have been discussed in detail in [1,3–5,8–16]. In spite of a wealth of prior research, strategies to incorporate RRNS techniques in MIMO (multiple-input multiple-output) have not received any consideration. In our prior work [17], we presented a preliminary model of an RRNS–STBC System. Understanding and quantifying the role of RRNS in MIMO systems in much greater detail, as compared to [17], is the objective of this effort.

In this paper, non-systematic RRNS codes [5,15] along with "direct mapping" and "indirect mapping" schemes are formulated as space-time block codes (STBCs) to support high performance, high-rate transmission. In contrast to orthogonal space-time block codes (OSTBCs) [18,19], RRNS–STBC does not require the channel to remain constant during its coding/decoding period. In the proposed transmission scheme, information bits are first mapped to integers and based upon a predetermined moduli set, the corresponding residues are calculated. Then, the obtained residues are mapped to complex constellation symbols using the "direct mapping" (DM) scheme which is similar to the one discussed in [20]. While mapping bits to residues, not all residues occur with equal probability. Since the direct mapping scheme maps residues directly to constellation points, the unequal apriori probabilities of residues can be effectively exploited. We propose a unique prior probability based distance-aware direct mapping (DA) scheme. In this scheme residues are mapped to complex symbol constellations in a distance aware manner based on their apriori probabilities. Alternately, we also propose an indirect mapping (IM) scheme whereby the residues are once again converted back to bits and then modulated by any *M-ary* complex constellation. Finally, the mapped symbols are constructed as space-time block codes and transmitted over multiple antennas using either of spatial multiplexing [21,22], full diversity [23] transmission or orthogonal STBC i.e., Alamouti's scheme [19] for a 2×2 system. At the receiver end, inverse operations including STBC demapping and the use of Chinese Remainder Theorem (CRT) [8] to convert residues back to integers are implemented to recover the original information. We derive upper bounds on the codeword error probability of RRNS–STBC assuming ML detection and *M-ary* QAM constellation. The achievable coding gain and diversity gain are clearly revealed from this analysis.

Using simulations, we compare the performance of RRNS–STBC and OSTBC i.e., Alamouti scheme for a 2×2 MIMO system and show the improvement provided by RRNS–STBC. With DA mapping, a further improvement in SNR (signal to noise ratio) of about 2 dB for spatially multiplexed case and about 1 dB for full diversity transmission case is obtained. The IM scheme also gives an improvement in SNR of about 1.5 dB over DM. It is important to note that this gain comes at the cost of increased receiver complexity as compared to Alamouti's scheme. The main advantage of the proposed scheme over other schemes like concatenated Reed–Solomon Codes as in [24] comes from the fact that the hardware implementation in case of RRNS is highly modular i.e., same hardware can encode and decode codes with different parameters. The implementation of CRT decoder, however, increases the receiver complexity. Alternative schemes like the Mixed Radix Conversion (MRC) and Base Extension (BEX) [15] can also be used for low complexity decoding.

This paper is organized as follows: Section 2 describes the system model, with emphasis on RNS arithmetic, the RRNS coding and decoding scheme and the direct and indirect mapping schemes. Then, we analyze the performance of the RRNS–STBC coding scheme in Section 3. Finally, in Section 4, we compare the performance of RRNS–STBC with OSTBC and other concatenated STBC schemes. The performance of direct and indirect mapping schemes is also compared using simulation results. Section 5 concludes the paper.

2. System model

The block diagram of RRNS–STBC coded MIMO system is given in Fig. 1. The system is assumed to have M_T transmit antennas and M_R receive antennas. Binary inputs are first converted to integer residues following the RRNS arithmetic (explained in Section 2.1). The generated residue digits are directly mapped to *M-ary* complex constellation points forming the so-called "direct-mapping" scheme, where each residue corresponds to one complex symbol. Alternatively, an indirect mapping scheme is also proposed. The mapping schemes are detailed in Section 2.2. In the STBC mapping block in Fig. 1, the mapped complex symbols are grouped into $M_T \times T$ code blocks, where T is the length of each block. The receiver decodes the transmitted symbols using ML decoding and consequently performs demapping and inverse RNS transform using the Chinese Remainder Theorem to obtain the binary output. The next section discusses RNS and RRNS arithmetic and the coding scheme.

2.1. RNS and RRNS arithmetic

Residue number system (RNS) is defined by the choice of v number of positive, mutually prime integers, m_i ($i = 1, 2, \ldots, v$), referred to as moduli [7]. If any integer N falls in the legitimate range of $[0, M_r)$, where $M_r = \prod_{i=1}^{v} m_i$, it can be uniquely and unambiguously denoted by the residue sequence $\{r_1, r_2, \ldots, r_v\}$ such that $r_i = N \bmod\{m_i\}$ for $i = 1, 2, \ldots, v$. This representation of the integer $N \in [0, M_r)$ by a v-tuple residue sequence is termed as an RNS code.

2.1.1. RRNS codes

In order to incorporate error control, RNS has to be designed with certain number of redundant moduli. A redundant RNS (RRNS) code is obtained by appending $(u - v)$ number of moduli $\{m_{v+1}, m_{v+2}, \ldots, m_u\}$ to the RNS in order to form an RRNS code of u positive, pairwise relative prime moduli, where $\min\{m_{v+1}, m_{v+2}, \ldots, m_u\} \geq \max\{m_1, m_2, \ldots, m_v\}$ must hold. Now, the integer N is represented by a u-tuple residue sequence $\{r_1, r_2, \ldots, r_u\}$

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