Symbol-level Random Network Coded Cooperation with Hierarchical Modulation in Relay Communication

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Abstract — In order to effectively minimize packet error rate in error prone wireless networks, a novel cooperative communication strategy jointly using symbol-level random network coding and hierarchical modulation is proposed in this paper. The source broadcasts random network coded symbols with hierarchical modulation to the relays and the destination. In following time slots, the relays, which have successfully decoded the original packet, transmit additional random network coded symbols to the destination. When the proposed scheme is applied in multi-hop relay consumer device networks which comprise a set of consumer devices, error free transmission with high efficiency can be achieved. We show with simulation results that the proposed joint symbol-level random network coding and hierarchical modulation strategy achieves a substantial gain compared to the channel coded cooperation scheme.

Index Terms — Network Coding, Cooperative Transmission, Hierarchical Modulation

I. INTRODUCTION

Multi-hop relay network is one of promising communication methods on wireless networks. Multi-hop relay network provides enhanced throughput performance and coverage extension. Consumer electronic devices (e.g., cell phones, televisions, set-top boxes, washing machines, refrigerators, etc) are getting more and more networked each other. Multi-hop relay wireless network can be a proper type of communication scheme for networking consumer electronic devices due to its low implementation cost and easy configuration. However, wireless multi-hop relay communication suffers from wireless channel impairment.

In order to overcome the wireless channel impairment, the coded cooperation in relay communication [1] has been proposed. The code cooperation in relay communication shows that the simple strategy using distributed channel coding in cooperative communication increases system performance. When hierarchical modulation is considered with the coded cooperation (denoted as “Co-HM”) [2], additional system performance improvement and simple transmission strategy can be obtained.

With respect to the objective of maximizing the resource usage performance, network coding has been originally proposed in information theory [3], [4] and has since emerged as one of the most promising information theoretic approaches to improve throughput. S. Katti et al. proposed MIXIT [5], a protocol for cooperative packet recovery by performing random network coding across correct symbols and opportunistic routing on groups of correctly received symbols. A. Alamdar et al. showed that the proposed pre-coded transmission scheme using random network coding outperforms the frequency diversity [6]. In [7], MAC layer Random Network Coding (MRNC) has been introduced to avoid the overhead problems incurred by HARQ in the application of WiMAX. Recent studies show that the random network coding can be applied in practical multi-hop wireless networks [5], [8].

Since modulation selection scheme affects the system performance in a wireless communication network, a sophisticated modulation selection scheme is required for optimal adaptive modulation scheme. By employing Co-HM, modulation selection scheme can be simplified [2]. However, Co-HM scheme cannot take full advantage of the benefits of relay communication for the transmission of one encoding blocks due to code rate limitation. The code rate of the all received blocks cannot be decreased less than the mother code rate used for encoding of the transmitted block in the sender. For example, when a mother code of rate 1/2 is used in the sender for certain encoding blocks, regardless of how many relays decode the transmitted encoding blocks and transmit re-encoded redundancy, the receiver can only receive the codes with rate 1/2. To overcome the inefficiency of Co-HM, we propose a scheme to take advantage of random network coding and coded cooperation with hierarchical modulation. To the best of our knowledge, symbol-level random network coded communication strategy with hierarchical modulation has not yet been proposed.

In this paper, we propose joint symbol-level random network coding and hierarchical modulation scheme in a relay communication (denoted as “Co-NC”). Simulation results for Additive White Gaussian Noise (AWGN) channel show that the proposed scheme, Co-NC outperforms the performance of Co-HM in terms of Packet Error Rate (PER).
increases the robustness of the high priority stream while decreases that of the low priority stream. We use relays (R1 and R2) to respectively map y1, y2, and y3 to the High Priority (HP), Medium Priority (MP), and Low Priority (LP) bit positions. 

In hierarchical modulation, the parameter determines the offset, if any, of the constellation’s origin [9]. Depending on the offsets from the origin of the constellation, hierarchical modulation can use uniform (α = 1) constellation or non-uniform (α = 2, 3) constellation. Hierarchical modulation with uniform constellation is using same constellation as normal modulation constellation but mapping bits to different priority classes. Hierarchical modulation with non-uniform constellation offsets the origin of the constellation. Therefore, with greater offsets of the constellation from the origin, the distance between symbols in different quadrants increases so the high priority class robustness increases. However, the increase in α decreases the distances between differing symbols within each quadrant which makes it more difficult for the receiver to differentiate the symbol and thus reduces the robustness of the low priority class. Consequently, increasing the value of α increases the robustness of the high priority stream while decreasing the robustness of the low priority stream.

In this paper, 64QAM with three classes and α = 1 is employed which is shown in Fig. 1. Three classes are used to achieve finer granularity of block delivery performance and α = 1 is selected in order to make no change with normal modulation. With three classes the two most significant bits of the 64QAM symbol convey high priority service data. The two bits in the middle are used to carry medium priority service data and the two least significant bits are used to carry lower priority service data. The reader is referred to [10], [2] and references therein for more information on hierarchical modulation.

**II. WHEN NETWORK CODING MEETS HIERARCHICAL MODULATION**

**A. Hierarchical Modulation**

Hierarchical modulation is supported in various standards including Digital Video Broadcasting (DVB) [9]. Hierarchical modulation takes in two streams with differing service requirements and transmits both streams over the same radio frequency (RF) channel. In the hierarchical modulation, the two most significant bits of the 16 or 64 Quadrature Amplitude Modulation (QAM) symbol convey high priority service data which mapped with Quadrature Phase Shift Keying (QPSK). The two least significant bits (for 16QAM) or four bits (for 64QAM) are used to carry lower priority service data using QPSK or 16QAM respectively.

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**B. How Does the Random Network Coding Work with Hierarchical Modulation?**

The example scenario showing the intuition of the proposed scheme is depicted in Fig. 2, where the sender (S) delivers data to the receiver (D) using the hierarchical modulation (64QAM, α = 1) with help of the relays (R1 and R2). We employed the same hierarchical modulation scheme as in [2]. As shown in Fig. 2, the sender first divides each single packet into a number of small blocks and encodes the blocks using random network codes. Each encoded block is mapped to one of the High Priority (HP), Medium Priority (MP), and Low Priority (LP) hierarchical modulation bit positions. Hence, the coded blocks, y1, y2 and y3 are mapped to the HP, MP, and LP bit positions respectively. The wireless broadcast nature allows the receiver and the relays to listen to the transmission of the sender. Depending on the link quality, receiver and relays detect different number of coded blocks. S transmits in the first time slot, R1 transmits in the second time slot and in the third time slot R2 transmits. In the first time slot, whereas the first Relay (R1) is able to correctly detect y1, y2, and y3 and the second relay (R2) detects y1 and y2, D is only able to detect y1 correctly because its link condition is poor due to the long distance from S. After successful decoding of the received blocks, R1 generates and transmits different coded
blocks, $y_4$, $y_5$ and $y_6$ using different random linear codes coefficients. In the second time slot, $R_2$ detects $y_4$, $y_5$, and $y_6$ correctly and $D$ detects $y_4$, and $y_5$. If the decoding is successful using received, $y_1$, $y_2$, $y_4$, $y_5$ and $y_6$ in $R_2$, $R_2$ generates different coded blocks, $y_7$, $y_8$, and $y_9$ and transmits them. Due to the rateless property of random network codes used across the blocks in the packet, all the blocks within one packet are equally useful. Thus, a receiver is analogous to holding a “bucket” to collect “blocks”: once the “bucket” is full with enough “clean blocks”, the packet is correctly recovered. Finally, $D$ can recover a packet using any three correctly received blocks out of detected blocks, $y_7$, $y_8$, and $y_9$. As number of relay nodes increases, receiver would collect more “clean blocks” which lead to higher probability of correct decoding.

Co-NC has two advantages over Co-HM. First, in contrast to Co-HM where code rate is limited to the mother code rate for one encoding block transmission, Co-NC can decrease the code rate as the number of relays increases since relays transmit different coded blocks. Second, at each transmission, no matter where a node resides in a network, there is no need to perform proper modulation selection procedure to adapt to the link quality, because the same modulation scheme (hierarchical modulation) is used every time and small random coded blocks are adaptively transmitted over different priority classes.

### III. SYSTEM DESCRIPTION

#### A. Basic Operation

A simplified block diagram is depicted in Fig. 3. The encoder divides input bit streams into certain fixed length segments and adds Cyclic Redundancy Check (CRC) which is used for error detection at receivers. A CRC appended segment is called a packet. The sender encodes the packets using random network coding to generate coded blocks and maps each encoded block to one of the priority classes’ bit positions of hierarchical modulation. The operation in Fig. 3 is the case where the highest modulation is 64QAM. The operation with 16QAM and 256QAM hierarchical modulations is similar to 64QAM hierarchical modulation with differences of mapping independent coded blocks to different priority classes: 16QAM with two priority classes, 64QAM with three priority classes, and 256QAM with four priority classes. Each class of given priority class consists of two bits. In Fig. 3, the coded blocks are divided into three sets and mapped to three classes: $Y_1 = \{y_1, y_4, y_7, \ldots\}$, $Y_2 = \{y_2, y_5, y_8, \ldots\}$, and $Y_3 = \{y_3, y_6, y_9, \ldots\}$ are mapped to the HP, MP, and LP respectively. Symbols modulated with hierarchical modulation are transmitted to the receiver. The transmitted symbols can also be received by the relays due to the broadcast nature of wireless communication. If relays can successfully decode and recover the transmitted packet, relays generate different encoded blocks with the packet using different set of random coefficients. Then, using the same method the sender employed, relays transmit encoded blocks with hierarchical modulation. Similar to Co-HM relays, because relays perform decoding and encoding for one packet in Co-NC, Co-NC relays are required to have same amount of storage as Co-HM relays. The receiver collects all the encoded blocks transmitted from the sender and the relays.

The average of all bits’ soft decision values in a coded block is used to decide whether the coded block is “clean” or not. Using the average soft decision values of coded blocks, the receiver selects “clean” blocks for decoding. Even though the probability of error is high for the coded blocks transmitted in the MP, and LP, there exist some coded blocks delivered error free among transmitted blocks in the MP and LP. Since the receiver selects the required number of coded blocks for decoding from all the received coded blocks, the more coded blocks the receiver receives the higher the probability of successful decoding it can achieve.

Since transmitters can generate and transmit as many coded blocks as necessary due to the flexibility of random network coding, the number of coded blocks that relays transmit can be...
dynamically adjustable depending on the channel conditions. Therefore, it is possible to efficiently utilize scarce wireless resources with the proposed scheme.

In order to reduce the overhead of communicating random coefficients between the sender and the receiver for each coded block, the random coefficient matrix can be pre-generated and kept as proposed in [6] at the sender, the receiver, and the relays. In Co-NC, we assume that the sender transmits the index of the pre-generated random coefficients matrix that are used for encoding to the relays and receiver, as a part of the session control information before starting to transmit actual data packets. As in [5], soft decision value from the demodulator in the physical layer on the receiver is used for error detection. Using the average soft decision values of coded blocks, the receiver constructs a set of blocks to decode from all the received coded blocks, which always include top n blocks with the highest average soft decision value. Soft decision values are estimation of code bit log likelihood ratios (LLRs) [13]. In case of perfect channel knowledge, the estimation of code bit LLR under $2^k$-QAM can be obtained by the following equation [13]:

$$\Lambda (b_1) = \ln \sum_{s^t \in [x_{2^k} = \pm 1]} \exp \left( -\frac{\|y_s - \alpha s^t\|_2^2}{\sigma^2} \right)$$

where $k$ is the bit order of used 2K-QAM symbol; $y_s$ is the received symbol; $\alpha$ is the channel gain; $s$ ($s \in \{s_1, s_2, \ldots, s_{2^k}\}$, $s = b_1 b_2 \cdots b_k$) is the transmitted QAM symbol; $\sigma^2$ is the variance of noise which is complex Gaussian random variable with zero mean.

When choosing a proper coded block size, it may appear that a smaller block is always preferable, as a smaller block leads to better delivery rate in the presence of error. Unfortunately, a block that is too small will lead to an inherent problem that is hard to address. A block with m bits uses $GF(2^m)$ to perform random network coding, and a smaller number of bits in a block leads to a smaller size of the Galois Field, with a smaller degree of freedom when coefficient vectors are randomly chosen. This leads to a higher probability of producing linearly dependent blocks with random network coding. It is therefore important to choose an appropriate size for the coded block, so that the block is sufficiently small, but there is still sufficient degree of freedom to produce randomized coefficient vectors that are linearly independent of one another.

### B. Encoding and Decoding of Symbol-level Random Network Coding

The random network code encoder divides each packet into blocks with a fixed size. Let us denote $n$ as the number of blocks in a single packet, $x_i$ ($i = 1, 2, \ldots, n$) as blocks in the packet, and $c_{ij}$ ($i = 1, 2, \ldots, n$) as the set of random coefficients generated in a given Galois field, the size of which is determined by the number of bits in a block (e.g. for a block with 8 bits, $GF(2^8)$ would be used). A coded block $y_j$ can then be produced as $y_j = \sum_{i=1}^{n} c_{ij} \cdot x_i$. Each coded block is a linear combination of all or a subset of the original data blocks. In this way, the encoder is able to generate a virtually unlimited number of coded blocks $y_j$ ($j = 1, 2, \ldots$) using different sets of coefficients which are independent of one another, and any $n$ of these coded blocks can be used to decode by inverting a matrix of coding coefficients. This is usually referred to as the rateless property.

### C. How Does Hierarchical Modulation Benefit Random Network Coding?

Because enough number of error free blocks is required to recover the original packet in random network coding, block error rate is more important than bit error rate. If coded blocks
are transmitted using normal modulation, block error rate is same for all coded blocks. However, block error rate of coded blocks transmitted over HP bit positions of hierarchical modulation is lower than block error rate of coded blocks transmitted over LP bit positions of hierarchical modulation. Therefore, overall block error rate can be decreased and decreased block error rate eventually lowers packet error rate. The simulation results for Additive White Gaussian Noise (AWGN) channel between a sender and a receiver are shown in Fig. 4. The benefit of jointly using hierarchical modulation with random network coding is more substantial when operating range is low SNR region which is the case with low code rate. As SNR gets lower, block error rate using hierarchical modulation becomes lower than the one using normal modulation. Because low code rate of random network coding can be achieved by increasing number of relays, the proposed scheme of jointly using hierarchical modulation with random network coding perfectly fits for relay communication.

The other benefit of joint use of hierarchical modulation with random network coding is simplicity of modulation scheme selection. In order to meet required block error rate with normal modulation, proper modulation scheme has to be selected. However, modulation scheme can be fixed with hierarchical modulation and simple coded block mapping to different priority class can guarantee certain block error rate. This scheme is extremely useful when there are relays with different channel conditions. Relays can adaptively collect error free coded blocks.

IV. PERFORMANCE EVALUATION

To evaluate the performance, we compare the PER performance of Co-NC with Co-HM for the same size packet. For this purpose, we take advantage of the latest communication toolbox in MATLAB for simulation implementation. Since our main interest is random network coding with hierarchical modulation in relay communication, PER performance and delay performance of random network coding with normal modulation in single hop transmission is omitted. Extensive discussion on random network coding with normal modulation in terms of PER and delay performance can be found in [6] and [7] and references therein.

With respect to the Co-HM, we used convolutional codes of rate 1/2 with well known soft combining [11] and soft output Viterbi decoding algorithm [12]. We also employed “decode-and-then-relay” strategy for each intermediate nodes as described in [2] for Co-HM. For simplicity, we used 16QAM hierarchical modulation for both the Co-NC and the Co-HM in the evaluation. For fair comparison with the Co-HM, in the Co-NC simulation, the source transmits 2n number of coded blocks to make the rate 1/2 when the original packet is divided into n number of blocks and the relays, which have successfully decoded the original packet, transmit new n number of coded blocks. We assume a path-loss exponent is 3.52 and that two relays are located between the sender and the destination with a distance d. The network topology used in the simulation is shown in Fig. 5. Each relay is located along the middle point d/2 so that the distance from the relay to the sender and to the destination equals 2d/3, forming a diamond shape where each edge is 2d/3 long. We perform the simulation based on the scenario where two protocols transfer a large file over AWGN channel between a sender and a receiver with help of one or two relays. A file is divided into segments with 16 bit CRC appended to each segment. A segment with CRC is called a packet. In the simulation, a packet size of 512 bits is simulated. Each packet is divided into a number of blocks, on which random network coding is performed. A block size of 8 bits is used which is chosen based on the extensive simulation and achieves the best performance with consideration of aspects described in Sec. III. The simulation results are shown in Fig. 5.

![Fig. 6. Packet error rate performance of Co-NC and Co-HM. SNR values are measured at the destination.](image-url)
blocks selected from all the received coded blocks either through the HP or LP in decoding. The one relay case, where one relay is helping the packet transmission, shows similar performance trend to the direct case. The Co-HM only benefits very little from the inclusion of the second relay. That is because the code rate of the Co-HM cannot be decreased less than the mother code rate used for encoding of the transmitted block in the sender. The gain mainly comes from the soft combining of blocks received from two relays. The Co-NC outperforms the Co-HM as the number of relays grows due to the rateless property of random network coding. The proposed relay communication scheme with joint symbol-level random network coding and hierarchical modulation achieves approximately 2.1dB, and 3.9dB gain at PER of 10–2 with one relay and two relays respectively as compared to the conventional coded cooperation scheme.

V. CONCLUSION

In this paper, we have explored the use of network coding to improve relay communication using hierarchical modulation. The joint use of random network coding and hierarchical modulation makes modulation selection scheme simple and relay communication more effective with flexible rate adjustment regardless of link quality. Using the proposed scheme, the communication scheme of multi-hop relay consumer device networks is expected to be simplified substantially which will eventually reduce implementation cost. Simulation results with AWGN channels showed that the proposed system can outperform the conventional coded cooperation scheme with hierarchical modulation.

REFERENCES


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