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Joint Virtual MIMO and Network Coding Scheme with Superposition ARQ in Two-way Relay System

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Abstract

A new two-way transmission protocol termed VMNC-SARQ (Virtual MIMO Network Coding with Superposition ARQ) was proposed in this paper, which could improve throughput efficiency of DF (Decode-and Forward) relay network significantly. In first step, two single-antenna nodes send messages to the double-antenna relay station simultaneously by using a method similar to 2×2 VBLAST (Vertical Bell Laboratories Layered Space Time) system. In step two, relay station processes the decoded signals received from two source nodes through Network Coding, and then broadcasts the combined messages with Alamouti Coding. A novel retransmission strategy will be implemented when demodulation and decoding failure presents. In order to reduce retransmission overhead, we attach the retransmitted packet to the latter normal packet by using higher modulation, and exploit the confidence value of previously packet with error to help to recover both packets. Theoretical analysis and simulation results show that the proposed scheme could greatly improve end-to-end throughput efficiency for two-way relaying systems.

***Keywords**: network coding, STBC (Space-Time Block Coding), automatic repeat request, two-way relay*

1. Introduction

Relay can be used in the circumstance where there is no direct-link. In this paper we mainly focus on the two-way relay network. T. Yang *et al*. introduced MIMO and network coding in relay system, which has been proved to be a reasonable and valid solution, to increase the throughput of relay network [1, 2].

Multi-antenna system has been demonstrated as a very successful strategy to improve capacity and Bit Error Rate (BER) performance of wireless network. Alamouti proposed a simple two-branch transmit diversity scheme [3]. With the development of MIMO, Laneman et al. put forward the idea of Virtual MIMO based on the cooperative relay network, and gave the theoretical analysis [4]. Considering the resource-constrained characteristic of wireless communication nodes and the well performance of MIMO, some people present Distributed STBC (DSTBC) [5, 6] in which many single-antenna nodes send and receive messages by forming a virtual antenna array. Chun et al. [7, 8] proposed Network Coding in cooperative relay network. However, there are still many issues needing to be resolved, such as high BER and bad spectrum efficiency, as well as low throughput.

In this paper's network model, two single-antenna nodes exchange messages through a multi-antenna relay station. We approach the throughput efficiency problem from a new angle. Like a dual antenna node, two single-antenna nodes send data to the relay station cooperatively through the method of Virtual VBLAST. Therefore, two source nodes could transfer the message simultaneously. Besides, Network Coding is used during broadcast phase to increase relay efficiency at the relay station, and the relay time was halved. Different from relaying with Bi-directional Amplification of Throughput (BAT-relaying) relaying and other Bi-directional traffic flows, this paper employed Alamouti coding during broadcast, and the link reliability was improved signally.

In reference [9] and [10], authors proved that physical-layer network coding (PNC) can achieve within 50% bit capacity in single-input single-output (SISO) Gaussian two-way relay channel. Yang et al. proposed a new MIMO PNC scheme [11] to extend PNC to MIMO two-way

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relay channel, where each user has two antennas. In this paper, we employ PNC in virtual MIMO environment.

In reference [12], an improvement was proposed to reduce the retransmission overhead by using the Symbol level Network Coding (SYNC) scheme, which could achieve 110 percent throughput gain over traditional transmission. However, the authors did not consider the fading channel effects. Furthermore, the higher modulation of SYNC occurs all the times, and it is not necessary when demodulation and decoding successfully. In this paper, another process to improve throughput is to reduce the cost of retransmission, the novel ARQ is an improvement from SYNC. Details on it will be discussed in later sections.

The remainder of this paper is organized as follows: Section 2 describes three-node relay network model and proposes a higher efficiency protocol for the relay network. In Section 3, an improved ARQ strategy is discussed. Section 4 gives simulation results and performance analysis. Conclusions will be presented in section 5.

2. System Structure

2.1. Model description

Our model is a three-node wireless network: two data source nodes need to exchange messages with each other and there is no direct-link between them, another node acting as relay station could communicate with the two source node simultaneously. Only one antenna was accommodated at each source node, but the relay station has double antennas. For simple, we denote two single-antenna nodes by SN_1 and SN_2. Assuming that they have to communicate with each other through a relay node R that is within range of both SN_1 and SN_2. We assume slow block fading and perfect channel estimation at all the nodes. Network model could be expressed as Figure 1.

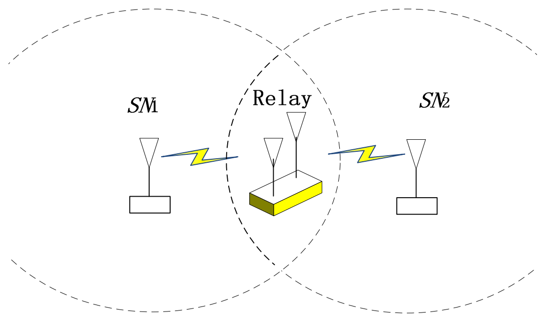

Figure 1. Relay Network Model with Three Nodes

In this paper, bold lowercase and bold uppercase letters denote vectors and matrices, respectively. We use $[\cdot]^*$, $[\cdot]^{-1}$ and $[\cdot]^{-H}$ to denote complex conjugate, inverse and Hermitian operations of a matrix or a vector, respectively. Furthermore, $\|\cdot\|^{F}$ stands for Frobenius norm of a matrix or a vector.

2.2. MA (Multiple Access Stage) Structure

In the first stage of VMNC, SN_1 and SN_2 send signal $x_{S_1,k}$ and $x_{S_2,k}$ (k =1, 2…) to relay station at the same time respectively, k stands for the transmission slot. Inspired by the idea of VBLAST, we could see SN_1 and SN_2 as two antennas of a node (see Figure 2), and the difference is that there is no serial parallel conversion at this virtual dual-antenna sender.

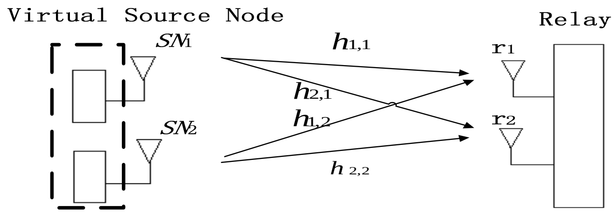

Figure 2. Virtual VBLAST Model of Multiple Access Stage

The received signals at relay station can be written as follows:

$$\begin{cases} y_{1,k} = h_{1,1}^k x_{S_1,k} + h_{1,2}^k x_{S_2,k} + n_{1,k} \\ y_{2,k} = h_{2,1}^k x_{S_1,k} + h_{2,2}^k x_{S_2,k} + n_{2,k} \end{cases} \quad (1)$$

$h_{j,i}^k$ represents complex Rayleigh flat-fading channel coefficient between SN_i and the j^{st} antenna of Relay at the k^{th} time slot, where $i, j \in (1,2)$. Obviously, $h_{j,1}$ and $h_{j,2}$ are completely uncorrelated since SN_1 and SN_2 are out of each other's communication range. $y_{1,k}$ and $y_{2,k}$ is the signals received at two antennas of relay station at the k^{th} time slot, $n_{1,k}$ and $n_{2,k}$ is complex Gaussian noise with zero mean and σ_N^2 variance at two antennas of the relay node, respectively. The formula can also be expressed by:

$$\mathbf{y} = \mathbf{hx} + \mathbf{n} \quad (2)$$

Where $\mathbf{y} = [y_{1,k}, y_{2,k}]^{\mathrm{H}}$, $\mathbf{h} = [h_{1,1}^k, h_{1,2}^k; h_{2,1}^k, h_{2,2}^k]$, $\mathbf{x} = [x_{S_1,k}, x_{S_2,k}]^{\mathrm{H}}$ and $\mathbf{n} = [n_{1,k}, n_{2,k}]^{\mathrm{H}}$.

There only two antennas at both sender and receiver of the Virtual 2×2 MIMO, we could easily detect the signal with joint Maximum Likelihood detection (ML) to get two independent signals.

$$\tilde{\mathbf{x}} = \arg\min_{\mathbf{x}\in \mathrm{M}} \|\mathbf{y} - \mathbf{hx}\| \quad (3)$$

M is the constellation points set of $x_{S_1,k}$ and $x_{S_2,k}$; this Virtual VBLAST strategy requires that the process of coding and modulation at both source node should be the same. Besides, compared to the MA stage of denoise-and-forward (DNF) protocol [13] and complex field network coding (CFNC) protocol [14], in which two terminals can also transmit signals to relay station simultaneously, joint ML detection of $x_{S_1,k}$ and $x_{S_2,k}$ can greatly improve the accuracy, and the relay station could select DF (Decoding and Forward) protocol and prevent error propagation. Another advantage is that the communication throughput through the MA channel is not restricted by the weaker link of the two terminals.

There is also disadvantage in this virtual MIMO. If we do not treat the relay system as a virtual 2×2 MIMO structure and still implement the classical 1×2 MIMO (SIMO) model here, the two-branch MRRC (Maximal-Ratio Receive Combining) scheme could be applied. The received signals after MRRC can be derived as follows:

$$\begin{aligned} &\begin{cases} r_1^k = h_{1,1}^k x_{s_1,k} + n_1^k \\ r_2^k = h_{2,1}^k x_{s_1,k} + n_2^k \end{cases} \\ &\tilde{x}_{s_1,k} = h_{1,1}^{k\,*} r_1^k + h_{2,1}^{k\,*} r_2^k \\ &\quad = (|h_{1,1}^k|^2 + |h_{2,1}^k|^2) x_{s_1,k} + h_{1,1}^{k\,*} n_1^k + h_{2,1}^{k\,*} n_2^k \end{aligned} \quad (4)$$

As we can see from Equation (3), this type of Virtual MIMO could not obtain extra diversity, and Equation (4) presents that the traditional 1×2 MIMO could acquire double diversity. However, relay station could receive two signals simultaneously by using this Virtual VBLAST strategy. So this VMNC method trades diversity gain for multiplexing gain, and could transmit more data than the two-1×2 MIMO in unit time. In other words, this Virtual MIMO could save as much as half the time than traditional two-1×2 MIMO to transmit the same data.

2.3. BC (Broadcast Stage) Structure

The second step of VMNC is broadcast stage. Before forwarding, two signals received from SN_1 and SN_2 were combined by using Network Coding. We denote the compressed message with $s_{R,k}$ (k is time slot corresponded to $\hat{x}_{S_1,k}$ and $\hat{x}_{S_2,k}$ respectively). The symbol could be acquired by $s_{R,k} = \hat{x}_{S_1,k} \oplus \hat{x}_{S_2,k}$, where $\hat{x}_{S_1,k}$ and $\hat{x}_{S_2,k}$ is the processed signals received from SN_1 and SN_2 respectively.

And then, the relay network is treated as a two-2×1 MIMO, $s_{R,k}$ and $s_{R,k+1}$ are processed with Alamouti coding [3] and sent out successively. Received signals at SN_1 are expressed as:

$$
\begin{aligned}
r_k &= h_{1,1}^k S_{R,k} + h_{2,1}^k S_{R,k+1} + n_k \\
r_{k+1} &= -h_{1,1}^k S_{R,k}^* + h_{2,1}^k S_{R,k+1}^* + n_{k+1}
\end{aligned}
\tag{6}
$$

We assume that the channel coefficient is constant during two continuous symbols. n_k is complex random Gaussian noise at the receiver. The combining scheme is the same as the original Alamouti method:

$$
\begin{aligned}
\tilde{s}_k &= h_{1,1}^{k\,*} r_k + h_{2,1}^k r_{k+1}^* \\
\tilde{s}_{k+1} &= h_{2,1}^{k\,*} r_k - h_{1,1}^k r_{k+1}^*
\end{aligned}
\tag{7}
$$

Substituting (6) into (7), we could get:

$$
\begin{aligned}
\tilde{s}_k &= (\left\|h_{1,1}^k\right\|^2 + \left\|h_{2,1}^k\right\|^2) S_{R,k} + h_{1,1}^{k\,*} n_k + h_{2,1}^k n_{k+1}^* \\
\tilde{s}_{k+1} &= (\left\|h_{1,1}^k\right\|^2 + \left\|h_{2,1}^k\right\|^2) S_{R,k+1} - h_{1,1}^k n_{k+1}^* + h_{2,1}^{k\,*} n_k
\end{aligned}
\tag{8}
$$

Those signals will be sent to ML Detector to get $\hat{s}_k$ and $\hat{s}_{k+1}$. Finally, the source node SN_1 could get two symbols simultaneously by following actions:

$$
\begin{aligned}
x_{S_2,k} &= \hat{s}_k \oplus x_{S_1,k} \\
x_{S_2,k+1} &= \hat{s}_{k+1} \oplus x_{S_1,k+1}
\end{aligned}
\tag{9}
$$

The receiving operation at SN_2 is the same as at SN_1. In this paper's transmit protocol, it only needs four time slots to complete the exchange of two signals, while the same work needs eight time slots in the classical relay transmit model. More importantly, it could get impressive diversity in broadcast stage by using Alamouti coding.

2.4. Impact of Traffic Asymmetry

When traffic of SN_1 and SN_2 is different, the throughput efficiency will decrease. Let α be the traffic asymmetry factor:

$$\alpha = \frac{K_{SN_1}}{K_{SN_1} + K_{SN_2}} \tag{10}$$

In this definition, K_{SN_1} and K_{SN_2} are the packets number of SN_1 and SN_2 within a sufficiently long observation period. Without loss of generality, we assume $K_{SN_1} \le K_{SN_2}$, then $0 \le \alpha \le 0.5$. Ideal communication channel is assumed so as to simplify the analysis. There are $K_{SN_1} + K_{SN_2}$ packets are received by relay station in K_{SN_2} time slots in multi-access stage, and the total number of slots for relay station to broadcast these packets is also K_{SN_2}. Every packet includes N symbols, and T_s denotes the duration of each time slot. The throughput could be written:

$$R_{VMNC}(\alpha) = \frac{(K_{SN_1} + K_{SN_2})N}{(K_{SN_2} + K_{SN_2})T_s} = \frac{R_s}{2-2\alpha} \tag{11}$$

Where $R_s = \frac{N}{T_s}$. In traditional one-way relay network, two nodes transmit packets to relay station one after another, and the relay station broadcast these packets to the two source nodes respectively. We could easily get the throughput in traditional one-way system:

$$R_{one-way}(\alpha) = \frac{(K_{SN_1} + K_{SN_2})N}{(2K_{SN_1} + 2K_{SN_2})T_s} = \frac{R_s}{2} \tag{12}$$

The gain of VMNC is:

$$G_{VMNC}(\alpha) = \frac{\frac{R_s}{2-2\alpha} - \frac{R_s}{2}}{\frac{R_s}{2}} = \frac{\alpha}{1-\alpha} \tag{13}$$

As we can see from this equation, throughput gain of VMNC is maximized when $\alpha = 0.5$. In order to increase throughput gain, we should try to make the traffic in SN_1 and SN_2 as symmetrical as possible.

3. Superposition ARQ Strategy

In order to further improve throughput of the proposed VMNC scheme mentioned above, this section introduce and modify a novel ARQ strategy [13] that could take full advantage of Network Coding. When demodulation and decoding failure presents at both SN_1 and SN_2, we employ a higher modulation retransmission method (named SARQ) to retransmit the signals according to NACK from SN_1 and SN_2. In order to retransmit $s_{R,k}$ without extra overhead, we combine the error received packet with the latter packet to form a new packet, and make up a quaternary data sequence (or 2-bit binary tuple). Table 1 illustrates forming process of the new packet:

Table 1. Process of Combining and Translation.

	Bits of packet					
$s_{R,k}$	0	1	0	1	…	end
$s_{R,k+1}$	1	0	0	1	…	end
New packet	2	1	0	3	…	end

This table is also a mapper to convert bits of $S_{R,k}$ and $S_{R,k+1}$ to 4-ary symbols. $S_{R,k+1}$ is the packet should be transmitted normally in the next time slot, and $S_{R,k}$ is the packet needing retransmission corresponding to the received NACK. After combining, this new packet will be mapped to a higher constellation, for example, if the normal constellation point is BPSK, the QPSK will be used when this combined packet is mapped. A of Figure 3 is the constellation mapping process.

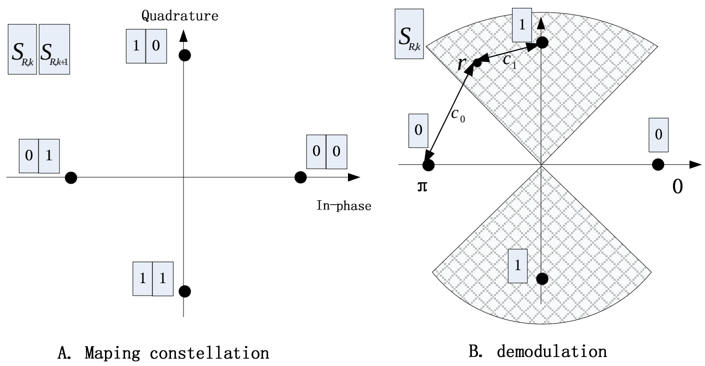

Figure 3. Higher Modulation and Demodulation

To perform this novel ARQ scheme, the signal confidence value c will be calculated and stored at SN_1 and SN_2 when demodulation and decoding failure presents. After receiving of the new combined packet, we demodulate and decode the superposition packet by c. Firstly, we will ignore $S_{R,k+1}$ (see B of Figure 3) and calculate the confidence value of $S_{R,k}$ individually in the higher constellation, and then add it on the old confidence value of $S_{R,k}$ stored at terminals, after that, the new comprehensive confidence value can be used to demodulate $S_{R,k}$. The confidence value of a symbol point r can be defined by following equation:

$$\begin{aligned} c_0 &= \min_{s_0 \in S} | r - s_0 |^2 \\ c_1 &= \min_{s_1 \in S} | r - s_1 |^2 \\ c &= c_1 - c_0 \end{aligned} \tag{14}$$

Where S is the constellation points set of $S_{R,k}$, s_0 and s_1 stand for the constellation points of 0 and 1 respectively. c_0 and c_1 are the distance of r from signal point corresponding to bit "0" and "1", respectively. c is defined as the confidence value of $S_{R,k}$, and we judge $S_{R,k}$ as follows equation:

$$\hat{S}_{R,k} = \begin{cases} 1 & \sum c_{R,K} \le 0 \\ 0 & \sum c_{R,K} > 0 \end{cases} \tag{15}$$

$\sum c_{R,K}$ is the sum of confidence value of both transmission and retransmission of $S_{R,k}$. It is easy to see that the confidence value and the Maximum Likelihood detection are of the same nature.

From Figure 3, we could easily find that the demodulate ability of $S_{R,k}$ in QPSK is not as good as normal transmission of BPSK, and the maximum confidence value between them is defined as:

$$c_{half-QPSK} = c_{BPSK} / \sqrt{2} \tag{16}$$

The time diversity of $S_{R,k}$ is obtained actually at the condition of superposition retransmission, and the diversity gain is $1+1/\sqrt{2} \approx 1.707$. Even though its diversity gain is lower than classical retransmission (traditional diversity gain is 2), the demodulate reliability could be still improved significantly. After successfully decoding of $S_{R,k}$, $S_{R,k+1}$ could be easily decoded as usual BPSK without losing any decoding accuracy, it could be found at part A of Figure 3. After de-Network Coding (XOR operation), SN_1 and SN_2 could get what they wanted without extra overhead.

$$\begin{aligned} x_{S_2,k} &= \hat{S}_{R,k} \oplus x_{S_1,k} \\ x_{S_2,k+1} &= \hat{S}_{R,k+1} \oplus x_{S_1,k+1} \end{aligned} \tag{17}$$

Different from SYNC proposed in [13], the Superposition ARQ in this paper occurs only when demodulation or decoding failure presents. Higher modulation requires more complex calculation and scheduling, which could cause unnecessary resource consumption. Therefore, the strategy in this paper is more reasonable.

4. Simulation Results

In this section, we provide simulation results for the classical one-way relay scheme and VMNC strategy. In classical one-way system, relay node receives the signal from only one source node with MRRC at a time slot, and then forwards it by using Alamouti coding. We employ the Superposition ARQ only at Broadcast Stage. In our emulation, the size of each packet is 80 bits, and 20000 packets are transmitted every time(after CRC coding). The independent identically distributed (i.i.d) Rayleigh-flat-fading channel is assumed between each antenna pair in the three-node relay system.

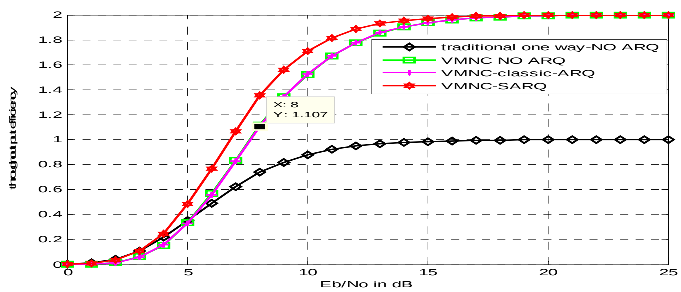

Figure 4. Throughput Analysis of Different Condition

To compare the throughput performance of different strategy, we use Sym/T (total symbols received at both terminals per time period) as the standard to measure throughput performance. Figure 4 is throughput efficiency analysis for different transmission condition. The throughput capacity of the traditional one-way system is much smaller than the others. It is easy to see that VMNC could greatly improve the throughput efficiency compared to the classical one-way protocol, that's because Multiple Access and Network Coding are employed, and the communication time during access and broadcasting could both be halved. The improved transmission strategy with the novel Superposition ARQ could get the best throughput performance than any others, especially when the Eb/No is between 3db and 14db. For example, when Eb/No is 8db, the throughput efficiency is 1.358 Sym/T in VMNC-SARQ, and 1.107 Sym/T in VMNC with traditional ARQ, however, only 0.7389 Sym/T in classical one-way relay channel with classical ARQ. Compared to classical one-way relay channel, the throughput gain of VMNC and VMNC-SARQ are GVMNC= (1.107-0.7389)/0.7389=49.82% and GVMNC-SARQ= (1.358-0.7389)/0.7389=83.79% respectively.

5. Conclusion

VBLAST is a very successful transmission strategy in wireless network which could get many performance gains, such as spectral efficiency, diversity gain and multiplexing gain. In this paper, we apply the idea of VBLAST and Network Coding in the three-node relay system, and proposed VMNC-SARQ protocol which could greatly improve the throughput efficiency when there are double antennas at the relay station. Compared to traditional one-way relay strategy, the throughput could be doubled without any other performance degradation by using our new protocol. All the extra investment is an antenna placed on the relay station. In order to reduce retransmission overhead in traditional ARQ, a novel retransmission scheme is introduced and improved at VMNC-SARQ. In fact, the Superposition in the new retransmission strategy is also a Network Coding in nature, in which the retransmitted information would not damage the normal transmission of the next packet. As a result, the throughput efficiency could be drastically improved without extra overhead. The performance evaluation results show that the improved protocol indeed work better than the traditional transmission scheme. In VMNC-SARQ, the network needs four time slots to complete a double-packet exchange. In the further, we plan to find a way to reduce the transmission delay in VMNC-SARQ without impairing the throughput performance.

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