Throughput improvement with Decode-Forward and Compress-Forward Channels

[I]A. Ramani, [II]Dr. P.Marichamy
[I]PG Scholar, P.S.R. Engineering College, Sivakasi, India
[II]Dean (Academic) & HOD/ ECE, P.S.R. Engineering College, Sivakasi, India

Abstract

Relay-based cooperative communication has become a research focus in recent years because it can achieve diversity gain in wireless networks. The multiuser communication channel, in which multiple users exchange information with the help of a relay terminal, termed the multi way relay channel (mRC), is introduced. In this model, multiple interfering clusters of users communicate simultaneously, such that the users within the same cluster wish to exchange messages among themselves, i.e., each user multicasts its message to all the other users in its own cluster. It is assumed that the users cannot receive each other's signals directly. Hence, the relay terminal in this model is the enabler of communication. It is shown that a throughput of 1/1.5N symbol per node per channel use was achieved using binary signaling. To further enhance the throughput, QPSK modulation scheme is implemented. It can provide an increase in throughput of 1/2N symbol per node per channel. This is achieved by separately (and concurrently) dealing with the in-phase and quadrature components of QPSK symbols. The error performance of the proposed algorithm is evaluated analytically.

Keywords

Relay Channels, Network Coding, Cooperative Communication

I. Introduction

With the appearance of bandwidth greedy applications such as streaming video, increasing the throughput of wireless networks is a grave challenge. Network coding, a technique that was originally proposed to maximize the throughput of lossless wireline networks in multicast scenarios [1], has been successfully applied to wireless relay networks [2]. Further, to simultaneously utilize the broadcast nature of the wireless environment and the superposition of electromagnetic waves, physical layer network coding (PNC) has been developed [3], [4]. PNC was originally considered for the two-way relay channel (TWRC) where two source nodes communicate with the aid of an intermediate relay. It has been shown that applying this technique can increase the throughput by 100%. More general scenarios, in particular the case where many nodes broadcast packets through a single relay, were investigated in [6]. These results provide insight into the difficult and open problem of multi-node network coding. For the multi-way relay channel considered in [5] where N source nodes exchange data through a relay, the throughput of plain routing, conventional network coding and PNC to conclude that as the number of source nodes increases, the performance gains of PNC over plain routing diminish. A novel cooperative approach based on complex field network coding (CFNC) which makes it possible for the sources to broadcast symbols in the same time slot (TS) and on the same resource blocks (RBs) after symbol-level operations are done at the physical layer. Deploying CFNC, a cooperative network with NS sources offers a throughput as high as 1/2 symbol per source per time slot (sym/S/TS), relative to 1/(2NS) sym/S/TS in traditional cooperative system and 1/(NS + 1) sym/S/TS in GFNC-based cooperative system. A technique called complex field network coding (CFNC) in which the network coding operations are performed in the complex field was introduced in [6] to better utilize the wireless medium. It was shown that using CFNC in a multi-way relay channel, a throughput of 1/2 sym/S/CU can be achieved. However, the main drawback of this technique is that as the number of users increases so that (e.g. $N \geq 4$), the performance deteriorates dramatically, thus limiting its applicability.

We propose a detect-and-forward relaying scheme that works on a symbol-by-symbol basis. For every received superposition of symbols at the relay, a hard-decision is made.

This method can increase the throughput of a multi-way relay channel with full data exchange to at least 1/1.5N sym/S/CU without requiring source nodes to overhear the transmissions of other nodes.Thus, for any number of nodes using binary signaling, a throughput gain of at least 33% is achieved over plain routing and conventional network coding. It is straightforward to show that the same throughput gain can be achieved when QPSK modulation is employed by the users. The proposed approach is not appropriate to higher order modulation because of the binary nature of the protocol.

The rest of this paper is organized as follows. In Section II, the network model and notation are introduced. The algorithm is described and the throughput of the system analyzed in Section III. The performance is analyzed in Section IV, and some conclusions are presented in V.

Energy efficiency has always been a critical design parameter for wireless networks. Recently, the trend towards designing energy-aware communication protocols has become more intense due to the scarcity of the energy resources. Cooperation among nodes and network coding are two techniques that have been introduced to improve the network performance and provide the communication with diversity, robustness, security and high data rates.

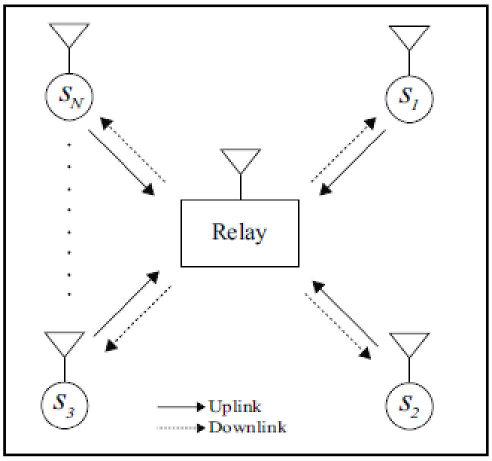

Fig. 1: The Communication Network Model

II. The Network Model

As shown in fig. 1, we consider a multi-way relay channel which has N source nodes, S1, S2, ..., SN, and one relay. We suppose full data exchange in which every node must receive the messages of all other source nodes. We assume there is no direct link between any two source nodes, so the relay is the enabler of communications. As with all cooperative relay networks, time synchronization is required. This can be achieved via techniques originally developed for MIMO systems. Furthermore, the transmissions are half-duplex. Relays usually work in the half duplex mode. where a transmission process often requires two TSs for the relay to receive the signal and then forward it respectively, which results in a loss in spectral efficiency. The single way relay scheme results in inter-relay interference (IRI). In network coding at relay nodes was applied to achieve inter-relay interference cancellation (IRIC).

The multiuser communication channel, in which multiple users exchange information with the help of a relay terminal, termed the multiway relay channel (mRC), is introduced. In this model, multiple interfering clusters of users communicate simultaneously, such that the users within the same cluster wish to exchange messages among themselves. The Fig 2 for the mRC with additive Gaussian noise on each link.

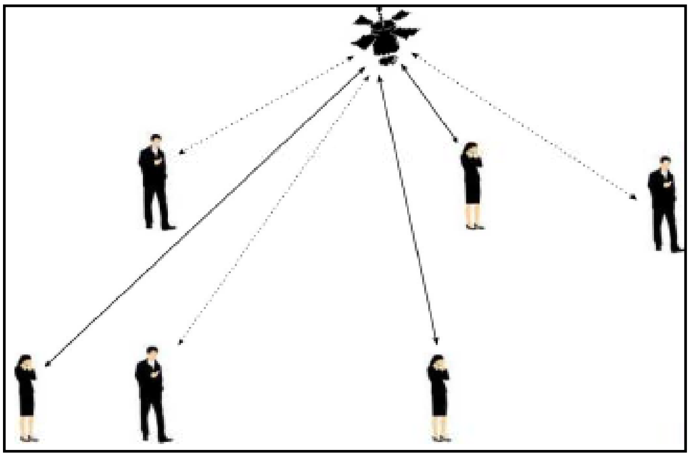

Fig. 2: Illustration of the mRC model in which the relay terminal helps two separate clusters of users in a social network to simultaneously exchange messages

In particular, the users send their messages to the relay terminal over an additive Gaussian multiple access channel (MAC), and the relay transmits a function of its received signals over a Gaussian broadcast channel to the users to help them decode the messages they desire. It is assumed that the users do not receive each other's signals directly, but only from the relay. We study the set of achievable rate tuples for all the messages in the network such that all the users can simultaneously multicast their messages to all the other users in their own clusters. The characterization of the capacity region, i.e., the set of all achievable rate tuples, for the mRC is an open problem. We propose achievable rate regions by using the most fundamental coding techniques that have been introduced in the literature for relay networks, as well as an outer bound. In particular, we derive achievable rate regions for the corresponding multiway extensions of decode-and-forward (DF), amplify-and-forward (AF), and compress-and-forward (CF) protocols.

III. Algorithm Description and Throughput Analysis

With plain routing, 2N channel uses (CUs) are required for full data exchange between N nodes. In this case, the throughput is 1 /2N sym/S/CU. Here we propose a network coding scheme that improves the throughput by at least 33%, i.e. 1/1.5N sym/S/CU, if binary signaling is used. Our transmission scheme consists of three main steps:

Step 1: All nodes transmit their BPSK symbols to the relay in the same time slot. Due to the network coding operation that naturally occurs in the air, the relay receives the superimposed electromagnetic waves, i.e., the sum of the symbols.

Step 2: The relay broadcasts the received sum back to the nodes. At this stage each node will know the exact number of nodes that have sent 1, and thus also the number those have sent -1.

Step 3: By exploiting this common information (the received sum signal from the relay), only some of the nodes, called minority nodes, send their symbols to the relay for broadcasting. The goal of this step is to identify these minority nodes to all source nodes. This is accomplished by a divide-and-conquer method in which nodes are successively divided into smaller groups over a number of rounds. The details of this step are later illustrated with examples.

Here it is worth noting that for the case N = 2 the transmission is done after Step 2 by using self information as in [3]. Since we are considering binary signaling for each of the N nodes, N + 1 different sum values can be received by the relay in Step 1. If the number of nodes sending 1 (-1) is less than the number of nodes sending -1 (1), those nodes are said to be 'in minority'. If the number of nodes sending 1 and -1 are the same, those nodes sending -1 are chosen to be in minority. By the end of Steps 1 and 2, each node has the following information: a) whether it is a minority node or not, b) the number of minority nodes. not, b) the number of minority nodes.

(a)0 transmission
Prob. Of occurrence: 1/2

(b) 2 transmission
Prob. Of occurrence: 1/2

Fig. 3: Node grouping in Step 3 for the two node case.

In Step 3, the objective is to identify the minority nodes, thus making available the symbol of each node to every other node. To achieve this, the nodes are divided into two approximately equal groups. If there are M nodes, the two groups are G1 = {S1, . . . , S_M/2_} and G2 = {S_M/2_+1, . . . , SM}. The minority nodes in G1 transmit"1" and the minority nodes in G2 transmit"-1" to the relay simultaneously. The relay then broadcasts the sum back. In this manner, the number of minority nodes in each group is known. By successively repeating this procedure, the minority nodes can be identified. This method is illustrated below for the two and three node cases. These cases will serve as the basis for the general throughput analysis for N nodes.

Table 1: Transmission Cases for Two Nodes

Sum	symbols	Prob.	# channel uses
-2	two (-1) and zero (1)	$\binom{2}{0}/2^2$	2+0

0	one (-1) and one (1)	$\binom{2}{1}/2^2$	2+2
2	zero (-1) and two (1)	$\binom{2}{0}/2^2$	2+0

A. Two Nodes

With two nodes, after the first two transmissions in Steps 1and steps 2, if both nodes had sent the same symbols, there are no minority nodes, and the communication is complete, i.e., both nodes know the information symbol of the other node and Step 3 is not required. This is shown in Fig. 2 (a). The case of two nodes having different symbols is shown in Fig. 2 (b) with the minority node colored. To identify the minority node, the two nodes are grouped into G1 = {S1} and G2 = {S2}. If the minority node is in G1, it sends '1' and if it is in G2 it sends '-1'. The relay broadcasts this information to both nodes. Thus in this case two transmissions are needed to identify the minority node in Step 3.

Table 1 shows the transmission cases for two nodes. The cases in which the received sum at the relay in Step 1 is -2 or 2 have no minority node, and the probability of this occurring is $\binom{2}{0}/2^2$. The case where the received sum at the relay in Step 1 is 0 has one minority node, and the corresponding probability of occurrence is $\binom{2}{1}/2^2$. Including the two transmissions needed in Steps 1 and 2, the average number of channel uses is

$$C(N) = 2 + \frac{1}{4}\left[\binom{2}{0}\times 0 + \binom{2}{1}\times 2 + \binom{2}{0}\times 0\right] = 3. \qquad (1)$$

Compared to plain routing where 4 channel uses are required, the information exchange is done in 0.75 × 4 = 3 channel uses on average, giving a 33% increase in throughput.

B. The General n Node Case

In the general case of N nodes operating in a multi-way relay channel, by induction on N it can be shown that the required number of channel uses is at most 0.75 times that of plain routing. The throughput gain will therefore not be less than 33%. The results for N = 2 given previously is used as the base for a proof by induction. In the inductive step, we assume N nodes require at most 0.75×2N channel uses, and then prove that N + 2 nodes will need at most 0.75×2(N+2) channel uses, i.e., a throughput gain no worse than 33%.

Proof

After Steps 1 and 2, and determining the total number of minority nodes, the N + 2 nodes are divided into groups of two and N nodes. The minority nodes that are placed in the two node group transmit '1', and the minority nodes that are placed in the N node group transmit '-1'. At this stage, the number of minority nodes in each group is known. If there are no or two minority nodes in the two node group, they are determined at this stage. If there is one minority node in the two node group, another two transmissions are needed. Therefore on average one channel use is required for the two node group in Step 3. Since we have assumed the N node group can complete transmissions in 0.75×2N channel uses, N + 2 nodes require 2 + 1 + 0.75 × 2N = 0.75 × 2(N + 2) channel uses. Thus N + 2 nodes require on average at most 0.75 of channels uses needed with plain routing.

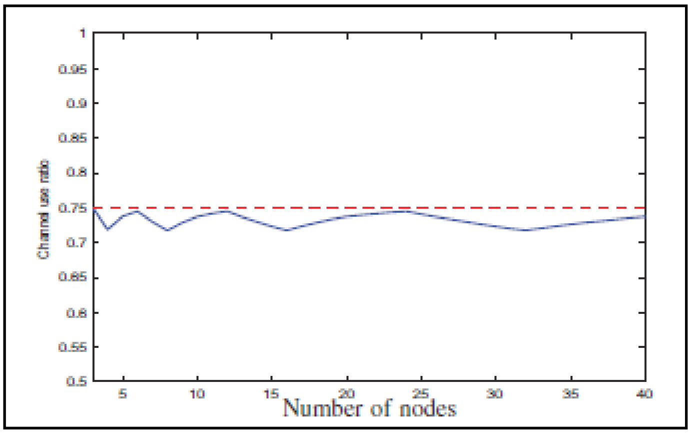

Fig. 4: The Ratio of the Number of Channel Uses With the Proposed Algorithm to That With Plain Routing (Solid Line) is Always Less Than or Equal to 0.75 (Dashed Line)

Fig. 4 shows the channel use ratio of the proposed algorithm to plain routing for up to 40 nodes. Each point was generated by averaging the number of channel uses over 6 × 105 runs. The ratio is always less that 0.75, confirming the result above.

A. Performance Analysis

We now analyze the error performance of our proposed scheme. The channels between the source nodes and relay are assumed to be additive white Gaussian noise (AWGN) with power spectral density (PSD) N0/2, thus the channels have the same coefficients and are symmetric. If the channels are asymmetric, pre-equalization can be performed before transmission by providing channel state information at the transmitter (CSIT) as in [7]. The algorithm has three steps with error probabilities Pe1, Pe2 and Pe3, respectively. The probability that a node receives the symbol of at least one other node in error is

$$P_e = 1 - (1 - P_{e1})\,(1 - P_{e2})\,(1 - P_{e3}) \qquad (2)$$

For N nodes, the probability of error in Step 1 (the uplink step), Pe1, is the error probability of (N+1)-PAM modulation with unequal symbol probabilities, which is always lower than (N + 1)-PAM modulation with equiprobable symbols. To prove this, we derive the symbol error rate (SER) of N-PAM modulation with unequal symbol probabilities.

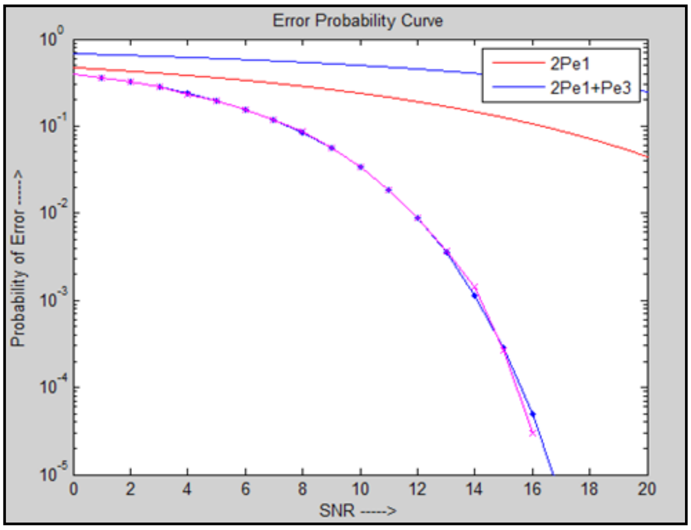

Fig. 5: The error probability Pe with and without Step 3

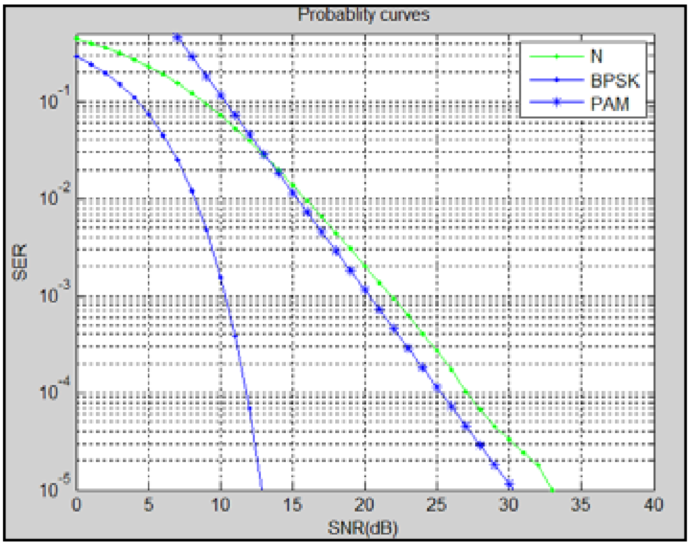

Fig. 6: The Performance of the N-PAM and BPSK for Different Numbers of Nodes

V. Conclusion

Full data exchange in a multi-way relay channel was considered. An algorithm that has been proposed provides a throughput of 1/1.5N sym/S/CU, a 33% improvement over plain routing. This shows that physical-layer network coding can also be beneficial in systems with more than two source nodes. Besides having low complexity, this algorithm can easily be scaled to higher numbers of nodes. It can also be employed with QPSK modulation, which provides a 33% gain. This is achieved by separately (and concurrently) dealing with the in-phase and quadrature components of QPSK symbols.

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Ramani. A received B.E degree(2012) in Electronics and Communication Engineering, from P.S.R.Rengasamy College for Women, Sivakasi, Anna University, Chennai and doing M.E degree in Applied Electronics(2014) from P.S.R Engineering College, an Autonomous Institute, sivakasi, under Anna University Chennai.