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Virtual MIMO broadcasting transceiver design for multi-hop relay networks

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A B S T R A C T

To improve end-to-end throughput and to reduce signaling overhead in multi-hop relay networks, broadcast virtual multiple-input and multiple-output (MIMO) systems (BVMSs) have been introduced. Conventionally, this research has been done for a limited environment where each node is equipped with a single-antenna and also interference from other networks is not included for the numerical analysis. In this paper, we propose a new virtual MIMO broadcasting transceiver (VMBT) to overcome the limitation of conventional BVMS and to improve end-to-end throughput for BVMS-based multi-hop-relay networks while the signaling overhead effectively reduced. Toward this goal, proposed VMBT is designed based on the following contributions: analysis of the channel ellipse property, convergence proof of the iterative algorithm and utilization of the null and span of channel vectors. The simulation results show that the proposed VMBT achieves the highest end-to-end throughput compared with that of other conventional technologies.

1. Introduction

In the past few years, wireless ad-hoc networks have been of interest to many researchers because of their potential applications, including in the areas of distributed computing, battlefield surveillance, and structural health monitoring system. In wireless ad-hoc networks, it is necessary to develop multi-hop relay network mechanisms when there is no cellular infrastructure, e.g., structural health monitoring of a bridge. Even for an environment with no cellular infrastructure, it is necessary for sensor nodes to be enabled in order to communicate with each other with high link capacity under a given power constraint. In addition, the rapid growth of multimedia services over wireless ad-hoc networks has led to an increase in demand for high link capacity [1,2].

Multiple-input and multiple-output (MIMO) techniques have been paid attentions as one of possible solutions to improve link capacity in wireless ad-hoc networks. However, it is impractical to apply MIMO techniques seamlessly to wireless ad-hoc networks because the system is designed for a specific application-based environment.

For this reason, the authors in [3,4] proposed a new cooperative beamforming technique, which is called virtual MIMO, by clustering single-antenna nodes. In conventional virtual MIMO multi-hop relay networks, the cluster is composed of adjacent nodes. In the cluster, the source node (SN) transmits a signal to the adjacent nodes that are located in the same cluster. This cluster then transmits the signal to a neighboring cluster. In each cluster, it is required that the master node (MN) collects the signals received from the adjacent nodes, decodes the symbol, and retransmits this symbol to the adjacent nodes. Therefore, there is additional time redundancy in collecting, decoding, and retransmitting at the MN. Moreover, in general, it is necessary for the MN to estimate the intra-cluster channel. Thus, the signaling overhead associated with the intra-cluster channel decreases the performance of the conventional virtual MIMO ad-hoc network. In addition, as the number of hops increases, the complexity of the conventional virtual MIMO system increases exponentially.

Recently, there exist some attempts to apply conventional multiple antennas applications to wireless ad-hoc networks owing to advances in manufacture of node architectures [5,6] so that virtual MIMO technology with multi-antenna nodes is being researched [7–10]. The problem of increasing complexity according to the number of hops has been one of major research issues in utilization of virtual MIMO technology for wireless ad-hoc networks using multi-antenna nodes [11–13]. Most studies on multi-hop relay networks with multi-antenna nodes assume that only a single node is considered for relaying the signal [14,15]. In addition, if the above schemes are applied to the virtual MIMO relay system,

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Table 1
Property description of the conventional and proposed schemes.

		MN	Transmit weight vector	Receive weight vector
Conventional Schemes	SVD BF	O	First right singular vector of the channel matrix	First left singular vector of the channel matrix
	M^2 BF	X	Construct based on GO M^2 BF	X
Proposed Schemes	VMBT-CEP		Construct based on GO M^2 BF w.r.t. receive weight vectors	Construct receive weight vector using CEP
	IA-VMBT			Construct receive weight vector using IA

the MN is required to exchange information with other nodes in the same cluster. After this data exchange, a conventional beamforming technique, e.g., singular value decomposition (SVD), can be applied to the multi-hop relay network. However, in this case, additional wireless resources should be allocated to the MN. This causes high signaling overhead and low time efficiency, leading to a decrease in the performance of the multi-hop relay network.

To reduce the complexity of the virtual MIMO relay system, we in [16] proposed a broadcast virtual MIMO system (BVMS). In the BVMS, there is no MN in the cluster; therefore, it is unnecessary to exchange the received signal in order to decode the symbol, as well as to estimate and feed back the intra-cluster channel to the MN. The simplicity of this signaling reduces the complexity and latency of the BVMS compared to conventional virtual MIMO systems. In addition, the max–min (M^2) beamforming (BF) technique has been proposed for the BVMS optimization in multi-hop relay networks. However, M^2 BF is designed for a limited environment in which each node is equipped with a single-antenna. In order to adapt MIMO technologies to ad-hoc networks, it is essential to cover the scenario in which each node is equipped with multiple antennas. In addition, designing the optimal receiver and transmitter in order to improve the end-to-end capacity in virtual MIMO systems is a new challenge. In general, while researchers in the area of virtual MIMO technologies have recognized the importance of this issue, no solid work has been presented. The design challenges include the difficulty of achieving both capacity improvement and networking simplicity, as well as the need to develop a novel network protocol architecture that provides the degree of freedom to enable the design of a new transceiver for multi-hop relay networks.

In this paper, we develop a framework comprising a virtual MIMO broadcasting transceiver (VMBT) designed for the BVMS when each node has multiple antennas. This framework seeks to improve the capacity of cooperative beamforming in multi-hop relay networks. In the generalized network architecture, each receive node composes a virtual multiple-input and single-output (MISO) channel by using a receive weight vector. Based on the virtual MISO channels, the transmit cluster constructs a transmit weight vector to maximize the link capacity. In particular, we show that the transmit weight vector of the cluster is tightly coupled with the operation of the receive weight vectors of the receive nodes for achieving the optimal transceiver design. The unique contributions of this paper are as follows:

- M^2 BF proposed in [16] is designed for a limited environment in which each node is equipped with a single-antenna. Therefore, there is limitation to applying M^2 BF to multi-hop relay network consisting of multiple antenna nodes. To overcome this limitation, we develop a framework of designing a transceiver as a generalization version of M^2 BF in which each node is equipped with multiple antennas.
- As a framework for designing the transceiver, we present an optimal VMBT as a closed form of the optimal solution based on the channel ellipse property (CEP) for a specific environment: the transmit cluster has two transmit antennas and two receive nodes, each with M receive antennas. In the VMBT based on the CEP (VBMT-CEP), the optimal transmit and receive weight vectors are obtained using the ellipse equations of the channel gains.
- For the general solution (more than two transmit antennas and receive nodes), we propose an iterative algorithm of the VMBT (IA-VMBT). This approach provides the benefit of simple networking protocol. That is, the receive nodes do not need to feed back their receive weight vectors to the transmit cluster in order to update the transmit weight vector; instead, the receive node only feeds back the channel state information (CSI).

In Table 1, the comparison between the conventional and proposed schemes are briefly summarized in terms of the MN, transmit weight vector and receive weight vector. In SVD BF, the MN in each cluster is required to collect the receive signal from the other nodes [11–13]. On the other hand, the BVMS-based schemes (M^2 BF, VMBT-CEP and IA-VMBT) do not require such signal collection by the MN since each cluster broadcasts the signal for relaying.

For SVD BF, the transmit weight vector is constructed using the first right singular vector of the channel matrix, which corresponds to the largest singular value. In [16], the transmit weight vector of M^2 BF relies on max–min (M^2) for link capacity maximization. VMBT-CEP and IA-VMBT construct the transmit weight vector with regard to the receive weight vector by employing GO M^2 BF, which maximizes the minimum link capacity of the virtual MISO channels.

The receive weight vector of SVD BF is the first left singular vector of the channel matrix corresponding to the largest singular value. M^2 BF only deals with nodes with a single-antenna, so there is no particular form of the receive weight vector. In contrast, VMBT is a generalized version of M^2 BF that extends the degree of freedom at each node by employing multiple antennas. Thus, as an optimal solution, VMBT-CEP constructs the receive weight vector utilizing the CEP, where the transmit and receive weight vectors are obtained simultaneously, according to the closed form equation. In addition, the receive weight vector of IA-VMBT is constructed using an iterative algorithm (IA), provided in Section 4.

The paper is organized as follows. Section 2 describes the system model for the BVMS in which each node is equipped with multiple antennas. In addition, the differences between the M^2 BF and proposed schemes are described. In Section 3, the proposed VMBT-CEP scheme which finds the optimal transmit and receive weight vectors as a closed form is described. For general cases, the proposed IA-VMBT scheme is described in Section 4. The simulation results are given in Section 5. Finally, Section 6 concludes this paper.