CITY UNIVERSITY OF HONG KONG
香港城市大學

Cooperative Strategies for Wireless Relay Channels under Slow Fading
慢衰落下無綫中繼信道的合作通信機制研究

Submitted to
Department of Electronic Engineering
電子工程系
in Partial Fulfillment of the Requirements
for the Degree of Doctor of Philosophy
哲學博士學位

by

Dai Mingjun
代明軍

May 2012
二零一二年五月

Abstract

Cooperative communication has the potential to provide better throughput and reliability to wireless systems when compared with direct communication. To realize the potential gain, it is important to design cooperative strategies for some representative scenarios. This thesis deals with three basic wireless relay channels, namely the parallel relay channel (PRC), the multiple-access relay channel (MARC), and the broadcast relay channel (BRC). For the first channel, which models a single unicast connection, various forwarding strategies are studied. For the second and third channels, which model, respectively, the uplink and downlink scenarios with multiple unicast connections, network codes are designed to exploit the possibility of coding among the connections. The common aim pertaining to the studies of all these three channels is to use the limited radio resource in the most efficient way.

This thesis starts with a comprehensive study of the PRC. Forwarding strategies for minimizing the end-to-end outage probability are investigated. For the special case of two relays, three cooperative schemes are proposed and their outage performance is compared with two analytical lower bounds. The first scheme, called Alamouti-Coded Amplify-Forward (ACAF), combines adaptive amplify-and-forward (AF) with the Alamouti space-time code. An optimal power control rule that minimizes the outage probability for this scheme is analytically derived. While ACAF with this optimal power control rule achieves full diversity order, its outage performance in the low signal-to-noise ratio (SNR) regime is poor due to noise accumulation at the relays. This problem can be remedied by using decode-and-forward instead, and the resultant scheme is called Alamouti-Coded Decode-Forward (ACDF). It is proven to achieve outage capacity to within one bit and within 50% for the whole SNR regime. To further narrow the performance gap, a scheme called Adaptive Decode-Forward Compress-Forward (ADFCF), which adaptively switches between DF and CF, is designed. There are four control parameters in ADFCF. An efficient alternating optimization method is proposed to optimize them. To compare the performance of these three schemes, computer simulations are conducted. Numerical

studies show that ACDF significantly outperforms ACAF in the low SNR regime, while ADFCF has the best performance for some fading scenarios. For the general case of more than two relays, only AF is considered due to its operational simplicity. It is combined with orthogonal space-time code, and an on-off power control rule, which can achieve full diversity, is proposed.

Next, relay-aided retransmissions for MARC are studied. Several network codes are designed for minimizing the average packet loss rate. For the special case where the relay is given one slot for retransmission, an optimal scheme with polynomial encoding and decoding complexity is found. For the general case where the relay is given multiple retransmission slots, three sub-optimal schemes are investigated and their performance is compared with two lower bounds. All these three schemes have polynomial encoding and decoding complexity. The first scheme, called Network Coding with Maximum Distance Separable code (NC-MDS), is proven to be asymptotically optimal in the high SNR regime. In the low SNR regime, however, NC-MDS is a poor choice. Another scheme, called Worst User First (WUF), which helps users who have poor channel conditions to retransmit uncoded packets, is proposed and is proven to be asymptotically optimal in the low SNR regime. To obtain the benefit from both NC-MDS and WUF, a hybrid between them is constructed and is shown to have good performance in the intermediate SNR regime.

Finally, relay-aided retransmissions for BRC are studied. Linear network code applied at the source or the relay is designed for minimizing the number of transmissions that is required to meet the requests of a number of users. In this problem, each user requests certain packets and has certain packets in cache. Hence, the problem studied is related to the so-called index coding problem. The major difference is that coded packets are cached and utilized, and the sender possesses coded packets which are linear combinations of the requested packets. The above generalizations ensure that the encoder design can be directly applied at the source or at the relay in BRC. To cope with this generalization, a two-step method is proposed. Firstly, the criterion that judges whether one transmission can meet the requests of each user in a group is derived. This group is called a coding group. An efficient algorithm is proposed in checking whether a set of users form a coding group and in constructing the coding for a coding group. Secondly, a heuristic algorithm is proposed to partition the users into disjoint coding groups. The number of transmissions required by this method is exactly the number of disjoint coding groups. Numerical studies show two things: First, the performance improvement of our algorithm upon existing scheme that utilizes only uncoded packets in cache is significant, over 10% for certain scenarios. Second, this performance improvement ratio increases as the number of users increases.

In summary, this thesis presents a comprehensive study on cooperative strategies for several basic wireless relay channels. For PRC, an outage capacity gap of one bit can be achieved for the two-relay case, and an efficient strategy is designed for the general case. For MARC and BRC, the benefit of adopting network codes in system design is demonstrated by construction of practical coding algorithms.

Contents

List of Figures

List of Tables

Abbreviations

AF	Amplify-and-Forward
AAF	Adaptive AF
ACAF	Alamouti-Coded Amplify-Forward
ACDF	Alamouti-Coded Decode-Forward
ADFCF	Adaptive Decode-Forward and Compress-Forward
AWGN	Additive White Gaussian Noise
BC	Broadcast Channel
BRC	Broadcast Relay Channel
CF	Compress-and-Forward
CSI	Channel State Information
CSIR	CSI available at the Receiver
CSIT	CSI available at the Transmitter
DF	Decode-and-Forward
DMT	Diversity-Multiplexing Tradeoff
DOSTBC	Distributed OSTBC
FGAF	Fixed Gain AF
FP	Full Power
GCOD	Generalized Complex Orthogonal Design
GF	Galois Field
GOD	Generalized Orthogonal Design
GROD	Generalized Real Orthogonal Design
IC	Index Coding
i.i.d.	Independent and Identically Distributed
MAC	Multiple-Access Channel
MARC	Multiple Access Relay Channel
MDS	Maximum Distance Separable
MIMO	Multiple-Input Multiple-Output
ML	Maximum Likelihood

NC	Network Coding
NP	Non-deterministic Polynomial-time
OOPC	On-Off Power Control
OPC	Optimal Power Control
OSTBC	Orthogonal STBC
PRC	Parallel Relay Channel
REF	Row Echelon Form
RREF	Reduced Row Echelon Form
RLNC	Random Linear Network Coding
SNR	Signal-to-Noise Ratio
STBC	Space-Time Block-Code
WUF	Worst User First

Notations

$(\cdot)^*$	Conjugate operation
$(\cdot)^T$	Transpose operation
$(\cdot)^\dagger$	Conjugate transpose operation
C	Capacity of a channel
$C(x)$	Capacity formula, $C(x) = \log_2(1 + x)$, x is the SNR
$(\cdot)^{(R)}$	Real part
$(\cdot)^{(I)}$	Imaginary part
$\Pr\{\cdot\}$	Probability
$\mathrm{E}[\cdot]$	Mathematical expectation
$\mathrm{tr}(\cdot)$	Trace operation
$\mathrm{Re}\{\cdot\}$	The real part
$\mathrm{Im}\{\cdot\}$	The imaginary part
$\|\boldsymbol{x}\|$	The Euclidean norm of vector $\boldsymbol{x}$
$\|\boldsymbol{X}\|_F$	The Frobenius norm of matrix $\boldsymbol{X}$
$\mathrm{diag}(\cdot)$	Diagonal matrix
$\mathcal{CN}(m, \delta^2)$	The circular symmetric complex Gaussian random variable with mean m and variance δ^2
$\mathrm{rank}(\boldsymbol{M})$	Rank of matrix $\boldsymbol{M}$
$\boldsymbol{I}_K$	$K \times K$ identity matrix
$\boldsymbol{e}_j$	The j-th natural basis column vector
$\binom{K}{n}$	K choose n