Cooperative Information Transmission in Wireless Networks

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Abstract — Mobile users data rate and quality of service are limited by the fact that they experience severe variations in signal attenuation, thereby necessitating the use of some type of diversity. Recently, user-cooperation diversity was introduced as an effective way of incorporating diversity in wireless networks. Diversity gains are possible via the cooperation of mobile users. In this paper, we consider channel codes that are capable of achieving the full diversity provided by user-cooperation. The codes continue to perform well, even when the inter-user channel is noisy, still offering significant improvements with respect to the non-cooperative case.

I. INTRODUCTION

Information transfer through wireless networks involves simultaneous communication among multiple source-destination pairs. In cellular systems, coordination of these multiple communications is done via the base station. The base station processes all the signals transmitted from the sources (uplink) and forwards them to their respective destinations (downlink). Ad-hoc networks on the other hand do not have a fixed infrastructure and utilize other mobiles as relays to transfer information from one source to its destination. Motivated by the diversity effects and power efficiency of communicating via relaying, recent research efforts have focused on the use of multi-hops/ad-hoc mode in the cellular architecture as well [3, 4, 6].

In the context of network information theory, the use of relays was first considered by Van der Meulen [1]. Capacity for the degraded relay channel was found by Cover and El Gamal [2]. The classical relay model consists of a source who wishes to communicate with a destination through the use of a relay. The relay receives the signal transmitted by the source through a noisy channel, processes it and forwards to the destination. The destination observes a superposition of the source and the relay transmissions. The relay does not have any information to send, hence the goal is to maximize the total rate of information flow from the source to the destination.

In wireless networks, unlike the classical model, the relay is another mobile who has its own information to transfer. One can then reformulate the problem as two or more mobiles, with each having its own data, cooperating through noisy fading links to achieve larger data rates [3]. This formulation is similar to a multiple access channel with generalized feedback, in which the users observe different corrupted and noisy versions of the transmitted signals. An achievable region for discrete memoryless multiple access channel with generalized feedback was found by Willems et. al. [5]. Sendonaris et. al. [3] showed that cooperating mobiles in a wireless network provide not only higher data rates, but also decreased sensitivity to channel variations. One can obtain spatial diversity through the use of this “virtual” antenna array even if the mobiles are connected via noisy links. Laneman et. al. [6] incorporated the fact, that in practice, the relaying mobile cannot receive and transmit at the same time, and illustrated that cooperation is still beneficial in reducing the outage probability. The approach to user-cooperation through orthogonal channels via time division multiplexing is given in Figure 1.

\[ \text{M1 Tx} - \text{M2 Tx} \]
\[ \text{N channel uses} \]
\[ \begin{array}{ccc}
\text{M1 Tx} & \text{M2 Tx} \\
N/2 & N/2 \\
\end{array} \]
\[ \text{M1 Tx} - \text{M2 Rx} \]
\[ \text{M2 Tx for M1} \]
\[ \text{M2 Tx for M1} \]
\[ \text{M1 Tx for M2} \]
\[ \begin{array}{ccc}
\text{N/4} & \text{N/4} & \text{N/4} \\
\end{array} \]

Figure 1: Time-division channel allocations: (a) simultaneous direct transmission, (b) orthogonal direct transmission and (c) orthogonal cooperative diversity transmission.

Laneman et. al. considered different protocols to achieve diversity gains such as amplify and forward or decode and forward. However, from a coding perspective these protocols resemble repetition coding, and there are more effective ways of designing channel codes. Hunter and Nosratinia [7] proposed the use of rate compatible punctured convolutional codes for the partnering mobiles. In this paper, we argue that an overall block fading channel model is appropriate, since users observe independently faded channels. This allows us to consider channel codes which are optimal in the presence of block fading.

Figure 2 illustrates the possible configurations of user-cooperation in an ad-hoc network and in a network with a fixed access point, which may be either a local area network (LAN) or a cellular system. In the first example user 1 cooperates with user 2 to transmit its message to user 3. Similarly, user 2 cooperates with user 1 to transmit its message to user 4. On the other hand in a network with a fixed access point both user 1 and user 2 cooperate to transmit their signals to the common access point (destination).

This paper is organized as follows. In the next section, we present the system model and review the design criteria for block Rayleigh fading channels. Section III describes the protocols suitable for user cooperation when channel coding is

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employed. Section IV presents the simulation results. Finally, the conclusions are given in section V.

II. THE SYSTEM MODEL

We consider a mobile communication system that employs one transmit and one receive antenna. The information bits are encoded by a channel encoder. The coded bits are multiplexed in order to be allocated to the cooperating users, so that the maximum possible diversity would be achievable. The multiplexed bits are passed through a serial to parallel converter, and are mapped to a particular signal constellation. At each time slot $t$, the output of the modulator is a signal $c_t$. The block diagram of the transmitter is given in Figure 3.

\begin{figure}
\centering
\includegraphics[width=0.5\textwidth]{transmitter_diagram.png}
\caption{The block diagram of the transmitter.}
\end{figure}

At time $t$ the received signal, denoted by $r_t$, is given by

$$r_t = \sqrt{E_s}\alpha_t c_t + \eta_t,$$

where the noise samples $\eta_t$ are modeled as independent samples of a zero mean complex Gaussian random variable with variance $N_0/2$ per dimension and $E_s$ is the energy per transmitted symbol. The coefficient $\alpha_t$ is the path gain from the transmit antenna to the receive antenna. We assume quasi-static fading. The path gains are constant during the transmission of any given user, but are independent from user to user, hence we can make an overall block fading assumption. We have Rayleigh fading, that is, the path gains $\alpha_t$ are modeled as samples of independent zero mean complex Gaussian random variable with variance 0.5 per dimension.

The block fading channel model, see [8] and references therein, is motivated by the fact that in many wireless systems, the coherence time of the channel is much longer than one symbol interval, resulting in adjacent symbols being affected by the same fading value. This model assumes that a codeword of length $N = FL$ spans $F$ blocks of length $L$, where the group of $F$ blocks is referred to as frame. The value of the fading in each block is constant and independent from other blocks. The independence assumption is realistic, provided we have sufficient separation in time, in frequency, or as in this case in space.

\section*{Coding for Block Fading Channels}

The problem of coding for block fading channels has been studied independently by Knopp and Humblet [9] and Malkamaki and Leib [10]. The pairwise error probability that codeword $c$ was decoded when codeword $c'$ was actually transmitted, over a block Rayleigh fading channel, may be upper bounded by [9]

$$P(c \rightarrow c') \leq \frac{1}{2} \left( \frac{1}{\Xi^2(c, c')E_s/4N_0} \right)^{d_H^P},$$

where

$$\Xi^2(c, c') = \left( \prod_{i=1}^{L} d_f^2(c, c') \right)^{1/d_H^P}.$$

The distance term $d_f^2(c, c') = \sum_{i=1}^{L} (c_{f,i} - c'_{f,i})^2$ denotes the squared Euclidean distance among the parts of the two codewords that experience the same fade during the fading block $f$. The number of non-zero Euclidean distances $d_f^2(c, c')$ is denoted by $d_H^P$. Note that $d_H^P$ represents the diversity the code achieves when used over a block fading channel with $F$ independently faded blocks.

Hence, the diversity and product distance criteria for channel codes over block fading channels are [9]

- **Diversity criterion:** Maximize the diversity advantage

$$d_H^P = \sum_{f=1}^{F} d_f^2(c, c')$$

over all pairs of distinct codewords $c, c' \in C$, where $I_X = 1$ if $X > 0$ and $I_X = 0$ if $X = 0$.

- **Product distance criterion:** Maximize the coding advantage

$$\Xi^2(c, c') = \left( \prod_{i=1}^{L} d_f^2(c, c') \right)^{1/d_H^P},$$

over all pairs of distinct codewords $c, c' \in C$.

This framework can be utilized to find channel codes that are suitable for user cooperation and that can obtain the full diversity provided by the cooperation of users. However, in this case the inter-user channel quality may vary, hence it is of interest to determine whether the codes would still provide improvements over the non-cooperative case even when the inter-user channel is noisy.

\section{III. COOPERATION PROTOCOLS}

In this section, we present the protocols that the mobile users can utilize during cooperation. We assume a time division scheme as presented in Figure 1. We first consider a fixed decode-and-forward protocol where the cooperation takes place all the time. Then, we propose an adaptive protocol where the cooperation between the mobiles takes places only when it is necessary, resulting in an increase of the users data rate.

\subsection*{Fixed Decode-and-Forward Protocol}

For decode-and-forward transmission, the mobiles partner receives the coded signal transmitted by the mobile and decodes it. Then it performs a CRC check [11] to determine
whether the received sequence matches the actual transmitted information sequence. If so, the partner re-encodes the data to obtain the best possible code (in combination with the original mobiles code) which achieves maximum possible diversity and coding gain in a block fading channel, as described in the previous section. If the transmission is not received successfully, as indicated by the CRC check, then the partner notifies the mobile about it, and the mobile transmits the rest of the coded bits (symbols) itself, instead of relying on cooperation from its partner. Note that, as far as the destination is concerned, it does not matter whether the transmission comes from the mobile or its partner, since the decoding algorithm remains unchanged. The only difference is in the achieved performance, i.e., diversity level.

Adaptive Protocol

Instead of the fixed protocol, it may be more advantageous to use an adaptive protocol. Since the initial transmission from the mobile will be received by the destination, it can decode the data and perform a CRC check to find out whether the bits were received successfully. If so, it can notify the mobiles, hence there would be no need for cooperation to take place. In this case the mobile could continue its transmission. This type of protocol is appealing since it may not be necessary to cooperate all the time. Cooperation would take place only when necessary, which would result in an increase of the mobiles data rate.

IV. Simulation Results

In this section we present the performance of the proposed cooperative coding scheme to illustrate the potential benefits. We assume a Rayleigh slowly-fading channel. Hence, we use the quasi-static model, where the fading coefficient remains the same for the duration of the entire frame for each user. Note, however that the users observe independently faded channels. Due to the slow fading, we assume perfect channel state information at the receiver. In the simulations we use a constraint length, \( K = 7 \), convolutional code with generator polynomials (161.135) in octal notation and BPSK modulation. This code was found in [9] as the best convolutional code of rate 1/2 for a block fading channel with two independently faded blocks per frame. This is an appealing solution due to the widespread use of the convolutional codes and the simple maximum likelihood decoding algorithm. The extensions to higher order modulations are also possible [9]. We will focus on the case of statistically similar networks, where all users experience similar fading statistics. We consider the case when both users communicate to a destination which is a fixed access point. As described in section II, we have a system with one antenna at each user and one antenna at the destination (access point). We present results for the fixed decode-and-forward protocol. We consider two scenarios based on the quality of each cooperating users channel to the destination. We first consider the case when both users channels to the destination are of similar quality. Then we focus on the case when one of the users has a better channel to the destination than the other. We will demonstrate that cooperation is beneficial in this case as well.

In the symmetric scenario, both users have channels of similar quality to the destination. Our goal is to study the performance of the cooperative coding scheme for various qualities of the inter-user channel. We demonstrate the performance in terms of the frame error rate (FER). Similar results could also be obtained in terms of the bit error rate.

From Figure 4, it can be observed that the cooperative coding scheme with perfect inter-user channel provides a performance improvement of about 4 dB at FER of \( 10^{-1} \), 8 dB at FER of \( 10^{-2} \) and about 12 dB at FER of \( 10^{-3} \). Note the graceful degradation in performance with the degradation of the inter-user channel quality and the gain with respect to the non-cooperative system. It is clear that the cooperative coding scheme achieves the full block fading diversity for moderate and low FER in the inter-user channel. When the inter-user channel quality is poor, resulting in a high FER, the diversity of the system is limited to the non-cooperative case. Nevertheless, we observe that there is still some coding gain with respect to the non-cooperative case, which results in performance improvements.

![Figure 4: Single user performance vs. two user cooperation, for different inter-user channel quality.](image)

We next focus on the asymmetric scenario. This happens when one of the users has a better channel to the destination than the other user. We consider this case by fixing one of the users channels to the destination at a relatively high signal to noise ratio. We then vary the quality of the other users channel to the destination and observe the performance of both cooperating users.

We consider the case when user one’s channel is fixed at 27 dB, which results in a frame error rate of \( 10^{-3} \) in the non-cooperative case. We vary the signal-to-noise ratio of user two. The inter-user channel frame error rate is 0.5. We observe from Figure 5 that even in this asymmetric scenario and a bad inter-user channel both users still benefit from cooperation. User one achieves the frame error rate of \( 10^{-3} \) when the signal-to-noise ratio of user two is about 13 dB. At higher signal-to-noise ratios its performance is better than in the non-cooperative case. Even with the limited degree of cooperation, due to the bad inter-user channel, user two still improves its performance by over 2 dB with respect to the non-cooperative case.

Hence, cooperative coding proves beneficial not only for users with similar channel qualities to the destination, but also in the case when the users have significantly different channel qualities. What is important to note is that both users benefit from cooperation.

Finally, we compare the performance in the symmetric vs. the asymmetric scenario and consider the effect of cooperative coding on packet routing and choice of partners. We envision
Figure 5: Single user performance vs. two user cooperation, for two users with different channel qualities.

Figure 6: Various cooperation scenarios.

Figure 7: Performance comparison for two user cooperation for symmetric and asymmetric source-destination channels.

V. CONCLUSIONS

In this paper we introduced the cooperative coding concept. This approach is useful due to the size limitations of the mobile units which prevent the use of transmit antenna diversity. The diversity that is available in the channel can be exploited by coding across the cooperating mobile users. We demonstrated that cooperative coding is beneficial for a wide range of scenarios, provides substantial improvements with respect to the non-cooperative coding approach and in fact can achieve the full increased diversity in the system provided by user-cooperation. We used the block fading model to provide a framework for the design of codes suitable for user cooperation. We demonstrated the usefulness of the cooperative coding approach through simulations where we considered various scenarios for the possible cooperation between mobile users. We found that cooperation proves beneficial when both users have similar, as well as different channel qualities to the destination. Cooperative coding is robust and provides gains with respect to the non-cooperative case, even when there is a severe degradation in the inter-user channel quality.

REFERENCES