COMPARATIVE ANALYSES OF CODED COOPERATIVE SCHEMES

L. Chen [1,*], R. A. Carrasco [1], I. J. Wassell [2], V. Ganepola [1]

[1] School of Electrical, Electronic and Computer Engineering, Newcastle University, UK

[2] Digital Technology Group, Computer Laboratory, University of Cambridge, UK

ABSTRACT

Cooperative communication is a spatial diversity technique that encourages users to assist each other for transmission. This creates a virtual multipath transmission to combat the effect of individual severe fading and path loss. There three main types of cooperative schemes: Amplify-and-Forward, Decode-and-Forward, and Coded Cooperation. This paper presents the convolutional coded signal model and comparative analyses for all the cooperative schemes. For comparison, our analyses will be focused on the cooperation percentage, diverse transmission feature reflected on a trellis, the distributed effect for the transmitted symbols of the Coded Cooperation schemes and the system complexity. It is shown that for Coded Cooperation, diverse received symbols are multiplexed and concatenated before decoding, while for the other two cooperative schemes diverse received symbols are directly combined. This helps the Coded Cooperation schemes to achieve a better diversity gain than other schemes. It is also revealed that for different level of Coded Cooperation, it will have different cooperation percentage and different distributed effect for the transmitted symbols. Depending on the quality of inter-user channel, one of the factors plays a more determinant role for the achievable diversity gains. Simulation results comparing all the coded cooperative schemes and analysing network topology are presented.

Keywords

Cooperative Communications, Diversity, Convolutional Code, Amplify-and-Forward, Decode-and-Forward, Coded Cooperation, Network Topology.

1. INTRODUCTION

Due to the effect of severe fading and path loss, spatial diversity technique is critical for a wireless network to have reliable communications. One of the well known spatial diversity techniques is to employ multiple transmit / receive antennas (MIMO) for users in the network [1]. This creates multiple transmission paths so that individual severe fading and path loss effect can be mitigated. However, due to some practical limitations, such as the size and cost, multiple antennas may not be practical to implement. An alternative solution to create spatial diversity is to encourage communication units equipped with single antenna to share their resources and assist each other for transmission. This can be simply described as one user "overhears" its partner's signal and "relays" it to its partner's intended destination. Since the transmission paths between different users are independent, this signal relaying creates a virtual multiple transmit antennas effect.

The earliest work of signal relaying can be traced back to Cover and El Gamal [2], in which capacity of the relay channel was derived. Laneman and Wornell [3, 4] presented some practical cooperative schemes: Amplify-and-Forward (AF) and Decode-and-Forward (DF). In the AF scheme, the cooperative user would amplify its overheard signal from its partner and re-transmit to the partner's intended destination. While in the DF scheme, the cooperative user still tries to decode and re-encode its partner's signal and re-transmit them to the partner's intended destination. Sendonaris et al. [5] implemented an effectively DF cooperative scheme in the Code-Division Multiple Access (CDMA) system. Later, Hunter and Nosratinia [6] as well as Stephanov and Erkip [7] proposed a new cooperative scheme in which signal relaying is integrated with channel coding design, called Coded Cooperation (CC). Similar as the DF scheme, cooperative user still tries to decode its partner's information. However, re-encoding is processed using a different encoder to generate extra parity bits, which results a lower rate code decoder in the destination. According to the level (percentage) of relaying transmission, the CC schemes can be further classified into CC (50%) and CC (25%). Both of the above cooperative schemes can achieve full diversity [4, 6]. In [8] a tutorial review of these cooperative schemes is given. While in [9], the authors presented a comparative investigation of all the existing schemes. This paper's work is based on [9], but with further extensive analyses.

In this paper, the signal model comparison of these three cooperative schemes is presented. They are incorporated in a coded system using non-recursive non-systematic convolutional codes [10]. Our comparative analyses for all the cooperative schemes include: the cooperation percentage, the diverse transmission feature reflected on a trellis, the distributed effect for the transmitted symbols of the CC schemes and the system complexity. In general, the difference between these three cooperative schemes can be represented by these four factors. For all the cooperative schemes, the achievable diversity gain is determined by the first three factors. Our simulation results show the CC schemes produce the best diversity gain. For the CC schemes itself, lower level of cooperation performs better in poor or moderate quality inter-user channel scenario, since it has a higher cooperation

*Corresponding author: *E-mail:* li.chen@newcastle.ac.uk

 ISSN: 1744-2397

percentage. However, in good quality inter-user channel scenario, higher level of cooperation performs better, since it has a better distributed effect for the transmitted symbols. A cooperative network topology analysis is also presented, showing the priority order to quality of the channels within the cooperative network.

The rest of the paper is organised as follows: Section 2 presents the common transmission signal model of all the cooperative schemes. Section 3 presents the three coded cooperative schemes. Section 4 presents the comparative analysis. Section 5 presents the simulation results. Finally, conclusions of the paper are given in Section 6.

2. TRANSMISSION SIGNAL MODEL

The cooperative network consists of three nodes: source (s), relay (r) and destination (d). Both source and relay share the same transmitting destination, and transmit using different carrier frequency to avoid interference with each other. In this paper, it is assumed the full-duplex system is employed so that simultaneous transmission and detection are achievable. The channels between source / relay to destination are called *uplink channels*; while the channels between source and relay are called *inter-user channels* which are assumed to be reciprocal in this paper. Its signal model can be described by a two time slots structure, shown by Fig. 1a. $x_s[n]$ and $x_r[n]$ are the transmitted signal from source and relay respectively. As the cooperative schemes are analysed in a coded system, $x_s[n]$ and $x_r[n]$ are the modulated symbols of a valid code word. Also notice that A and A' denote the first and second time slot signals / coefficients respectively.

Due to the symmetric transmission status between source and relay, in this paper, the transmission of source signal $x_s[n]$ and decoding of source information will be focused on. In the first time slot, source transmits $x_s[n]$ to relay and destination as:

$$y_{sr}[n] = \sqrt{\varepsilon}\, a_{sr} x_s[n] + z_{sr}[n] \tag{1}$$

$$y_{sd}[n] = \sqrt{\varepsilon}\, a_{sd} x_s[n] + z_{sd}[n] \tag{2}$$

where $n = 1, 2, \ldots, N_1$, and N_1 is a positive integer indicating the length of the transmitted signal in the first time slot.

Based on the "overheard" signal $y_{sr}[n]$ of source transmission in the first time slot, relay generates signal $x'_r[n]$ to be transmitted to the destination in the second time slot as:

$$y'_{rd}[n] = \sqrt{\varepsilon}\, a_{rd} x'_r[n] + z'_{rd}[n] \tag{3}$$

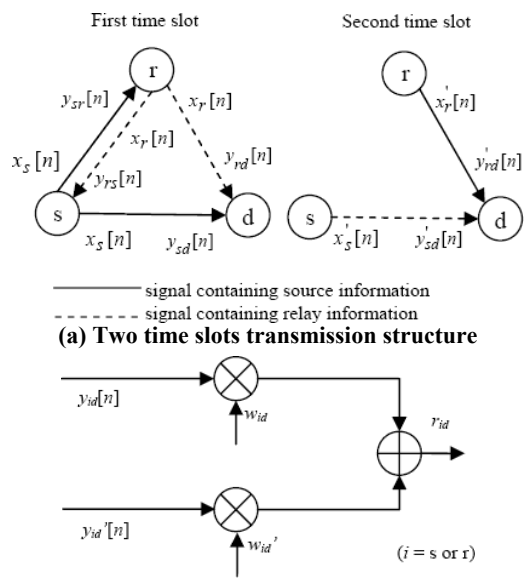
where $n = 1, 2, \ldots, N_2$, and N_2 is a positive integer indicating the length of the transmitted signal in the second time slot. The way to obtain $x'_r[n]$ from $y_{sr}[n]$ depends on the cooperative scheme, which will be discussed in Section 3.

In Eq. (1) to (3), ε is the energy per transmitted symbol. a_{sd} and a_{rd} are the fading coefficients of the uplink channels, a_{sr} is the fading coefficient of the inter-user channel. a_{sd}, a_{rd} and a_{sr} are zero-mean, mutually independent complex Gaussian variables with variances σ_{sd}^2, σ_{rd}^2 and σ_{sr}^2 respectively. As slow fading is assumed in our analysis, a_{sd}, a_{rd} and a_{sr} are constant during the two time slots and change independently after every two time slots. The additive noise $z_{sd}[n]$ ($z'_{sd}[n]$), $z_{rd}[n]$ ($z'_{rd}[n]$), and $z_{sr}[n]$ ($z'_{sr}[n]$) are modelled as zero-mean, mutually independent, complex Gaussian sequence with variances $N0_{sd}$, $N0_{rd}$ and $N0_{sr}$ respectively. The instantaneous channel Signal-to-Noise Ratio (SNR) is defined as:

$$\gamma_{ij} \overset{\Delta}{=} |a_{ij}|^2 \varepsilon / N0_{ij} \quad \left(i = s, r \text{ and } j = r, d, \text{ but } i \neq j\right) \tag{4}$$

Further, the expected value of channel SNR is defined as:

$$\overline{\gamma_{ij}} \overset{\Delta}{=} E[\gamma_{ij}] = E[|a_{ij}|^2]\varepsilon / N0_{ij} = \sigma_{ij}^2 \varepsilon / N0_{ij} \tag{5}$$



(a) Two time slots transmission structure

(b) Optimal combiner at the destination

Figure 1. Cooperative signal model

At the destination, the received signals in the two time slots are combined using the optimal combiner shown by Fig. 1b. In order to design the optimal combining gains w_{id} and w'_{id} for the incoming signals in the first and second time slots, perfect Channel State Information (CSI) of the three node network is assumed to be available at the destination. The destination obtains the perfect CSI by receiving the pilot symbols sent by the source and relay periodically. The combined received signal rid is passed to a decoder in order to retrieve the information of a user. Again, the design of w_{id} and w'_{id}, and the way to obtain rid through the optimal combiner depend on the cooperative schemes and the transmission status, which will be discussed later.

If the first and second time slots are with equal duration, from the above analysis it can be seen that the information throughput of each individual user is half of that in direct transmission due to half of the total transmission time is used for relaying (the second time slot). In a coded cooperative system, in order to maintain the identical information throughput for each user as in direct transmission, it could either employ a higher rate code or a higher order modulation scheme. This paper adopts the first strategy while the second strategy is analysed in paper [11].

3. CODED COOPERATIVE SCHEMES

This section presents a signal model comparison of the three cooperative schemes in a coded system by using non-recursive non-systematic convolutional codes. The decoder is implemented by using soft-decision Viterbi decoding algorithm [12].

3.1 Coded Amplify-and-Forward

Assuming that convolutional code C_1 is employed in the AF scheme, modulated symbols of source $x_s[n]$ are transmitted to both relay and the destination in the first time slot, as shown by Eq. (1) and (2). Relay amplifies its received signal $y_{sr}[n]$ as:

$$x'_r[n] = \beta y_{sr}[n] \tag{6}$$

and

$$\beta = (|a_{sr}|^2 \varepsilon + N0_{sr})^{-1/2} \tag{7}$$

$x'_r[n]$ is transmitted to the destination in the second time slot. The received signals of these two time slots are optimally combined as [3]:

$$r_{sd}[n] = w_{sd} y_{sd}[n] + w'_{rd} y'_{rd}[n] \tag{8}$$

and the combining gains w_{sd} and w'_{er} are

$$w_{sd} = \frac{a^*_{sd}\sqrt{\varepsilon}}{N0_{sd}},\ w_{rd}' = \frac{a^*_{rd}\beta a^*_{sr}\sqrt{\varepsilon}}{|a_{rd}|^2 \beta^2 N0_{sr} + N0_{rd}} \tag{9}$$

$r_{sd}[n]$ is then passed to the decoder of code C_1 to retrieve the source information.

3.2 Coded Decode-and-Forward

Different to the coded AF scheme, instead of simply amplifying the received symbols of the first time slot, relay tries to decode source information. They will be re-encoded and modulated before being transmitted to the destination in the second time slot. There exist non-selective and selective coded DF schemes. For the non-selective coded DF scheme, the relay will always transmit an estimation of the source transmitted symbols to the destination no matter whether it can decode correctly or not. For the selective coded DF, the relay will transmit its estimation of the source transmitted symbols only if it can decode source information correctly (confirmed by Cyclic Redundancy Check (CRC) code). Otherwise, relay will retransmit its own symbols in the second time slot. Analyses in [4] showed that selection is necessary for the system to achieve diversity gains. Therefore, this paper employs the selective coded DF scheme by using code C_1. As it is slow fading and there is no amplification effect, for the coded DF scheme, the optimal combining gains for the first and second time slot incoming signals are:

$$w_{sd} = w_{sd}' = \frac{a^*_{sd}\sqrt{\varepsilon}}{N0_{sd}}, w_{rd} = w_{rd}' = \frac{a^*_{rd}\sqrt{\varepsilon}}{N0_{rd}} \tag{10}$$

Depending on the decoding status of source and relay after the first time slot, there are four possible transmission scenarios in the second time slot:

Scenario 1: *Both source and relay decode the information of their partners successfully*. In the second time slot, relay (source) will transmit the signal of source (relay) to the destination. As correct information has been retrieved, accurate estimation of their partner's first time slot transmission can be achieved as:

$$x'_r[n] = x_{sr}[n] \tag{11}$$

In order to decode source information at the destination, the received signal of these two time slots can be obtained by the optimal combiner as:

$$r_{sd}[n] = w_{sd} y_{sd}[n] + w'_{rd} y'_{rd}[n] \tag{12}$$

Scenario 2: *Source decodes the information of relay, while relay does not decode the information of source*. In the second time slot, both source and relay will transmit the signal of relay. In order to decode the information of source after two time slots, destination can only employ the received symbols from source in the first time slot as:

$$r_{sd}[n] = w_{sd} y_{sd}[n] \tag{13}$$

Scenario 3: *Relay decodes the information of source, while source does not decode the information of relay*. In the second time slot, both source and relay will transmit the signal of source as:

$$x'_r[n] = x_s[n], \text{and}\ x'_s[n] = x_s[n] \tag{14}$$

In order to decode the information of source after these two time slots, the received symbols are obtained as:

$$r_{sd}[n] = w_{sd} y_{sd}[n] + w'_{sd} y'_{sd}[n] + w'_{rd} y'_{rd}[n] \tag{15}$$

Scenario 4: *Neither source nor relay decodes the information of their partner*. Therefore, in the second time slot, source and relay will retransmit their own signal:

$$x'_s[n] = x_s[n] \tag{16}$$

In order to decode the information of source, the received symbols of the two time slots are obtained as:

$$r_{sd}[n] = w_{sd} y_{sd}[n] + w'_{sd} y'_{sd}[n] \tag{17}$$

From the above analysis it can be seen that, the destination should have knowledge of the transmission status of this three nodes network over the two time slots, so that it can adapt its optimal combiner to obtain the received symbols. The received symbols $r_{sd}[n]$ are again passed to a decoder of code C_1. The same process described above can be symmetrically applied to relay.

3.3 Coded Cooperation

The CC scheme is an advanced generation of the selective DF scheme. In the CC scheme, instead of using the same encoder (C_1 in coded DF) to generate a repetition signal of its partner when cooperation is encouraged, it uses a different encoder (C_2) to generate extra parity bits for its partner. This distributed coding design results in a different decoder structure at the destination. As extra parity bits are transmitted, the decoder structure is determined by C_1 and C_2. To achieve a full diversity gain, C_1 shall serve the purpose of guaranteeing the inter-user channel transmission, while C_2 shall serve the purpose of good performance of the overall code (C_1, C_2) in the cooperative fading channel.

Again, depending on the decoding status of source and relay after the first time slot, the four possible transmission scenarios discussed in Section 3.2 will apply. For brevity, they will be analysed with emphasis on their differences to the coded DF scheme. The optimal combining gains at the destination are the same as the coded DF defined by Eq. (10).

Scenario 1: Relaying transmission in the second time slot ($x'_r[n]$, $x'_s[n]$) is generated by encoding the information of their partners using the C_2 encoder. At the destination, instead of simply combining the received symbols from the two time slots as shown by Eq. (12), they are multiplexed and concatenated as:

$$r_{sd}[n] = (w_{sd} y_{sd}[n] + w'_{rd} y'_{rd}[n]) \tag{18}$$

The length of the symbols $r_{sd}[n]$ is $N_1 + N_2$. $r_{sd}[n]$ is passed to a decoder of code (C_1, C_2) in order to decode the information of source.

Scenario 2: For this scenario, the signal of source is not transmitted in the second time slot. Received symbols $r_{sd}[n]$ has length N_1 and will be decoded by a decoder of code C_1.

Scenario 3: The transmission of both source and relay in the second time slot ($x'_s[n]$, $x'_r[n]$) will be generated by encoding the information of source using the C_2 encoder. The received symbols of the second time slot from source and relay will be combined together, then multiplexed and concatenated with the received symbols from of the first time slot as:

$$r_{sd}[n] = (w_{sd} y_{sd}[n], w'_{sd} y'_{sd}[n] + w'_{rd} y'_{rd}[n]) \tag{19}$$

$r_{sd}[n]$ has length $N_1 + N_2$ and to be decoded by the decoder of code (C_1, C_2).

Scenario 4: Source and relay will generate their retransmission ($x'_s[n]$, $x'_r[n]$) by encoding their own information using the C_2 encoder. The received symbols are multiplexed and concatenated as:

$$r_{sd}[n] = (w_{sd} y_{sd}[n], w'_{sd} y'_{sd}[n]) \tag{20}$$

$r_{sd}[n]$ has length $N_1 + N_2$ and will be decoded by the decoder of code (C_1, C_2).

For the CC scheme, according to different transmission scenarios, the destination should not only adapt its way to obtain the received symbols but also adapt its decoder structure. Summarizing these four scenarios for both coded DF and CC schemes, for source, diversity gains will be achieved when *Scenario 1 and 3* happen. For relay, it is *Scenario 1* and 2. *Scenario 4* is identical to direct transmission with no diversity gain for both users.

As the CC scheme is not a recurrence cooperative protocol, the transmission lengths N1 and N2 of the first and second time slots can be different, which will depend on the encoder structure of C_1 and C_2. This encourages the use of another parameter for the CC scheme: level of cooperation which is defined as $N_2/(N_1 + N_2)$ [6]. Level of cooperation indicates the percentage of relaying signals in a two time slots transmission. In this paper, CC (50%) and CC (25%) will be investigated.

4. COMPARATIVE ANALYSES

Based on the above description, this section will present the comparative analyses of these coded cooperative systems, including the cooperation percentage, diverse transmission feature reflected on a trellis, the distributed effect for the transmitted symbol of the CC schemes and the system complexity. In the following analyses, it is assumed that for coded AF, coded DF and CC (50%), C_1 is a rate 1/2 $(31, 27)_8$ convolutional code. This code achieves a good coding gain over the inter-user fading channel [6]. For CC (50%), C_2 is rate 1/2 $(35, 33)_8$ convolutional code. For CC (25%), C_1 and C_2 are rate 1/3 $(31, 27, 35)_8$ and rate 1 $(33)_8$ convolutional code respectively. For the CC schemes, each information bit is encoded into four coded bits. For example, in the CC (50%), two coded bits generated by the source and two coded bits generated by the relay. In the CC (25%), three coded bits generated by the source and one coded bit generated by the relay. Therefore, the overall code rate of the CC scheme is 1/4. The rate 1/4 $(31, 27, 35, 33)_8$ convolutional code achieves a good coding gain for cooperative fading channel. In order to compare with direct transmission under the constraints of identical information throughput and power consumption, direct transmission result is obtained by using rate the 1/4 $(31, 27, 35, 33)_8$ convolutional code. For all the simulations, the length of information is 128 bits and Binary Phase Shift Keying (BPSK) modulation scheme is employed.

4.1 Cooperation Percentage

From Section 3, it can be seen that both coded DF and CC schemes are selective cooperative schemes, for which cooperation of the second time slot is based on the successful transmission of the first time slot. While for the coded AF scheme, it is a constant cooperative protocol since no decoding is required after the first time slot transmission. Therefore, for the selective cooperative schemes, we define another parameter called cooperation percentage. It represents the percentage of the cooperative scenarios (*Scenarios 1, 2, and 3*) within all the cooperation attempts. For code DF and CC schemes, a higher cooperation percentage results in a better diversity gain. Here we further define:

Full cooperation: both users assist their partners to transmit signal in the second time slot (*Scenario 1*);

Partial cooperation: only one user assists its partner to transmit signal in the second time slot while the other user transmits its own signal (*Scenario 2 and 3*).

The cooperation percentage (full, partial and full) for coded DF, CC (50%) and CC (25%) are measured against the quality of inter-user channel and presented in Fig. 2.

As the quality of inter-user channel improves, there are more successful first time slot transmissions. As a result, the cooperation percentage will improve correspondingly as

shown in Fig. 2. As coded DF and CC (50%) use the same code C_1 = (31, 27)$_8$ for the first time slot transmission, their percentages of cooperation remain similar. However, for CC (25%), C_1 = (31, 27, 35)$_8$ which has better error-correction capability is employed and it results in improved first time slot transmission. Therefore, higher cooperation percentage is achieved. For example, at 6dB inter-user channel, CC (25%) can achieve 89% of cooperation while CC (50%) and coded DF can achieve 82% of cooperation. This difference of cooperation percentage is more significant in low quality inter-user channel scenario. As the quality of inter-user channel improves, the cooperation percentage difference between CC (25%) and CC (50%) / coded DF becomes less significant. When $\overline{\gamma_{sr}}$ = 16dB, they merge to a similar value of 98%.

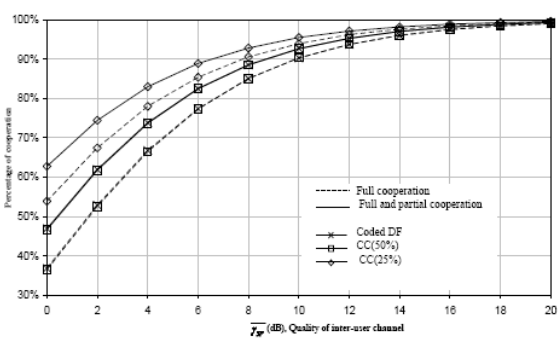


Figure 2. Cooperation percentage analysis

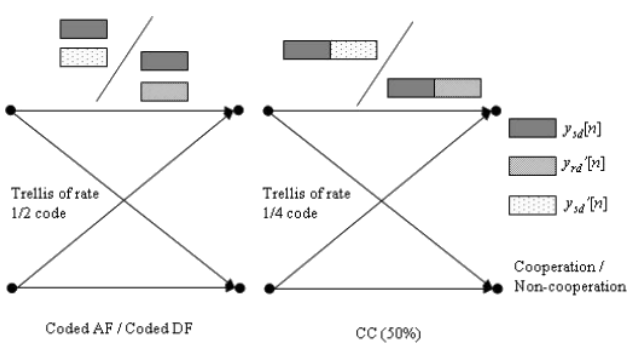


Figure 3. Diverse transmission features of the cooperative schemes reflected on a trellis

4.2 Diverse Transmission Feature Reflected on a Trellis

The main advanced feature of the CC schemes is that they are not a repetition transmission protocol. For the CC schemes, the second time slot transmission of a cooperative user is achieved by employing a different encoder to generate extra parity bits. As a result, the diverse received symbols at the destination are multiplexed and concatenated as shown by Eq. (18) to (20), rather than being directly combined as shown by Eq. (8), (12), (15) and (17). This diverse transmission reflected on a trellis can be shown in Fig. 3 where it can be seen that for the coded AF and coded DF schemes, a rate 1/2 trellis is resulted. While for the CC schemes, rate 1/4 trellis is resulted. Therefore, for the CC schemes, the decoder employed in the destination will be different to the decoder employed at the cooperative users. This extra parity bits transmission can adaptively guarantee the overall cooperative fading channel transmission. As a result, the CC schemes can outperform the coded AF and coded DF schemes which will be shown by Section 5. However, it is worthy to mention that this performance advantage is achieved by sacrificing the system complexity, which will be discussed by Section 4.4.

4.3 Distributed Effect for the Transmitted Symbols of the Coded Cooperation Schemes

The analysis of Section 4.1 shows that CC (25%) has higher cooperation percentage than CC (50%). However, this does not guarantee CC (25%) will outperform CC (50%). The other parameter that affects their performance is the distributed nature for the transmitted symbols, which is not the same for these two schemes. For example, for full cooperation with CC (50%), half of the user's symbols are transmitted via its own uplink channel while the other half are transmitted via its partner's uplink channel. For CC (25%), 75% and 25% of a user's symbols are transmitted through its own and partner's uplink channels respectively. Therefore, cooperative diversity produces a different distributed effect to the transmitted symbols. To analyze this distributed effect, the Pairwise Error Probability (PEP) [13] is referred to. If d_s and d_r denote the error event bits in a user's received word through the uplink channel transmissions of source and relay respectively, and $d_s + d_r = d$, under full cooperation, the PEP value for both users can be bounded by [6]:

$$P(d)_f \le \frac{1}{2}\left(\frac{1}{1+d_s\overline{\gamma_{sd}}}\right)\left(\frac{1}{1+d_r\overline{\gamma_{rd}}}\right) \tag{21}$$

Under partial cooperation, the PEP value for source in *Scenario 3* can be bounded by [6]:

$$P(d)_p \le \frac{1}{2}\left(\frac{1}{1+d\overline{\gamma_{sd}}}\right)\left(\frac{1}{1+d_r\overline{\gamma_{rd}}}\right) \tag{22}$$

Similar to Eq. (22), the PEP value for relay in *Scenario 2* is straight forward to be derived.

To compare the PEP values of CC (50%) and CC (25%), symmetric uplink transmission is assumed so that $\overline{\gamma_{sd}} = \overline{\gamma_{rd}} = \overline{\gamma}$. For CC (50%), as equal amount of symbols are transmitted through both users' uplink channels, $d_s \cong d_r \cong d/2$ is assumed. Based on Eq. (21), under full cooperation:

$$P(d)_f \le \frac{1}{2}\left(\frac{1}{1+\frac{d\overline{\gamma}}{2}}\right)\left(\frac{1}{1+\frac{d\overline{\gamma}}{2}}\right) = \frac{2}{4+4d\overline{\gamma}+d^2\overline{\gamma}^2} \tag{23}$$

Based on Eq. (22), under partial cooperation:

$$P(d)_p \le \frac{1}{2}\left(\frac{1}{1+d\overline{\gamma}}\right)\left(\frac{1}{1+\frac{d\overline{\gamma}}{2}}\right) = \frac{1}{2+3d\overline{\gamma}+d^2\overline{\gamma}^2} \quad (24)$$

For CC (25%), $d_s \cong 3d/4$ and $d_r \cong d/4$ are assumed. Then based on Eq. (21), under full cooperation:

$$P(d)_f \le \frac{1}{2}\left(\frac{1}{1+\frac{3d\overline{\gamma}}{4}}\right)\left(\frac{1}{1+\frac{d\overline{\gamma}}{4}}\right) = \frac{2}{4+4d\overline{\gamma}+\frac{3d^2\overline{\gamma}^2}{4}} \quad (25)$$

Based on Eq. (22), under partial cooperation:

$$P(d)_p \le \frac{1}{2}\left(\frac{1}{1+d\overline{\gamma}}\right)\left(\frac{1}{1+\frac{d\overline{\gamma}}{4}}\right) = \frac{1}{2+\frac{5d\overline{\gamma}}{2}+\frac{d^2\overline{\gamma}^2}{2}} \quad (26)$$

From the above derivation, it can bee seen that under both full and partial cooperation, the CC (25%) has higher PEP upper bound than the CC (50%). This is due to its unequal distributed effect for the transmitted symbols. Summarizing the above analyses, CC (25%) encourages higher cooperation percentage, while CC (50%) has a better distributed effect for its transmitted symbols. Simulation result discussion of Section 5 will show depending of the quality of inter-user channel, one of the factors plays a more important role for the achievable diversity gain.

4.4 System Complexity

Comparing the system complexity of all the cooperative schemes, coded AF is the simplest one to implement. In coded AF, cooperative users are not required to decode the information of their partners. Instead, a cooperative user would only amplify its overheard signal and re-transmit it to the destination. This would reduce the processing time during cooperation. Compared with the coded AF scheme, the coded DF scheme does require cooperative users to decode and re-encode the information of their partners. Also, information about the decoding status after the first time slot shall be exchanged between cooperative users, in order to let the cooperative users decide their transmission in the second time slot. Among all the cooperative schemes, the CC schemes require the most system complexity. A cooperative user not only performs decoding / re-encoding for its partner, but also employs a different encoder for the two time slots transmissions. More importantly, the destination shall adapt its decoder structure according to the decoding status of the first time slot. As discussed in Section 3.3, in order to decode source information, the destination should either employ a rate 1/4 $(31, 27, 35, 33)_8$ convolutional code decoder if *Scenarios 1, 3, or 4* happens, or employs a rate 1/2 $(31, 27)_8$ convolutional code decoder if *Scenario 2* happens. If the same amount of information bits is to be retrieved, the rate 1/4 decoders would cost more processing time than the rate 1/2 decoder. Therefore, the CC schemes have the most system complexity.

5. SIMULATION RESULTS

This presents the authors' simulation result of all the coded cooperative systems. They are simulated under both the symmetric uplinks scenario for which $\overline{\gamma_{sd}} = \overline{\gamma_{rd}}$ and the asymmetric uplinks scenario for which $\gamma_{sd} \ne \gamma_{rd}$. Also, a network topology analysis is shown to indicate the priority order for the quality of the three channels within a cooperative network.

5.1 Symmetric Uplinks

The performance comparison between all the coded cooperative schemes under symmetric uplink scenario is shown in Fig. 4. It can be seen that all the coded cooperative schemes achieve significant diversity gains over direct transmission. The diversity gain improves as the quality of inter-user channel improves.

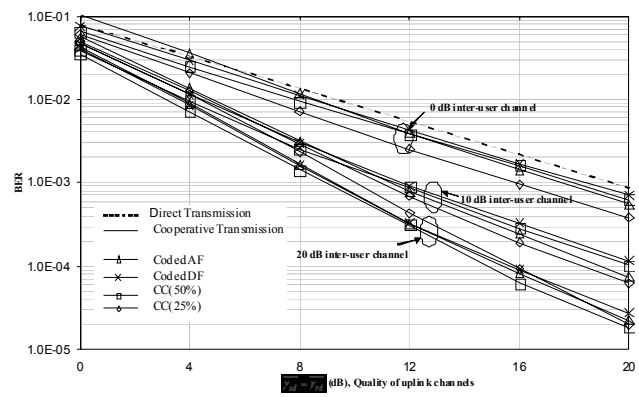


Figure 4. Performance comparison under symmetric uplinks

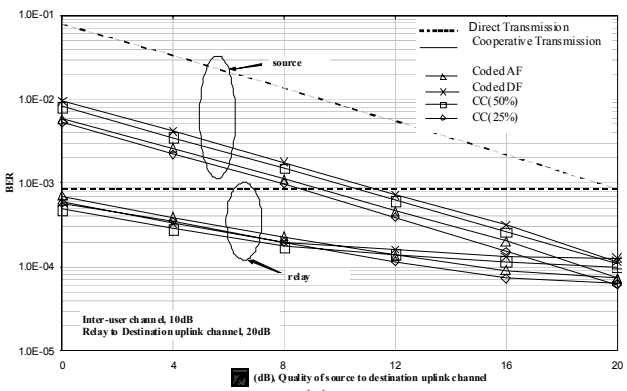
Comparing the results of all the coded cooperative schemes, the CC schemes outperform both coded AF and coded DF schemes. This illustrates that integrating cooperative transmission with coding design, which results extra parity bits being transmitted in the second time slot is better than simple repetition transmission. According to Section 4.2, this extra parity bits transmission results a different diverse transmission feature reflected on a trellis as shown in Fig. 3. As a result, a different decoder will be employed at the destination. Our simulation results indicate that multiplexing and concatenating the received symbols can produce better diversity gains than directly combining the received symbols. However, for the CC schemes, its performance advantage is also on the expanse of system complexity.

Comparing CC (50%) with CC (25%), CC (25%) outperforms CC (50%) in poor (0dB) or moderate (10dB) quality inter-user channel scenario. This indicates under these circumstances, having higher cooperation percentage plays a more important role in performance improvement. However, when the inter-user channel quality is sufficiently good (20dB), CC (50%) outperform CC (25%). Referring to Fig. 2, when the inter-user channel is 20dB, the percentages of cooperation for CC (50%) and CC (25%) are similar. Since CC (50%) has a better distributed effect for the transmitted symbols as shown by Section 4.3, it can outperform CC (25%). Among all, the coded AF scheme produces the second most favorable result due to its constant cooperation and amplification features.

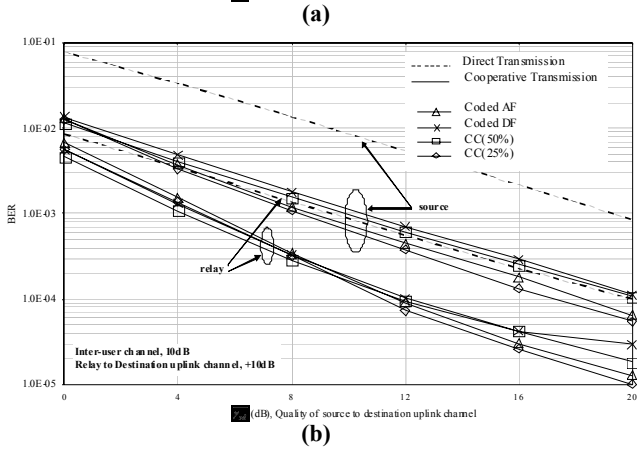
5.2 Asymmetric Uplinks

Fig. 5a and 5b show the performance comparison of all the coded cooperative schemes under asymmetric uplinks. For both of the simulations, the quality of inter-user channel is 10dB and the bit error rate (BER) performance is measured against the quality of source's uplink channel. For Fig. 5a, the quality of relay's uplink channel is fixed as 20dB. For Fig. 5b, the quality of relay's uplink channel is always 10dB higher than the source's uplink channel.

From Fig. 5, it can be observed that while the cooperative users have unequal uplink channels, both the users with poorer and stronger uplink channels will benefit from cooperation. Similar to the symmetric uplink scenario, when the inter-user channel quality is of 10dB, CC (25%) will produce the most favorable result.



(a)

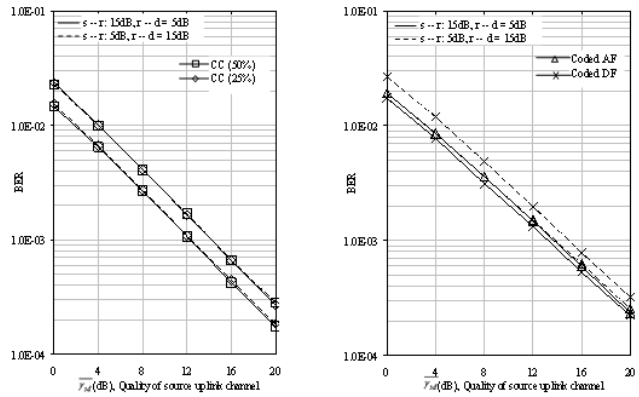


(b)

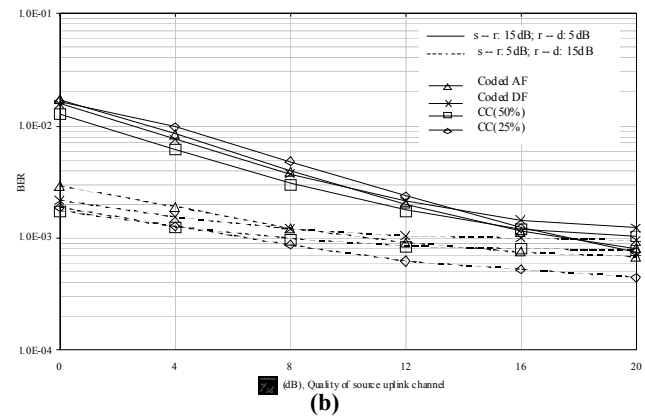
Figure 5. Performance comparison under asymmetric uplinks

5.3 Network Topology

In this subsection, the cooperative network topology will be analysed based on our simulation results. The priority order for the quality of the three channels within the network will be concluded. Two network scenarios are proposed and compared. First, there exists a strong inter-user channel with quality of 15dB, but a weak relay's uplink channel with quality of 5dB. Second, there exists a strong relay's uplink channel with quality of 15dB, but a weak inter-user channel with quality of 5dB. The BER performance of source and relay are measured against the source's uplink channel quality under these two scenarios. Notice that for these two scenarios, the average quality of the inter-user channel and the relay's uplink channel remains similar.



(a)



(b)

Figure 6. Network topology analyses of the cooperative schemes

Fig. 6a shows the performance comparison of source under these two scenarios. It can be seen that for the CC (50%) and coded DF schemes, having a strong inter-user channel can produce better diversity gain than having a strong relay's uplink channel. But for CC (25%), having a strong relay's uplink channel is preferred. For the coded AF scheme, similar performance is given under these two scenarios. As discussed in Section 4.1, CC (25%) achieves a higher cooperation percentage than CC (50%) and coded DF, while coded AF remains constant cooperation. Observing from Fig. 2, for CC (25%), the differences of cooperation percentage between 5dB and 15dB inter-user channels is not as significant as the differences for the CC (50%) and the coded DF. For CC (25%), even though at 5dB inter-user channel, it can still achieve 84% of full and partial cooperation. In this case, CC (25%) would prefer to have a strong relay's uplink channel to guarantee its transmission quality in the second time slot. But for CC (50%) and coded DF, at 5dB inter-user channel, they could only achieve 77% of full and partial cooperation. Therefore, good quality inter-user channel is preferred in order to improve the cooperation percentage in the second time slot. Since the coded AF scheme is constant cooperation, as far as the average quality of the inter-user channel and partner's uplink channel remains similar, similar performance will be resulted from the two scenarios.

Fig. 6b shows the performance of relay under these two scenarios for all the cooperative schemes. It can be easily observed from Fig. 6b that for relay, it would prefer to have a strong uplink channel rather than a strong inter-user channel.

Its performance improves as source's uplink channel quality improves.

Summarizing the above discussion, it could be concluded that within a cooperative network, cooperative user would prefer to have a strong uplink channel to guarantee its transmission. For the inter-user channel and the partner's uplink channel, the CC (50%) and coded DF schemes would prefer to have a strong inter-user channel while the CC (25%) scheme would prefer to have a strong partner's uplink channel. For coded AF scheme, having a strong inter-user channel and having a strong partner's uplink channel produce similar diversity gain.

6. CONCLUSIONS

This paper has presented a convolutional coded signal model and comparative analyses for all the cooperative schemes. Our analyses showed that for all the selective cooperative schemes, CC (25%) achieves the highest cooperation percentage. For the CC schemes, extra parity bits are transmitted in the second time slot and at the receiver they are multiplexed and concatenated. This results a lower rate decoder at the destination. Our simulation results showed that this diverse transmission feature produces better diversity gains than the repetitive cooperation schemes. Comparing the CC (25%) and CC (50%) schemes, the CC (25%) scheme produces a better diversity gain in poor or moderate quality inter-user channel. When the quality of inter-user channel is good, the CC (50%) scheme produces a better diversity gain since it has a better distributed effect for the transmitted symbols. However, our analyses also showed that the performance advantage of the CC schemes is on the expanse of higher system complexity. A network topology study has also been presented, showing one should have a good uplink channel for reliable transmission. For the quality of the inter-user channel and partner's uplink channel, the CC (50%) and coded DF schemes prefer to have a strong inter-user channel, while the CC (25%) scheme prefers to have a strong partner's uplink.

ACKNOWLEDGEMENT

This project is sponsored by the Engineering and Physical Sciences Research Council (EPSRC) under Grant EP/E012108/1.

REFERENCES

[1] S. M. Alamouti, "A simple transmit diversity technique for wireless communications", IEEE JSAC, Vol. 16, 1998, pp. 1451-1458.

[2] T. M. Cover, A. E. Gamal, "Capacity theorems for the relay channel", IEEE Trans. Inform. Theory, Vol. IT-25, 1979, pp. 572-584.

[3] J. N. Laneman, G. W. Wornell, "Energy-efficient antenna sharing and relaying for wireless networks", presented at IEEE Wireless Comm. and Networking Conf. (WCNC), Chicago, IL, 2000, pp. 7-12.

[4] J. N. Laneman, G. W. Wornell, "Cooperative diversity in wireless networks: efficient protocols and outage behavior", IEEE Trans. Inform. Theory, Vol. 50, 2004, pp. 3062-3080.

[5] A. Sendonaris, E. Erkip, B. Aazhang, "User cooperation diversity: Part I and Part II", IEEE Trans. Comm., Vol. 51, 2003, pp. 1927-1948.

[6] T. Hunter, A. Nosratinia, "Diversity through coded cooperation", IEEE Trans. Wireless Comm., Vol. 5, 2006, pp. 283-289.

[7] A. Stefanov, E. Erkip, "Cooperative coding for wireless networks", IEEE Trans. Comm., Vol. 52, 2004, pp. 1470-1476.

[8] A. Nosratinia, T. Hunter, A. Hedayat, "Cooperative communication in wireless networks", IEEE Comm. Mag., Vol. 42, 2004, pp. 74-80.

[9] L. Chen, R. A. Carrasco, V. Ganepola, S. L. Goff, I. J. Wassell, "Comparative investigation of coded cooperative communication systems", presented at the 6th symposium on communication systems, networks and digital signal processing, Graz, Austria, 2008, pp. 58-62.

[10] J. Hagenauer, "Rate-compatible punctured convolutional codes (RCPC codes) and their applications", IEEE Trans. Comm., Vol. 36, 1988, pp. 389-400.

[11] I. Chatzigeorgiou, W. Guo, I. J. Wassell, R. A. Carrasco, "Comparison of cooperative schemes using joint channel coding and high-order modulation", presented at IEEE International Symposium on Communications, Control and Signal Processing (ISCCSP), Malta, 2008, pp. 994-998.

[12] J. C. Moreira, P. G. Farrell, Essentials of Error-Control Coding: John Wiley & Sons Ltd., 2006, ISBN: 978-0-470-02920-6.

[13] M. K. Simon, M. S. Alouini, Digital communication over fading channels: a unified approach to performance analysis. New York: John Wiley and Sons, 2000, ISBN-13: 978-0471317791.

Biographies

Li Chen received his BSc degree in applied physics from Jinan University, P. R. China, 2003, the MSc degree in communication and signal processing from Newcastle University, UK, 2004, and was awarded the Ph.D degree in mobile communications from Newcastle University in 2008. He is currently a Research Associate with the School of Electrical, Electronic and Computer Engineering, Newcastle University. His research interests include algebraic geometric coding schemes, list decoding systems, other non-binary coding schemes and their applications in the cooperative wireless network. Dr. Chen is a Member of the Institute of Electrical and Electronic Engineering (IEEE) and a Member of the institution of Engineering and Technology (IET).

Rolando. A. Carrasco obtained his Bachelors BEng (Hon.) degree in Electrical Engineering from Santiago University, Chile in 1969; his Ph.D degree in Signal Processing from the University of Newcastle-upon-Tyne in 1980. He was awarded the IEE Heaviside Premium in 1982 for his work in multiprocessor systems. Between 1982 and 1984 he was employed by Alfred Peters Limited, Sheffield (now Meditech) and carried out research and development in signal processing associated with cochlear stimulation and response. He had been with Staffordshire University since 1984 and joined Newcastle University in 2004 as Professor of Mobile Communications. His principle research interests are digital signal processing algorithm for data communication systems, mobile and network communication systems, speech recognition and processing. Professor Carrasco has over two

hundred scientific publications, 5 chapters in Telecomm. reference texts and a patent to his name.

Ian. J. Wassell was born in Wolverhampton, England on October 22, 1960. He received the BSc, BEng (Hon.) degree (First Class) in electrical and electronic engineering from the University of Loughborough, UK in 1983 and the Ph.D degree in electronic and electrical engineering from the University of Southampton, UK in 1990. He is a Senior University Lecturer at the Computer Laboratory, University of Cambridge. Prior to this he has held positions at the University of Huddersfield, Hutchison Personal Communications Ltd., Multiple Access Communications Ltd. and Marconi Ltd. He has published more than 130 papers concerning wireless communication systems since joining the University of Cambridge in May 1999. His research interests include fixed wireless access networks, wireless sensor networks, radio propagation, coding and signal processing for communication systems. Dr. Wassell is a Member of the Institution of Engineering and Technology (IET).

Vajira. S. Ganepola received his BSc degree in electrical engineering from University of Moratuwa, Sri Lanka in 2000, the MSc in communications and signal processing from the Newcastle University, UK in 2006. From 2000 to 2006 he was with the industry as electrical engineer and a project manager. His research interests fall in the general areas of wireless communications and signal processing, specifically cooperative communication schemes, non binary LDPC codes, Algebraic Geometric codes, reduced complexity decoding algorithms for wireless communications.