# Comparative Investigation of Coded Cooperative Communication Systems

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*Abstract* -- **Cooperative communication uses multipath transmission to combat the effect of individual severe fading and path loss. So far, there are mainly three types of cooperative schemes: Amplify-and-Forward, Decode-and-Forward, and Coded Cooperation. This paper presents a convolutional coded system model and performance comparison between these three schemes. Also, this paper reveals two important parameters that determine the performance of different levels of Coded Cooperation schemes: percentage of cooperation and distributed effect for the transmitted symbols. They will be analysed and some contributing conclusions of our work will be drawn.**

## I. INTRODUCTION

Due to the effect of severe fading and path loss, space diversity technique is critical for wireless network to have reliable communications. One of the well known space diversity techniques is to employ multiple transmit/receive antennas 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, multiple antennas may not be practical to implement. An alternative solution to create space diversity is to encourage communication units with single antenna to share their resources and help 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. This signal relaying using independent path 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). Sendonaris [5] implemented an effectively DF cooperative scheme in the code-division multiple access (CDMA) system. Later, Hunter and Nosratinia [6] proposed a new cooperative scheme in which signal relaying is integrated with channel coding design, called Coded Cooperation (CC). Both of the above cooperative schemes can achieve full diversity [4, 6]. Ref [7] gave a tutorial review of these cooperative schemes.

Different to the previous work, this paper presents a signal model comparison of these three cooperative schemes. They are incorporated in a coded system using non-recursive non-systematic convolutional codes [8]. This paper also reveals and analyses two important parameters for the performance of CC scheme. They are the percentage of cooperation and distributed effect for the transmitted symbols. Further, a performance comparison of these coded cooperative schemes is presented.

The following of the paper is organised as: section II will give the transmission signal model of a cooperative system; section III will present the three coded cooperative schemes; section IV will present our analyses and simulation results of the three coded cooperative schemes; and finally, conclusion of the paper will be presented in section V.

## II. TRANSMISSION SIGNAL MODEL

Our cooperative network consists of 3 nodes: source (s), relay (r) and destination (d). Both source and relay share the same transmitting destination, and transmit through frequency orthogonal channel in a full-duplex system 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 2 time slots structure, shown by Fig. 1(a). $x_s[n]$ and $x_r[n]$ are the transmitted signal from source and relay respectively. As we analyse cooperative schemes 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 1st and 2nd time slot signals/coefficients respectively.

Due to the symmetric transmission status between source and relay, in this paper, we focus on the transmission of source signal $x_s[n]$ and decoding of source information. In the 1st time slot, source transmits $x_s[n]$ to relay and destination as:

$$y_{sr}[n] = \sqrt{\varepsilon}\ a_{sr}x_s[n] + z_{sr}[n] \quad (1)$$

$$y_{sd}[n] = \sqrt{\varepsilon}\ a_{sd}x_s[n] + z_{sd}[n] \quad (2)$$

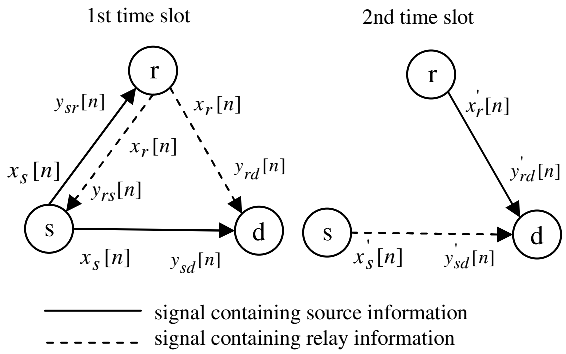
where $n$ = 1, 2, …, $N_1$ and $N_1$ is a positive integer indicating the length of the transmitted signal in the 1st time slot.

Relay "overhears" source transmission $y_{sr}[n]$ based on which it generates signal $x_r'[n]$ to be transmitted to the destination in the 2nd time slot as:

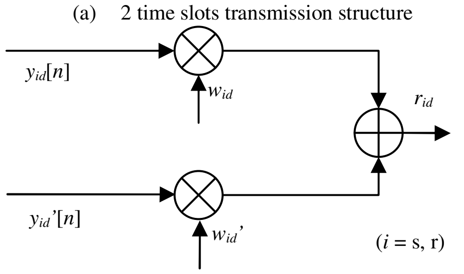
$$y_{rd}'[n] = \sqrt{\varepsilon}\ a_{rd}x_r'[n] + z_{rd}'[n] \quad (3)$$

where $n$ = 1, 2, …, $N_2$, $N_2$ is a positive integer indicating the length of the transmitted signal in the 2nd time slot. The way to obtain $x_r'[n]$ from $y_{sr}[n]$

depends on the cooperative scheme, which will be discussed later.




(a) 2 time slots transmission structure




(b) optimal combiner at the destination

Figure 1. Cooperative signal model

In equations (1) – (3), $\varepsilon$ 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 $\sigma_{sd}^2$, $\sigma_{rd}^2$ and $\sigma_{sr}^2$ respectively. As slow fading is assumed in our analysis, $a_{sd}$, $a_{rd}$ and $a_{sr}$ are constant during the 2 time slots and change independently after every 2 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: $\gamma_{ij} \overset{\Delta}{=} |a_{ij}|^2 \varepsilon / N0_{ij}$ ($i = s, r$ and $j = r, d$, but $i \neq j$). Further, the expected value of channel SNR is defined as:

$$\overline{\gamma_{ij}} \overset{\Delta}{=} E[\gamma_{ij}] = E[|a_{ij}|^2]\varepsilon / N0_{ij} = \sigma_{ij}^2 \varepsilon / N0_{ij} \quad (4)$$

At the destination, the received signals in the 2 time slots are combined using the optimal combiner shown by Fig. 1(b). In order to design the optimal combining gains $w_{id}$ and $w_{id}'$ for the incoming signals in the 1st and 2nd time slots, perfect channel state information (CSI) of the 3 node network is assumed to be available at the destination. The combined received signal $r_{id}$ is passed to a decoder in order to retrieve user's information. Again, design of $w_{id}$ and $w_{id}'$, and the way to obtain $r_{id}$ through the optimal combiner depend on the cooperative schemes and the transmission status.

If the 1st and 2nd time slots contain the same period of time, 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. 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 [9].

## III. 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 [10].

### *A. Coded Amplify-and-Forward*

Assuming that convolutional code $\boldsymbol{C}_1$ is employed in the AF scheme, source's coded and modulated symbols $x_s[n]$ are transmitted to both relay and destination in the 1st time slot. Relay amplifies its received signal $y_{sr}[n]$ as:

$$x_r'[n] = \beta\, y_{sr}[n], \text{ and } \beta = \sqrt{\frac{1}{|a_{sr}|^2 \varepsilon + N0_{sr}}} \quad (5)$$

$x_r'[n]$ is transmitted to the destination in the 2nd time slot. The received signals of these 2 time slots are optimally combined as [3]:

$$r_{sd}[n] = w_{sd} y_{sd}[n] + w_{rd}' y_{rd}'[n], \text{ and}$$

$$w_{sd} = \frac{a_{sd}^* \sqrt{\varepsilon}}{N0_{sd}},\ w_{rd}' = \frac{a_{rd}^* \beta a_{sr}^* \sqrt{\varepsilon}}{|a_{rd}|^2 \beta^2 N0_{sr} + N0_{rd}} \quad (6)$$

$r_{sd}[n]$ is then passed to the decoder whose structure is determined by code $\boldsymbol{C}_1$ to retrieve the source information.

### *B. Coded Decode-and-Forward*

Different to the coded AF scheme, instead of simply amplifying the received symbols of the 1st time slot, relay tries to decode source information. They will be re-encoded and modulated before being transmitted to the destination in the 2nd 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 symbols in the 2nd time slot. Analyses in [4] showed that selection is necessary for the system to achieve diversity gain. Therefore, this paper employs the selective coded DF scheme by using code $\boldsymbol{C}_1$ as in the coded AF scheme. As it is slow fading and there is no amplification effect, for the coded DF scheme, the optimal combining gains for the 1st and 2nd time slot incoming signals are:

$$w_{sd} = w_{sd}' = \frac{a_{sd}^* \sqrt{\varepsilon}}{N0_{sd}},\ w_{rd} = w_{rd}' = \frac{a_{rd}^* \sqrt{\varepsilon}}{N0_{rd}} \quad (7)$$

Depending on the decoding status of source and relay after the 1st time slot, there are 4 possible transmission scenarios in the 2nd time slot:

*Scenario 1: Both source and relay decode their partner's signal successfully.* In the 2nd time slot, relay (source) will transmit source (relay)'s signal to the destination. As correct information has been retrieved, accurate estimation of their partner's 1st time slot transmission can be achieved as:

$$x_r'[n] = x_s[n] \quad (8)$$

In order to decode source information at the destination, the received signal of these 2 time slots can be obtained by the optimal combiner as:

$$r_{sd}[n] = w_{sd}y_{sd}[n] + w_{rd}'y_{rd}'[n] \quad (9)$$

*Scenario 2: Source decodes relay's information, while relay does not decode source's information.* In the 2nd time slot, both source and relay will transmit relay's signal. In order to decode source's information after 2 time slots, destination can only employ the received symbols from source in the 1st time slot as:

$$r_{sd}[n] = w_{sd}y_{sd}[n] \quad (10)$$

*Scenario 3: Relay decodes source's information, while source does not decode relay's information.* In the 2nd time slot, both source and relay will transmit source's signal as:

$$x_r'[n] = x_s[n], \text{ and } x_s'[n] = x_s[n] \quad (11)$$

In order to decode source's information after these 2 time slots, the received symbols are obtained as:

$$r_{sd}[n] = w_{sd}y_{sd}[n] + w_{sd}'y_{sd}'[n] + w_{rd}'y_{rd}'[n] \quad (12)$$

*Scenario 4: Neither source nor relay decodes their partner's information.* Therefore, in the 2nd time slot, source will retransmit its own signal, so will relay:

$$x_s'[n] = x_s[n] \quad (13)$$

In order to decode source's information, the received symbols of the 2 time slots are obtained as:

$$r_{sd}[n] = w_{sd}y_{sd}[n] + w_{sd}'y_{sd}'[n] \quad (14)$$

From the above analysis it can be seen that, the destination should have knowledge of the transmission status of this 3 nodes network over 2 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 whose structure is determined by code $\boldsymbol{C}_1$. The same process described above can be symmetrically applied to relay.

*C. Coded Cooperation*

CC scheme is an advanced generation of the selective DF scheme. In the CC scheme, instead of using the same encoder ($\boldsymbol{C}_1$ in coded DF) to generate a repetition signal of its partner when cooperation is encouraged, it uses a different encoder ($\boldsymbol{C}_2$) 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 $\boldsymbol{C}_1$ and $\boldsymbol{C}_2$. To achieve full diversity gain, $\boldsymbol{C}_1$ shall serve the purpose of guaranteeing the inter-user channel transmission, while $\boldsymbol{C}_2$ shall serve the purpose of good performance of overall code ($\boldsymbol{C}_1$, $\boldsymbol{C}_2$) in the slow fading channel.

Again, depending on the decoding status of source and relay after the 1st time slot, the four possible transmission scenarios discussed in Section III.*B* 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 equation (7).

*Scenario 1*: Relaying transmission in the 2nd time slot ($x_r'[n]$, $x_s'[n]$) is generated by encoding their partner's information using $\boldsymbol{C}_2$ encoder. At the destination, instead of simply adding the received symbols from the 2 time slots, they are multiplexed and concatenated as:

$$r_{sd}[n] = (w_{sd}y_{sd}[n], w_{rd}'y_{rd}'[n]) \quad (15)$$

The length of combined symbols $r_{sd}[n]$ is $N_1 + N_2$. $r_{sd}[n]$ is passed to a decoder whose structure is determined by ($\boldsymbol{C}_1$, $\boldsymbol{C}_2$) in order to decoder source's information.

*Scenario 2*: For this scenario, source's signal is not transmitted in the 2nd time slot. Received symbols $r_{sd}[n]$ has length $N_1$ and will be decoded by a decoder with structure determined by $\boldsymbol{C}_1$.

*Scenario 3*: Both source and relay's transmission in the 2nd time slot ($x_s'[n]$, $x_r'[n]$) will be generated by encoding source's information using $\boldsymbol{C}_2$ encoder. The received symbols of the 2nd time slot from source and relay will be added together, then multiplexed and concatenated with the received symbols from of the 1st time slot as:

$$r_{sd}[n] = (w_{sd}y_{sd}[n], w_{sd}'y_{sd}'[n] + w_{rd}'y_{rd}'[n]) \quad (16)$$

$r_{sd}[n]$ has length $N_1 + N_2$ and the decoder structure is determined by ($\boldsymbol{C}_1$, $\boldsymbol{C}_2$).

*Scenario 4*: Source and relay will generate their retransmission ($x_s'[n]$, $x_r'[n]$) by encoding their own information using $\boldsymbol{C}_2$ encoder. The received symbols are multiplexed and concatenated as:

$$r_{sd}[n] = (w_{sd}y_{sd}[n], w_{sd}'y_{sd}'[n]) \quad (17)$$

$r_{sd}[n]$ has length $N_1 + N_2$ and will be decoded by the decoder with structure determined by ($\boldsymbol{C}_1$, $\boldsymbol{C}_2$).

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. Summarising these four scenarios for both coded DF and CC schemes, for source, diversity gain 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 CC is not a recurrence cooperative scheme, the transmission lengths $N_1$ and $N_2$ of the 1st and 2nd time slots can be different, which will depend on the encoder structure of $\boldsymbol{C}_1$ and $\boldsymbol{C}_2$. 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 2 time slots transmission. In this paper, CC(50%) and CC(25%) will be investigated.

## IV. ANALYSES AND SIMULATION RESULTS

Based on the above description, this section will present some analyses of these coded cooperative systems as well as simulation results. For coded AF, coded DF and CC(50%), $\boldsymbol{C}_1$ is rate 1/2 $(31, 27)_8$ convolutional code which is reported to be good for inter-user channel transmission [6]. For CC(50%), $\boldsymbol{C}_2$ is rate 1/2 $(35, 33)_8$ convolutional code. For CC(25%), $\boldsymbol{C}_1$ and $\boldsymbol{C}_2$ are rate 1/3 $(31, 27, 35)_8$ and rate 1 $(33)_8$ convolutional codes respectively. 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 1/4 $(31, 27, 35, 33)_8$ convolutional code. For all the simulations, the length of information is 128 bits and BPSK modulation scheme is employed.

*A. Percentage of Cooperation*

From the Section III, it can be seen that both coded DF and CC schemes are selective cooperative schemes, for which cooperation of the 2nd time slot is based on the successful transmission of the 1st time slot. Therefore, a higher percentage of cooperation results in a better diversity gain. Here we define full cooperation as both users assist their partners to transmit signal in the 2nd time slot (*Scenario 1*), and partial cooperation as only one user assists its partner to transmit signal in the 2nd time slot while the other user transmits its own signal (*Scenario 2* and *3*). The percentage of cooperation (full, partial and full) for coded DF, CC(50%) and CC(25%) are measured against the quality of inter-user channel by running 40 000 realisations and presented by Fig. 2.

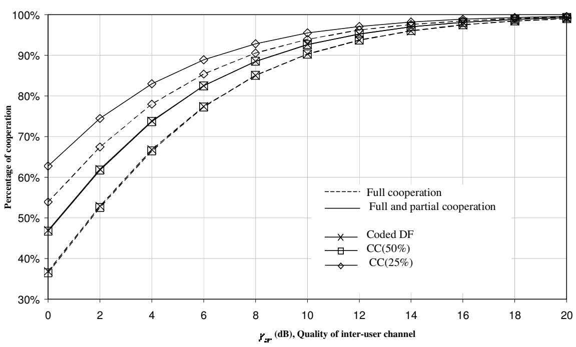



Figure 2 Percentage of cooperation analysis

From Fig. 2, it can be seen that the percentage of cooperation increases as the quality of inter-user channel improves which results in improved 1st time slot transmission. As coded DF and CC(50%) use the same code $\boldsymbol{C}_1 = (31, 27)_8$ for the 1st time slot transmission, their percentages of cooperation remain similar. However, for CC(25%), $\boldsymbol{C}_1 = (31, 27, 35)_8$ which has better error-correction capability and it results in improved 1st time slot transmission. Therefore, higher percentage of cooperation is achieved. 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%.

*B. Distributed effect for the transmitted symbols of CC schemes*

The above analysis 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 of the transmitted symbols that is not the same for these two schemes. For example, for full cooperation with CC(50%), half 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 analyse this distributed effect, the pairwise error probability (PEP) [11] is referred to. If $d_s$ and $d_r$ denote the error event bits in a user's received word through the source's and relay's uplink channel transmissions respectively, and $d_s + d_r = d$, under full cooperation, the PEP value for both users can be bounded by [6]:

$$P(d)_f \le \frac{1}{2}\left(\frac{1}{1+d_s\overline{\gamma_{sd}}}\right)\left(\frac{1}{1+d_r\overline{\gamma_{rd}}}\right) \tag{18}$$

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

$$P(d)_p \le \frac{1}{2}\left(\frac{1}{1+d\overline{\gamma_{sd}}}\right)\left(\frac{1}{1+d_r\overline{\gamma_{rd}}}\right) \tag{19}$$

Similar to (19), the PEP value for relay in *Scenario 2* is straight forward to be derived.

To compare the PEP values for 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, $d_s \cong d_r \cong \frac{d}{2}$ is assumed. Based on (18), under full cooperation:

$$P(d)_f \le \frac{1}{2}\left(\frac{1}{1+\frac{d\overline{\gamma}}{2}}\right)\left(\frac{1}{1+\frac{d\overline{\gamma}}{2}}\right) = \frac{2}{4+4d\overline{\gamma}+d^2\overline{\gamma}^2} \tag{20}$$

Based on (19), under partial cooperation:

$$P(d)_p \le \frac{1}{2}\left(\frac{1}{1+d\overline{\gamma}}\right)\left(\frac{1}{1+\frac{d\overline{\gamma}}{2}}\right) = \frac{1}{2+3d\overline{\gamma}+d^2\overline{\gamma}^2} \tag{21}$$

For CC(25%), $d_s \cong \frac{3d}{4}$ and $d_r \cong \frac{d}{4}$ are assumed. Then based on (18), under full cooperation:

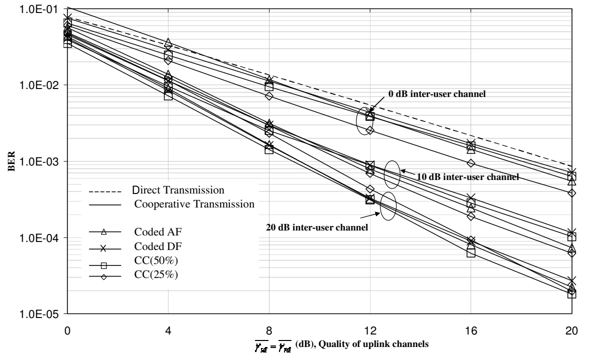
$$P(d)_f \le \frac{1}{2}\left(\frac{1}{1+\frac{3d\overline{\gamma}}{4}}\right)\left(\frac{1}{1+\frac{d\overline{\gamma}}{4}}\right) = \frac{2}{4+4d\overline{\gamma}+\frac{3d^2\overline{\gamma}^2}{4}} \tag{22}$$

Based on (19), under partial cooperation:

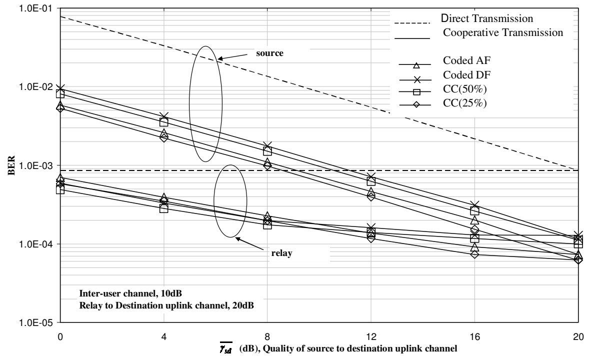
$$P(d)_p \le \frac{1}{2}\left(\frac{1}{1+d\overline{\gamma}}\right)\left(\frac{1}{1+\frac{d\overline{\gamma}}{4}}\right) = \frac{1}{2+\frac{5d\overline{\gamma}}{2}+\frac{d^2\overline{\gamma}^2}{2}} \tag{23}$$

From the above derivation, it can bee seen that under both full and partial cooperation, CC(25%) has higher pairwise error probability upper bound than CC(50%). This is due to its unequal distributed effect for the transmitted symbols. Summarising the above analyses, CC(25%) encourages higher percentage of cooperation, while CC(50%) has a better distributed effect for its transmitted symbols. Which of these two parameters plays a more important role in the performance improvement depends on the quality of the inter-user channel. This is addressed in the next section.

*C. Symmetric/Asymmetric uplink simulations*




(a) Symmetric uplink channels




(b) Asymmetric uplink channels

Figure 3 Performance comparison of coded cooperative schemes

This section presents our comparative investigation of all the coded cooperative schemes under symmetric uplink channel scenario ($\overline{\gamma_{sd}} = \overline{\gamma_{rd}}$) and asymmetric uplink channel scenario ($\overline{\gamma_{sd}} \neq \overline{\gamma_{rd}}$). They are shown by Figs. 3(a) and 3(b) respectively.

Fig. 3(a) shows that for all the coded cooperative schemes, diversity gain can be achieved over the direct transmission. And the diversity gain improves as the quality of inter-user channel improves. Fig 3(b) shows that even though under unequal uplink scenario, not only the user (source) with poorer uplink channel benefits, but also the user (relay) with stronger uplink channel does.

Comparing all the coded cooperative schemes' results, CC schemes outperform coded AF and coded DF. This illustrates that integrating cooperative transmission with coding design, which results extra parity bits being transmitted in the 2nd time slot, is better than simple repetition transmission. However, this is also on the expense of extra system complexity because the destination needs to have the knowledge of 2 time slots transmission and adapt its decoder structure accordingly. Comparing CC(50%) with CC(25%), CC(25%) outperforms CC(50%) in poor or moderate quality (0dB or 10dB) inter-user channel. This indicates under this circumstance, having higher percentage of cooperation plays a more important role in performance improvement. However, when the inter-user channel quality is sufficiently good (20dB), CC(50%) outperforms 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, as CC(50%) has better distributed effect for the transmitted symbols, it can outperform CC(25%). Among all, coded AF produces the second most favourable result due to its constant cooperation (non-selective) combining with amplification feature. From the implementation point of view, it is the simplest one as neither decoding/encoding is involved in the cooperative users nor transmission status knowledge is needed in the destination.

## V. CONCLUSION

This paper presented a signal model and performance comparison for all the cooperative schemes in a coded system. Two important parameters that determine the performance of CC schemes were revealed and analysed. They are the percentage of cooperation and the distributed effect for the transmitted symbols. Analyses in this paper showed that when the inter-user channel quality is poor or moderate, having higher percentage of cooperation is more important in performance improvement. When the inter-user channel quality is sufficiently good, the percentages of cooperation for all the CC schemes become similar, and having a good distributed effect for the transmitted symbols is more important.

## ACKNOWLEDGEMENT

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

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