Cross Layer Hybrid ARQ 2 Cooperative Diversity in Next Generation Wireless Networks

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Abstract—Coded cooperation can achieve diversity through channel coding. The traditional Coded Cooperation framework is not an efficient transmission scheme since in some cases the base station has already decoded a particular set of information bits using a user's initially transmitted parity and not all parity bits are required. The user however is not informed by the base station of this. This paper proposes an efficient transmission scheme called Cross Layer Hybrid ARQ 2 Cooperative Diversity (HARQ 2). By combining HARQ 2 (at the link layer) with Cooperative Diversity (at the physical layer) feedback from the base station is available for users. Users can then transmit incremental parity packets and await feedback from the base station to decide whether further parity is required for a particular set of information bits. Improvements in Bit Error Rate (BER) and throughput are observed by the cross layer design over Coded Cooperation. BER theoretical bound analysis is performed and is validated by simulations in a block fading channel.

Index Terms—Cooperative Diversity, Cross Layer Hybrid ARQ 2 Cooperative Diversity, Coded Cooperation, Block Fading Channel.

I. INTRODUCTION

WIRELESS partnership pairs are formed between wireless nodes in [1]-[7] in an effort to achieve diversity via a signalling method that enables two single antenna mobiles to transmit their information jointly using both their antennas over independently faded uplink channels. In [1]-[7], the method of cooperative diversity implemented allows for a user to "listen" to the partner's transmission and retransmit the received version of the partner's signal - using repetition coding methods.

The repetition coding methods involves the user either retransmitting an amplified version of the partner's signal (amplify and forward) or estimating the partner's signal and retransmitting an estimate of the partner's signal (detect and forward). In [8]-[16] a cooperative diversity framework called Coded Cooperation was implemented which introduced channel coding into cooperative diversity. Here code words are segmented into two frames which are transmitted from the user and partner's antennas, over independent uplink channels respectively.

The traditional Coded Cooperation framework is not an efficient transmission scheme since in some cases the base station has already decoded a particular set of information bits using a user's initially transmitted parity and not all the parity bits. The user however is not informed by the base station of this. In order to improve the efficiency over Coded Cooperation, this paper introduces a cross layer network design into the Cooperative Diversity area, called Cross Layer Hybrid ARQ 2 Cooperative Diversity.

This framework combines HARQ 2 at the data link layer with cooperative diversity at the physical layer in an effort to allow for feedback to occur between the base station and the users. With feedback available and by the use of the incremental redundancy nature of HARQ 2, the users transmit the amount of parity required by the base station. Cross Layer Cooperation partitions a full parity code word into incremental parity packets or sub code words. In this paper the sub code words or incremental parity packets are created by the use of Rate Compatible Punctured Convolutional (RCPC) Codes [18].

ARQ 2 signalling from the base station and incremental parity transmission differentiates Cross Layer Cooperation from Coded Cooperation and results in BER and throughput improvements over Coded Cooperation. Coded Cooperation allows for a lot of parity to be wasted by partners cooperating with the base when the base station has already decoded a user's information bits.

The cross layer design consists of two users communicating with the base station. The inter user and uplink channels are modelled as block fading channels. This is due to each incremental parity packet undergoing a different fading and is thus modelled as identically independent distributions (i.i.d).

Users' transmissions occur orthogonally and can be adopted on a Time Division Multiple Access (TDMA), Code Division Multiple Access (CDMA) or Frequency Division Multiple Access (FDMA) scheme. Perfect Channel State Information (CSI) is assumed at all receivers. The instantaneous Signal to Noise Ratio (SNR) between users i and j, during fading block l and time instant n, is given by $\gamma_{i,j,l}(n)$ and is exponentially distributed. The mean value of $\gamma_{i,j,l}(n)$ is $\Gamma_{i,j,l}$.

The fading coefficients $\alpha_{i,j,l}(n)$ are modelled as independent samples of a Rayleigh random process for a particular block l.

In Section II the fading channel model is explained. Section III presents Cross Layer Hybrid ARQ 2 system model based on incremental redundancy. In Section IV the end to end Bit Error Probability (BEP), analytical bound derivation for Cross Layer Hybrid ARQ 2 Cooperation is explained based on the Pairwise Error Probability (PEP). Section V contains the performance analysis of Cross Layer Hybrid ARQ 2 cooperation. The simulations confirm the analytical BER bounds from Section IV. Section VI concludes the paper.

II. FADING CHANNEL MODEL

A block fading model is adopted based on [17].Binary Phase Shift Keying (BPSK) modulation is employed and the received sample at time instant n is, for a particular block l , is given by:

$$y_{i,j,l}\left(n\right)=\alpha_{i,j,l}\left(n\right)\sqrt{E_{b,i}}x_{i,j,l}\left(n\right)+n_j\left(n\right) \tag{1}$$

where $i\in\left\{1,2\right\},\ j\in\left\{0,1,2\right\},i\neq j,l\in\left\{1,2,3,4\right\}$
and $n\in\left\{1,2,\cdots,K\right\}$

In (1), i denotes the transmitting user for that transmission, j is the receiving user and l is the fading block index. Note that $j=0$ denotes the base station. $E_{b,i}$ is the energy of a transmitted symbol, $x_{i,j,l}$ is a BPSK modulated symbol i.e. $x_{i,j,l}(n)\in\{-1,1\}$ at time instant n and $n_j\left(n\right)$ accounts for additive noise at receiver j and is modelled as samples of a zero mean Gaussian random variable with variance of $N_j/2$.

III. CROSS LAYER HYBRID ARQ 2 COOPERATION SYSTEM MODEL

A brief discussion of cross layer cooperation is presented here. The reader is also referred to [20]. Cross Layer Cooperation maintains the same code rate R as that of a comparable non cooperative system but allows for the transmitted symbols to be shared across both users' uplinks, with independent fading via the use of HARQ 2.

The two users i and j have K bit information blocks which include c Cyclic Redundancy Check (CRC) concatenated bits. Each K bit information block is encoded into a N bit parity block using a rate ¼ mother convolutional code from the RCPC code family of codes in [18]. Each user's N parity bits are partitioned into four parity packets i.e. $B_{i,1},B_{i,2},B_{i,3},B_{i,4}$ of equal size $N_{i,1},N_{i,2},N_{i,3},N_{i,4}$.The length of N is calculated such that $length(N)=\sum_{r=1}^{4}length\left(N_r\right)$.

TABLE I
CROSS LAYER HYBRID ARQ 2 TRANSMISSION SCENARIOS

Case	dcrc$_1$	dcrc$_2$	crc$_1$	crc$_2$
1.1	0	0	0	0
1.2	0	0	0	1
1.3	0	0	1	0
1.4	0	0	1	1
2.1	0	1	0	0
2.2	0	1	0	1
2.3	0	1	1	0
2.4	0	1	1	1
3.1	1	0	0	0
3.2	1	0	0	1
3.3	1	0	1	0
3.4	1	0	1	1
4.1	1	1	0	0
4.2	1	1	0	1
4.3	1	1	1	0
4.4	1	1	1	1

Even though an RCPC code implementation using the Cross Layer Hybrid ARQ 2 framework is presented here - the framework is generic to any puncturing, concatenating or product code family. The best case cooperation level $\lambda_{i,j}$ is defined to be the maximum amount of parity bits a user i transmits for user j divided by the mother code encoded length. Two cooperation levels are considered i.e. 50% and 25%. During 50% best case cooperation a user transmits two incremental packets to the base station initially i.e.

$$B_{i/j}\left(t\right)=B_{i/j,1}+B_{i/j,2}=\sum_{q=1}^{N_1}\left|B_{i/j,1}\right|\delta(t-q)+\sum_{q=N_1+1}^{N_2}\left|B_{i/j,2}\right|\delta(t-q) \tag{2}$$

where the notation i/j denotes either i or j. Note that $\delta(.)$ denotes the unit impulse function. During 25% cooperation a user transmits 3 incremental packets initially to the base station i.e.

$$B_{i/j}\left(t\right)=B_{i/j,1}+B_{i/j,2}+B_{i/j,3}=\sum_{q=1}^{N_1}\left|B_{i/j,1}\right|\delta\left(t-q\right)+...$$
$$\sum_{q=N_1+1}^{N_2}\left|B_{i/j,2}\right|\delta\left(t-q\right)+\sum_{q=N_2+1}^{N_3}\left|B_{i/j,3}\right|\delta\left(t-q\right) \tag{3}$$

Since the initially transmitted packets collectively allow for sufficient parity to be available for the decoding of a user's information bits - the base station might already decode a user's parity based on the initial transmission. This results in the initially punctured parity not being required to be transmitted for that set of information bits for a user and results in bandwidth savings. Based on the feedback from the base station i.e. the base station CRC syndrome calculation and the inter user CRC states, 16 transmission scenarios are possible for a user. These scenarios are tabulated in Table (1) above.

A user will first evaluate his inter user CRC flag and the base station CRC for himself and his partner and then decide on whether to cooperate or not. Generally user i will evaluate crc$_i$, dcrc$_i$ and dcrc$_j$ and decide upon the transmission scenario. In order for user i to cooperate the inter user CRC flag, crc_i has to reflect correct CRC syndrome calculations for the decoded partner's initial transmission. User i will then look at his partner's CRC flag i.e. dcrc_j and will transmit incremental parity for the partner if dcrc_j=0. If dcrc_j=1 then no further incremental parity is required for the partner for that set of information bits. If user i's inter user CRC flag is incorrect then user i can only transmit incremental parity for himself based on the base station's feedback.

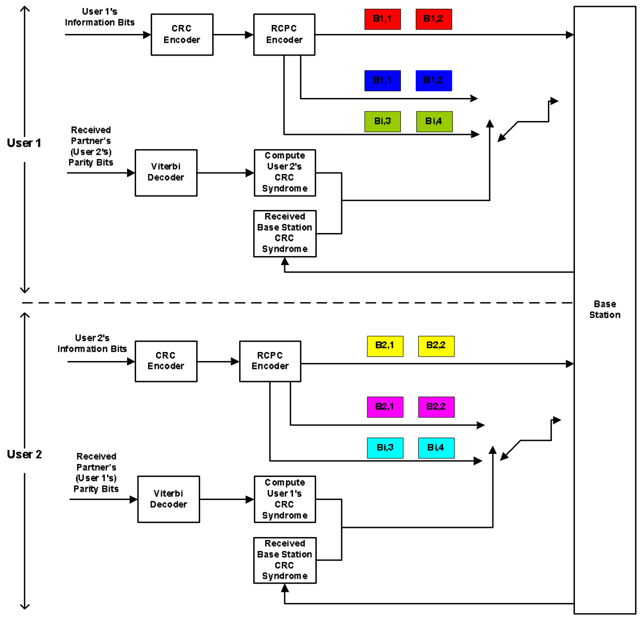

Fig. 1. Cross Layer HARQ 2 Cooperation System Diagram

As an example take case 1.4 from Table 1, here dcrc1=0, dcrc_2=0, crc_1=1 and crc_2=1. User_1 looks at crc_1 which is 1 (ACK) and hence realises that he has decoded user 2's initial transmission correctly and can transmit incremental parity for user 2 after realising that extra parity is needed for user 2 since dcrc_2=0 (NACK). Similarly user 2 has crc_2=1 (ACK) and can transmit incremental parity for user 1 after realising that incremental parity is required for user 1 since dcrc_1 is equal to 0 (NACK). This is a full cooperation case.

Fig. 1 above illustrates the system diagram for Cross Layer Hybrid ARQ 2 Cooperative Diversity. Initially user 1 transmits $B_{1,1}$ and $B_{1,2}$ to the base station shown by the red packets in Fig. 1. The base station and the partner receive these two red packets and decode them using a Viterbi decoder and then compute the CRC syndrome. The base station sends either an ACK or NACK to user 1, on the downlink, which is inherited by user 2. Based on the received CRC signal from the base station and the inter user CRC, the users decide whether to cooperate or not. If for example user 1's red packets were decoded correctly the first time by the base station, and user 1 is not cooperating, then user 1 will transmit the two dark blue packets which is new parity ($B_{1,1}$ and $B_{1,2}$) for a new information packet for himself.

On the other hand if the red packets were decoded incorrectly then user 1 will incrementally transmit the green packets for himself which would be parity ($B_{1,3}$ and $B_{1,4}$ if needed). Note that the subscript "i" is used in the green packets for $B_{i,3}$ and $B_{i,4}$ because user 1 could also be transmitting incremental cooperation packets for user 2 (user 1 is cooperating) since $i\in\{1,2\}$ in this context.

Similarly user 2 transmits $B_{2,1}$ and $B_{2,2}$ (yellow packets) for himself initially. Based on the feedback from the base station to user 2, which is inherited by user 1, and the inter user CRC states, user 2 will either cooperate with user 1 by transmitting the light blue packets for the partner ($B_{1,3}$ and $B_{1,4}$ if needed) or user 2 would not have to cooperate and could have his own initial parity decoded correctly by the base station, in which case user 2 will transmit the purple packets for himself (which is new parity for a new set of information bits) i.e. $B_{2,1}$ and $B_{2,2}$. The subscript "i" is used in the light blue packets for $B_{i,3}$ and $B_{i,4}$ because user 2 could also be transmitting incremental parity packets for himself since again $i\in\{1,2\}$ in this context (during non cooperation). Note that in Fig. 1 the transmissions of user 1 and 2 are symmetrical about the dashed line.

IV. THE END TO END BEP BOUNDS

The end to end BEP for Cross Layer Hybrid ARQ 2 Cooperative Diversity is a weighting of the cooperation case probability and the uplink BEP for that specific case. The factor $p_b(\theta=w,r)_j$ denotes the BEP for a specific case on the uplink channel whilst the factor $p(\theta=w,r)_j$ denotes the case probability. The end to end BEP bound for during 50% best case cooperation is given by:

$$p_{50}=\sum_{w=1}^{2}\sum_{r=1}^{4}\sum_{j=2}^{4} p_b(\theta=w,r)_j\; p(\theta=w,r)_j \qquad (4)$$

And during 25% best case cooperation:

$$p_{25}=\sum_{w=1}^{2}\sum_{r=1}^{4}\sum_{j=3}^{4} p_b(\theta=w,r)_j\; p(\theta=w,r)_j \qquad (5)$$

The only difference between (4) and (5) is that the 25% cooperation level is taken into account in (5) by changing the lower limit of the subscript j i.e. 3 initial parity packets are transmitted. Since $p_b(\theta=w,r)_j$ is the BEP at a specific instance of θ (the transmission case probability) it can be generalized as:

$$p_b(\theta=w,r)_j \le \int_{\gamma} \min\left[\frac{1}{2},\frac{1}{k_c}\sum_{d=d_{free}}^{\infty} c(d)\,p(d\,|\,\gamma)\right] p(\gamma)\,d\gamma \qquad (6)$$

Since γ is the vector state of the channel, for a specific transmission scenario, (6) has to be expanded based on the individual case. The conditional PEP i.e. $p(d \mid \gamma)$ has to also be determined for each case. Note that d_{free} is the free distance of the convolutional code and $c(d)$ is the multiplicity of information bit error events with hamming weight d. The function $p(\gamma)$ is the exponential instantaneous SNR distribution.

The transmission case probability is dependant on the block error probability (BLEP) of the first frame transmissions by the user. The BLEP for a convolutional code is bounded below:

$$P_{block}(\gamma) \le 1-\left(1-P_E(\gamma)\right)^B \le B \cdot P_E(\gamma) \tag{7}$$

The number B denotes the number of branches in the trellis for the transmitted code and k_c is the amount of input information bits in each branch of the trellis. $P_E(\gamma)$ is the first event error probability as is bounded by – [19]:

$$P_E(\gamma) \le \sum_{d=d_f}^{\infty} a(d) P(d \mid \gamma) \tag{8}$$

In (8) $a(d)$ is the multiplicity of code word error events with hamming weight d. The conditional PEP for case 1.1, as in Table 1, is given by:

$$p(d \mid \gamma_{1,1}, \gamma_{1,2}, \gamma_{1,3}, \gamma_{1,4}) = Q\left(\sqrt{2\sum_{i=1}^{4} d_{1,i}\gamma_{1,i}}\right) \tag{9}$$

Equation (8) and (9) are used in (7) together with the limit before averaging techniques, as outlined in [21], to obtain tight bounds for the transmission case probabilities. In (9) $Q(.)$ denotes the Gaussian Q function. During case 1.1 the conditional probability given by:

$$p(\theta = 1.1 \mid \gamma_{1,2,1}, \gamma_{1,2,2}, \gamma_{1,1}, \gamma_{1,2}, \gamma_{2,1}, \gamma_{2,2})_{2Trans} = \ldots$$
$$\left[\prod_{i=1}^{2}\left(1-\left(1-\min\left(1, \sum_{d=d_{free}}^{\infty} a(d)\, p(d \mid \gamma_{1,2,i})\right)\right)^B\right)\right]^2 \cdot \ldots$$
$$\prod_{j=1}^{2}\left(1-\left(1-\min\left(1, \sum_{d=d_{free}}^{\infty} a(d)\, p(d \mid \gamma_{1,j})\right)\right)^B\right) \cdot \ldots$$
$$\prod_{k=1}^{2}\left(1-\left(1-\min\left(1, \sum_{d=d_{free}}^{\infty} a(d)\, p(d \mid \gamma_{2,k})\right)\right)^B\right) \tag{10}$$

To obtain the unconditional case probability the conditional case probability is averaged over the fading distribution i.e.

$$P(\theta) = \int_{\gamma} P(\theta \mid \gamma)\, p(\gamma)\, d\gamma \tag{11}$$

Using (10) the case probability for case 1.1 is derived to be:

$$p(\theta = 1.1)_{2Trans} = \int_0^{\infty}\int_0^{\infty}\int_0^{\infty}\int_0^{\infty}\int_0^{\infty}\int_0^{\infty} p\begin{pmatrix}\theta = 1.1 \mid \gamma_{1,2,1}, \gamma_{1,2,2}, \gamma_{1,1}, \ldots \\ \gamma_{1,2}, \gamma_{2,1}, \gamma_{2,2}\end{pmatrix}$$
$$\prod_{i=1}^{2} p(\gamma_{1,2,i}) \cdot \prod_{j=1}^{2} p(\gamma_{1,j}) \cdot \prod_{k=1}^{2} p(\gamma_{2,k}) \cdot \prod_{z=1}^{2} d\gamma_{1,2,z} \cdot \prod_{s=1}^{2} d\gamma_{1,s} \cdot \ldots$$
$$\prod_{h=1}^{2} d\gamma_{2,h} \tag{12}$$

This happens during 50% best case cooperation, hence the subscript "2Trans." Note that in (12) the unconditional case probability is not averaged over $\gamma_{1,2,1}, \gamma_{1,2,2}, \gamma_{2,1,1}, \gamma_{2,1,2}$ but only over $\gamma_{1,2,1}, \gamma_{1,2,2}$ since the channel is assumed to be reciprocal.

During 25% best case cooperation the case probability for case 1.1 can be calculated in a similar way but taking into account that three incremental packets are transmitted first and by performing integration over all the fading distributions of the uplinks of the users. Similarly the case probabilities can be calculated for the other transmission cases based on the inter user and base station CRC states.

V. PEFORMANCE ANALYSIS

The performance analysis of Cross Layer HARQ 2 Cooperation is analysed here using the BER performance metric. The mother code is still kept at R= 1/4, the memory length, $M = 4$ and the family of RCPC codes is again used from [18]. The amount of information bits in the source packet is kept at $K = 128$ bits. The distance spectra $a(d)$ and $c(d)$ are computed via computer enumeration as well as the separation of the minimum distance d into $d_{1,v}$ or $d_{2,v}$, where $v \in \{1,2,3,4\}$.

Error detection is handled via 16 bit CRC (augmented into the K bit source packet) with the generator polynomial equal to $g_{crc}(x) = 15935$ in hexadecimal notation.

Fig. 2 shows the performance of BER under symmetrical uplink ($\Gamma_{1,0} = \Gamma_{2,0}$) channels for 50% best case

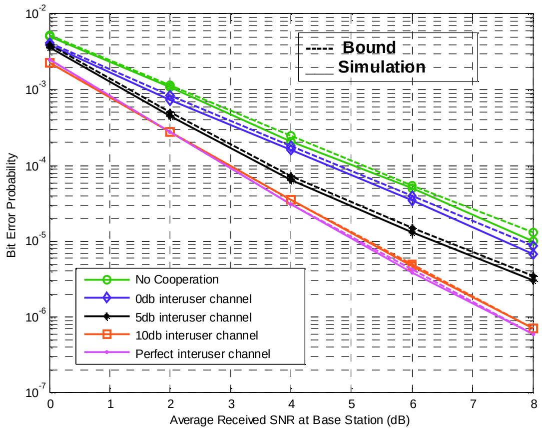

Fig. 2. 50% cooperation with symmetric uplinks.

cooperation, with reciprocal inter user channel conditions i.e. $\gamma_{1,2,l} = \gamma_{2,1,l}$ where $l \in \{1,2\}$.

Cross layer HARQ 2 cooperation shows massive improvements in performance over non cooperation, for the block fading channel, as the inter user channel quality improves. Even under 0dB inter user channel conditions, Cross layer HARQ 2 cooperation shows a 0.6 dB improvement in performance over non cooperation. As the inter user channel quality improves the BER of Cross Layer HARQ 2 cooperation also improves. At 10dB inter user channel conditions Cross Layer HARQ 2 Cooperation maintains a 2.1 dB gain over non cooperation at a BER of 10^{-4}. Note that since this is a block fading channel the SNR regime is smaller over the range of BER.

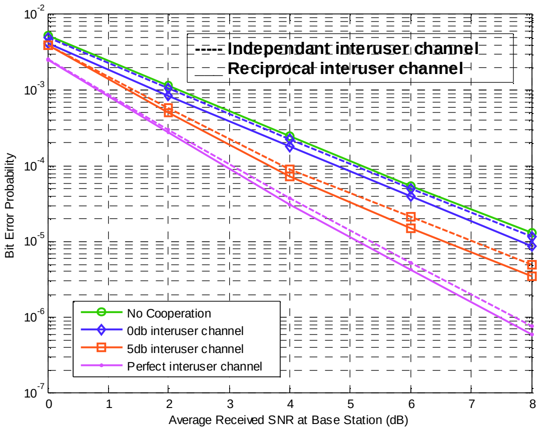

Fig. 3. Independent vs. Reciprocal inter user channels for 50% best case cooperation.

Fig. 3 shows a comparison between reciprocal and independent inter user channel conditions for 50% best case cooperation. The loss in BER performance between coded cooperation and cross layer HARQ 2 cooperation is always within 1 dB.

In Fig. 4 Cross Layer HARQ2 Cooperation during asymmetric uplink channels is shown. User 1’s uplink channel is fixed at 8dB and user 2’s uplink varies form 0-8dB. User 2’s BER improves dramatically by cooperating with user 1 even under poor inter user channel conditions. The performance of user 1 reduces slightly by cooperating under poor uplink conditions but this is negligible and improves as the uplink quality improves. Note that the inter user channel quality is set to 5dB so this also contributes to the slight degradation of BER for user 1. In Fig. 5 comparisons are done between Cross Layer HARQ 2 Cooperation and Coded Cooperation at 0dB and 5dB inter user channel conditions. Cross Layer Hybrid ARQ 2 Cooperation always performs better than coded cooperation even under poor inter user channel conditions with a performance gain of as high as 2.1 dB at 0dB inter user channel conditions. Note that during higher inter user channel conditions 25% cooperation outperforms 50% cooperation with high uplink conditions for both Coded Cooperation and Cross Layer HARQ 2 Cooperation.

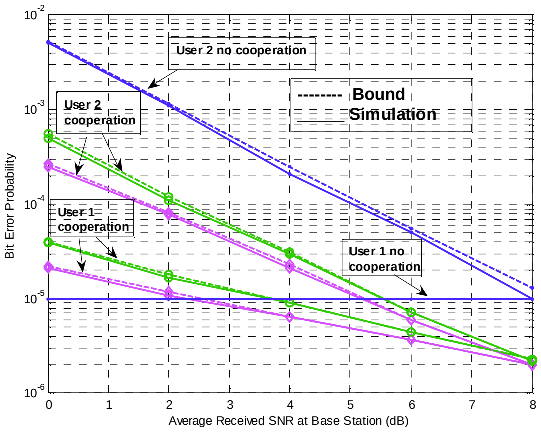

Fig. 4. Asymmetric uplink conditions.

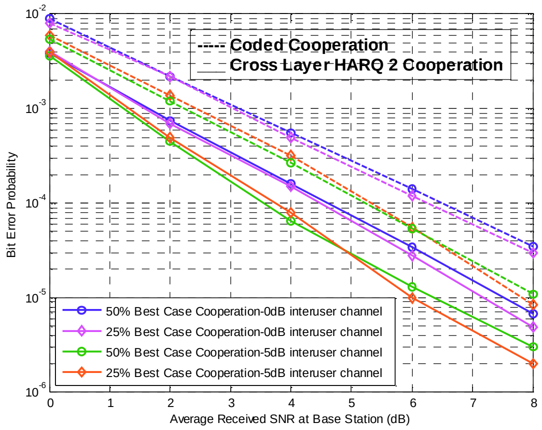

Fig. 5. Comparison between Cross Layer HARQ 2 Cooperation and Coded Cooperation

Due to space considerations, throughput analysis and simulations could not be included in this paper. The reader is referred to [20], where the throughput of the Cross Layer Hybrid ARQ 2 Cooperative Diversity is derived, from first principles, and then confirmed via simulations. The results show that higher throughput performance is observed for Cross Layer HARQ 2 Cooperation, over Coded Cooperation, under both 50% and 25% best case cooperation levels.

Cross Layer HARQ 2 Cooperation always maintains a competitive throughput performance gain over Coded Cooperation due to the incremental nature of the protocol over Coded Cooperation, which in some cases transmits parity when it is not needed.

Cross Layer HARQ 2 Cooperation is thus bandwidth efficient whilst also using CRC to adapt to channel conditions. In this way BER and throughput are improved during Cross Layer HARQ 2 Cooperation over Coded Cooperation since Coded Cooperation will always result in a user transmitting all its available parity without checking or realizing that sufficient parity has been transmitted to the base station - for the decoding of a particular information bit block.

VI. CONCLUSION

In this paper a new framework called Cross Layer Hybrid ARQ 2 Cooperative Diversity is presented. RCPC codes are used for this specific implementation of the Cross Layer Cooperation framework in a block fading channel. Analytical bound analysis is performed for this cross layer design using the PEP to compute the BEP. The simulation results presented for cross layer cooperation are confirmed via the computed analytical bounds. Cross Layer Cooperation saves bandwidth over previous coded cooperation framework by transmitting incremental parity packets on demand as required by the base station. This results in throughput improvements of Cross Layer Hybrid ARQ 2 Cooperative Diversity over Coded Cooperation as explained in Section V. The BER simulation and analytical bounds of Cross Layer Cooperation out perform coded cooperation in almost all inter user and uplink SNR conditions. The variance in BER performance loss lies within a dB with regard to the independent or reciprocal inter user channel assumptions.

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