Cross-Layer Design for Combining Cooperative Diversity with Truncated ARQ in Ad-hoc Wireless Networks♣

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***Abstract*—We propose a cross-layer design which combines truncated ARQ at the link layer and cooperative diversity at the physical layer. In this scheme, both the source node and the relay nodes utilize an orthogonal space-time block code for packet retransmission. In contrast to the previous cooperative diversity protocols, here cooperative diversity is invoked only if the destination node receives an erroneous packet from the source node. In addition, the relay nodes are not fixed and are selected according to the channel conditions using CRC. It will be shown that this combination of adaptive cooperative diversity and truncated ARQ can greatly improve the system throughput compared to the conventional truncated ARQ scheme and fixed cooperative diversity protocols.**

Keywords- *Cooperative diversity, Truncated ARQ, Cross-layer design, MIMO systems, Ad-hoc wireless network.*

I. INTRODUCTION

The use of multiple antennas at both the transmitter and receiver can bring significant capacity gains [1]. Unfortunately, this could be impractical in an ad-hoc wireless network, due to the size of the node or the mobile unit. In order to overcome this limitation, a new form of spatial diversity, whereby diversity gains are achieved via the cooperation of nodes, has been proposed. The main idea behind this approach, which is called cooperative diversity, is to use orthogonal relay transmission to achieve diversity gain. In particular, each node has one or several partners. The node and its partner(s) are responsible for transmitting not only their own information, but also the information of their partner(s). Therefore, a virtual antenna array is obtained through the use of the relays' antennas without complicated signal design or adding more antennas at the nodes.

Sendonaris *et al* proposed the idea of cooperative diversity and showed that node cooperation increases the sum-rate over non-cooperative transmission for ergodic fading links [2-3]. Laneman *et al* further presented several cooperative protocols, such as amplify-and-forward, decode-and-forward, selection relaying and space-time-coded cooperation [4-5]. Other important works include coded cooperation [6-7], cooperative regions analysis [8], diversity-multiplexing tradeoff analysis on cooperative protocols [9], and symbol error rate analysis for Rayleigh-fading channels with K amplifying relays [10].

In most of the present cooperative protocols, no restrictions are imposed on the selection of relays. Therefore, when the channel between the source node and the relay node (s-r channel) is poor, cooperative diversity may result in even worse performance than the non-cooperative case due to severe error propagation [4]. In [4], a selection relaying protocol with 2 nodes cooperation was proposed, where the relay forwards the source node's information only if the s-r channel fading coefficient is above a given threshold. Obviously, such selective protocol can achieve better performance than the fixed ones. However, it is usually not trivial to select a suitable threshold since it depends on the actual value of the channel fading coefficients. A higher threshold will reduce the possible performance gain while a lower one will allow more error propagation which also degrades the performance.

ARQ protocol at the link layer is an effective means to overcome the channel fading, where CRC is usually used for error check and retransmissions are requested if the packet is received erroneously [11-12]. In practice, the maximum number of retransmissions is usually limited so as to minimize the delay and buffer size and such variant ARQ is called truncated ARQ protocol [11]. In this paper, we propose a novel cross-layer design which combines truncated ARQ at the data link layer and cooperative diversity at the physical layer. We will show that through this combination, adaptive cooperative diversity gain can be achieved without any specific threshold. In this new scheme, Q idle nodes around the source node are defined as *relay candidates*. These nodes also receive the packet transmitted from the source node to the destination node and check the CRC results. Only the ones who detect the correct CRC are selected to be relays and involved in the possible retransmission. Specifically, if the destination node fails to detect the packet correctly, retransmission will start where both the source node and the relays utilize a suitable orthogonal space-time block code to retransmit this packet. It can be seen that this new scheme is adaptive to the s-r channels by virtue of the CRC bits instead of some specific threshold and so no error propagation will be incurred by relaying. As a result, this scheme, which is referred to as Selective Cooperative diversity with ARQ (SCA), can be expected to bring significant performance gain over the previous ARQ-only or fixed cooperative diversity schemes. Another scheme which combines truncated ARQ and fixed node cooperation is also considered in this paper. This scheme, which is referred to as Fixed Cooperative diversity with ARQ (FCA), is similar to SCA, except that the relays are pre-assigned and are always fixed during the whole transmission. Compared to SCA, FCA

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requires lower complexity, while it may cause some performance loss due to error propagation.

Throughput is defined as the data rate successfully received and regarded as a key measure of QoS for wireless systems [13]. In this paper, we focus on the throughput at the data link layer. The loss due to retransmissions of the packet is also included here. The throughput expressions of SCA and FCA are derived and compared to that of the pure truncated ARQ scheme. It will be shown that when the s-r channels are perfect, both SCA and FCA can achieve substantial gains over the truncated ARQ scheme thanks to cooperative diversity. However, with poor s-r channels, the performance of FCA will deteriorate rapidly and even become worse than the truncated ARQ scheme due to error propagation. On the other hand, SCA will always keep the highest throughput among all the schemes, which is due to its adaptability to the s-r channels.

This paper is organized as follows. The channel model and the details of the proposed SCA are provided in Section II. Section III presents the throughput comparison of SCA, FCA and the pure truncated ARQ scheme. The numerical results are shown in Section IV. Finally, Section V summarizes and concludes this paper.

II. Cooperative Diversity with Truncated ARQ

In this section, we will propose a new cross-layer design which combines truncated ARQ at the link layer and cooperative diversity at the physical layer.

A. Scheme Description

We consider an ad-hoc network with K nodes and assume that each node is equipped with only one antenna. Q idle nodes are assumed to be available as the possible relays for the source node during the packet transmission. These Q nodes are referred to as *relay candidates*. Particularly, the source node transmits a data packet with a C-bit CRC attached. The destination node detects the CRC and then sends an acknowledgement that is either positive (ACK) or negative (NACK) back to the source node. At the same time, all the Q relay candidates check the CRC received from the source node and the ones who get the positive results are selected to be relays. If the packet is correctly detected by the destination node (with ACK feedback), the source node continues to transmit a new data packet and the above process is repeated. Otherwise, retransmission will start. Both the source node and the relays will jointly retransmit the packet by utilizing a suitable orthogonal space-time block code. The retransmission continues until the packet is successfully delivered, or the number of retransmissions exceeds $N_r^{\max}$ which is a preset parameter indicating the maximum number of retransmissions allowed per packet.

It can be seen that this new scheme can adapt to the s-r channels thanks to the use of CRC bits. Only the relay candidates who correctly detect the packet are selected to be relays. Adaptive cooperative diversity gain is actually achieved and error propagation can be avoided. Besides, node cooperation is adopted only when the destination node fails to detect the packet correctly. Higher efficiency can therefore be obtained compared to the previous cooperative diversity protocols. As a result, it can be expected that the proposed SCA scheme can bring significant throughput gains over those ARQ-only or cooperative-diversity-only schemes.

B. Channel Model

The communication between a source and a destination node is assumed to be over a quasi-static flat Rayleigh fading channel and facilitated by v relays which are selected from Q relay candidates, as shown in Fig. 1. In addition, a perfect channel knowledge is assumed to be available at the receiver side only, through the use of training sequences.

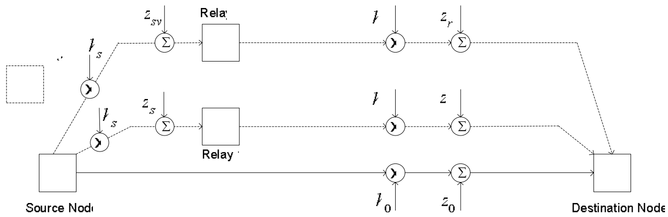

Fig. 1: Channel model. Here Q idle nodes around the source node are assumed to be available as the relay candidates.

At time slots $t_1, \ldots, t_L$, the source node sends a packet $x^s_{t_1}, \ldots, x^s_{t_L}$ with transmission power P_t per symbol, where L is the packet length and $x^s_{t_i}$ is an M-QAM modulated symbol, i=1,…, L. The signal received by the destination node at time slot t_i, i=1,…, L, is then given by

$$y^d_{t_i} = h_0 x^s_{t_i} + z_0 \tag{1}$$

where h_0 is the channel gain, which is assumed to be a complex Gaussian random variable with zero-mean and variance σ_0^2. Here σ_0^2 accounts for the effect of large-scale path loss and shadowing [5-6]. Also, z_0 represents the additive white Gaussian noise with mean zero and variance N_0. At the *j-th* relay candidate, j=1,…, Q, the received signal is given by

$$y^{r_j}_{t_i} = h_{sj} x^s_{t_i} + z_{sj} \tag{2}$$

where $z_{s1}, \ldots, z_{sQ}$ are i.i.d. complex Gaussian random variables with zero-mean and variance N_0. Likewise, the fading coefficients $h_{s1}, \ldots, h_{sQ}$ are i.i.d. complex Gaussian random variables with zero-mean and variance σ_s^2. In the following, the transmission of the packet $x^s_{t_1}, \ldots, x^s_{t_L}$ is referred to as *direct transmission*.

If the destination node fails to detect the packet correctly, retransmission will start at time slot t_{L+1}. Let N_r be the number of retransmissions, then the received signal at the destination node at time slot t_{L+N_rL+i} is given by

$$y^d_{t_{L+N_rL+i}} = h_0 x^s_{t_{L+N_rL+i}} + z_0 + \sum_{j=1}^{v} h_{rj} x^{r_j}_{t_{L+N_rL+i}} + z_{rj} \tag{3}$$

for i=1,…, L. $x^s_{t_{L+N_rL+i}}$ and $x^{r_j}_{t_{L+N_rL+i}}$ are the space-time block coded symbols transmitted by the source node and the *j-th* relay node with the transmission power $P_t/(v+1)$, respectively. The additive noise $z_{r1}, \ldots, z_{rv}$ and fading coefficients $h_{r1}, \ldots, h_{rv}$ are i.i.d. complex Gaussian random variables with zero-mean and variance N_0 and σ_r^2, respectively. In this paper, it is assumed that Q relay candidates are nearby the source node so that the large scale fading of r-d channels (the channel between the relay node and the destination node) can be approximated to be the same as that of the s-d channels (the channel between the source node and the destination node), i.e., $\sigma_r^2 = \sigma_0^2$.

In this paper, γ_{sd} and γ_{sr} represent the average SNR per symbol of the direct transmission and the retransmission, respectively. p_{pd} and p_{pr} denote the packet error rate (PER) of the direct transmission and the retransmission, respectively. Similarly, p_{sd} and p_{sr} are the symbol error rate (SER) of the direct transmission and the retransmission, respectively.

III. THROUGHPUT ANALYSIS

In this section, the throughput of SCA is analyzed. For the sake of comparison, the throughput expressions of the pure truncated ARQ scheme and FCA are also provided. Recall that FCA is similar to SCA, except that the relays are pre-assigned and always fixed during the whole transmission. Therefore, FCA requires lower complexity than SCA, while it may cause some performance loss due to error propagation, as will be shown later.

A. Throughput of the truncated ARQ scheme

Assume that the total length of a data packet is L, where a C-bit CRC is attached and a square M-QAM is adopted with $b=\log_2 M$ bit/symbol. The symbol rate R_s is assumed to be constant and thus omitted in the following. For a point-to-point single transmission, the throughput is given by [13]

$$T = \frac{L-C}{L} b(1-p_{sd})^{L/b} \tag{4}$$

where p_{sd} is the SER of the direct transmission.

With truncated ARQ, retransmission will start if the packet is detected erroneously and will continue until the packet is successfully delivered or the number of retransmissions N_r exceeds $N_r^{\max}$. In the retransmission, the data rate will be reduced since the packet is repeated. Therefore, the throughput of the truncated ARQ scheme can be obtained as

$$T_{ARQ} = \frac{L-C}{L} b \cdot P_A / \bar{N}_A \tag{5}$$

where

$$P_A = 1 - p_{pd}(p_{pr})^{N_r^{\max}} \tag{6}$$

is the packet successful rate. $\bar{N}_A$ is the average weight due to retransmissions, which is given by

$$\bar{N}_A = 1\cdot(1-p_{pd}) + \sum_{i=2}^{N_r^{\max}} i \cdot p_{pd}(p_{pr})^{i-2}(1-p_{pr}) + \left(N_r^{\max}+1\right)\cdot \left(p_{pd}(p_{pr})^{N_r^{\max}-1}(1-p_{pr}) + p_{pd}(p_{pr})^{N_r^{\max}}\right) \tag{7}$$

where p_{pd} and p_{pr} are given by

$$p_{pd} = 1-(1-p_{sd})^{L/b} \text{ and } p_{pr} = 1-(1-p_{sr})^{L/b} \tag{8}$$

Obviously in the truncated ARQ scheme, the SER of the retransmission $p_{sr} = p_{sd}$. Therefore, we have $p_{pr} = p_{pd}$ and (5) can then be simplified as

$$T_{ARQ} = \frac{L-C}{L} b \cdot (1-p_{pd}) \tag{9}$$

From (9) and (4), it can be seen that the truncated ARQ scheme has exactly the same throughput as the direct transmission. Although the truncated ARQ scheme can effectively improve the reliability, it requires more transmission time. As a result, no throughput gain can be actually achieved. Nevertheless, we will show that by combining the truncated ARQ scheme and cooperative diversity, the SER of the retransmission will be improved greatly so that significant throughput gains can be obtained.

In this paper, it is assumed that the s-d channel is a flat Rayleigh fading channel. As such, the closed-form expression for the average SER of M-QAM is given by [14]

$$p_{sd} = 2\left(1-\frac{1}{\sqrt{2^b}}\right)\left(1-\sqrt{\frac{g\gamma_{sd}}{1+g\gamma_{sd}}}\right) + \left(1-\frac{1}{\sqrt{2^b}}\right)^2 \cdot \left[\frac{4}{\pi}\sqrt{\frac{g\gamma_{sd}}{1+g\gamma_{sd}}}\arctan\left(\sqrt{\frac{1+g\gamma_{sd}}{g\gamma_{sd}}}\right) - 1\right] \tag{10}$$

where $g = 3/[2(2^b-1)]$. γ_{sd} is the average SNR per symbol of the direct transmission, which is given by $\gamma_{sd} = \sigma_0^2 P_t / N_0$. Therefore, by substituting (10) into (8) and (9), the throughput of the pure truncated ARQ scheme, T_{ARQ}, can be computed.

B. Throughput of FCA

In FCA, v pre-assigned relays and the source node are used in the retransmission and both of them utilize a (v+1)-symbol orthogonal space-time block code to send the packet together. Therefore, the throughput of FCA can be obtained as

$$T_{FCA} = \frac{L-C}{L} b \cdot P_F / \bar{N}_F \tag{11}$$

where P_F is the packet successful rate which can be computed by (6). $\bar{N}_F$ is the average number of retransmissions per packet, which is given by

$$\bar{N}_F = 1\cdot(1-p_{pd}) + \frac{1}{R}\left[\sum_{i=2}^{N_r^{\max}} i \cdot p_{pd}(p_{pr})^{i-2}(1-p_{pr}) + \left(N_r^{\max}+1\right)\cdot p_{pd}(p_{pr})^{N_r^{\max}-1}\right] \tag{12}$$

where R is the rate of STBC (for a k-symbol-T-slot STBC, $R=k/T$). In this case the average SER of the retransmission $p_{sr} \neq p_{sd}$ since multiple antenna transmission is adopted in the retransmission. In FCA, the retransmission can be regarded as (v+1)-transmit-1-receive STBC with M-QAM symbols over Rayleigh fading channels. From [15], we know that the average SER of m-transmit STBC with M-QAM over an m by n Rayleigh fading channel is given by

$$p_s = \frac{2q\phi_r(g)}{\sqrt{\pi}}\frac{\Gamma(mn+1/2)}{\Gamma(mn+1)} \cdot {}_2F_1\left\{mn; \frac{1}{2}; mn+1; \frac{1}{1+g\gamma_s}\right\} - \frac{2q^2}{\pi}\frac{\phi_r(2g)}{2mn+1} F_1\left\{1, mn, 1; mn+\frac{3}{2}; \frac{1+g\gamma_s}{1+2g\gamma_s}, \frac{1}{2}\right\} \tag{13}$$

where γ_s is the average SNR per symbol, $q = 1-1/\sqrt{2^b}$, and $\phi_r(s)$ $(1+s\gamma_s)^{-mn}$. ${}_2F_1(a,b;c;x)$ and $F_1(a,b,b';c;x,y)$ are the Gauss hypergeometric function and Appell hypergeometric function, respectively [15]. Therefore, p_{sr} can be obtained by substituting m=v+1, n=1, and $\gamma_s = \gamma_{sr}$ into (13).

The computation of γ_{sr} should include the effect of error propagation since in FCA the relay nodes retransmit their estimates instead of the original signals. We provide the expression of γ_{sr} of FCA in Theorem 1. Due to space limitation, the proof is omitted here.

Theorem 1: The average SNR per symbol of the retransmission in FCA, γ_{sr} *, is given by*

$$\gamma_{sr}=\frac{\gamma_{sd}}{a\gamma_{sd}+(v+1)R} \tag{14}$$

where

$$a=\frac{24(v+1)}{2^{b}-1}(1-2^{-b/2})\left[\left(1-\sqrt{\frac{g\gamma_{ss-r}}{1+g\gamma_{ss-r}}}\right)+(1-2^{-b/2})\cdot\left(\frac{4}{\pi}\sqrt{\frac{g\gamma_{ss-r}}{1+g\gamma_{ss-r}}}\arctan\left(\sqrt{\frac{1+g\gamma_{ss-r}}{g\gamma_{ss-r}}}\right)-1\right)\right] \tag{15}$$

γ_{ss-r} *is the average SNR per symbol of the s-r channel, which is given by* $\gamma_{ss-r}=\sigma_s^2 P_t / N_0$.

By combining Theorem 1 and (11-12), the throughput of FCA, T_{FCA}, can be obtained.

C. Throughput of SCA

In SCA, the number of relay nodes *v* is not fixed. Only the candidates who detect the correct CRC results are involved in the retransmission. Therefore, the throughput expression of SCA should be written as

$$T_{SCA}=\frac{L-C}{L}b\cdot P_S/\bar{N}_S \tag{16}$$

where P_S and $\bar{N}_S$ are the packet successful rate and the average number of retransmissions per packet, respectively. They are given by

$$P_S=\sum_{j=0}^{Q}\left(1-p_{pd}(p_{pr}(j))^{N_r^{\max}}\right)\cdot P(v=j) \tag{17}$$

and

$$\bar{N}_S=\sum_{j=0}^{Q}N(j)\cdot P(v=j) \tag{18}$$

with $N(j)$ given by

$$N(j)=1-p_{pd}+\frac{p_{pd}}{R(j)}\left[\sum_{i=2}^{N_r^{\max}} i\cdot p_{pr}(j)^{i-2}(1-p_{pr}(j))+\left(N_r^{\max}+1\right)\cdot p_{pr}(j)^{N_r^{\max}-1}\right] \tag{19}$$

for j=0,…, Q.

In (19), $R(j)$ is the rate of a $(j+1)$-symbol STBC (let $R(0)=1$) and $p_{pr}(j)$ is the PER of the *j*-relay retransmission. In SCA, no error propagation is introduced by relays. Therefore, with a *j*-relay retransmission (j>0), $p_{sr}(j)$ can be obtained via (13) by substituting $m=j$, n=1 and $\gamma_s=\gamma_{sr}(j)=\frac{\gamma_{sd}}{jR(j)}$. Otherwise, $p_{sr}(j)=p_{sd}$ (for j=0). $P(v=j)$ is the probability that *j* relay candidates detect the correct CRC results and given by

$$P(v=j)=\binom{Q}{i}\left(1-p_{ps-r}\right)^{j}\left(p_{ps-r}\right)^{Q-j} \tag{20}$$

where j=0,…,Q. p_{ps-r} is the packet error rate of the s-r channel and we have $p_{ps-r}=1-(1-p_{ss-r})^{L/b}$. p_{ss-r} is the SER of the s-r channel and can be computed by substituting γ_{ss-r} into (10).

By combining (16-20), the throughput of SCA, T_{SCA}, can be obtained.

IV. THROUGHPUT COMPARISON

Assume that Q=2, which means that only the nearest Q=2 idle nodes around the source node are the relay candidates. C=16 bit CRC is assumed to be adopted in each packet. Assume that the packet length L is 120 and QPSK is adopted (i.e., b=2). The maximum number of retransmission $N_r^{\max}$ is assumed to be 3.

Fig. 2 shows the throughput results of the pure truncated ARQ, FCA with 1 relay, FCA with 2 relays and SCA when the average SNR per symbol of s-r channel γ_{ss-r} is 20dB. The *x*-axis "SNR" is referred to the average SNR per symbol of the direct transmission γ_{sd}. γ_{ss-r}=20dB indicates a rather good s-r channel. In this case, cooperative diversity gain can be fully exploited to improve the SER of the retransmission and so substantial throughput gains can be expected to be achieved by SCA and FCA. As Fig. 2 shows, both FCA and SCA can achieve substantial throughput gains over the truncated ARQ scheme. SCA always obtains the highest throughput thanks to its adaptability to the s-r channels. In FCA, the effect of error propagation is rather slight thanks to the good quality of the s-r channels. Therefore, the throughput can be improved significantly compared to the truncated ARQ scheme. It should be noticed that at high SNR, FCA with 1 relay gets better performance than the 2 relay case. This is because with 3 nodes cooperation, the space-time block code is not full rate.[1] When the SNR of the s-d channel (also the r-d channels) is high enough (which implies a good diversity gain), rate loss will significantly influence the throughput. Therefore, although in low SNR FCA with 2 relays can achieve a better throughput, this throughput will become less than that of the 1 relay case when SNR is high enough.

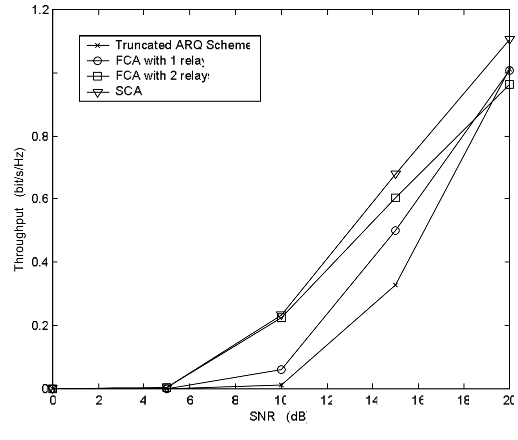

Fig. 2: Throughput curves of the truncated ARQ scheme, FCA with 1 relay, FCA with 2 relays and SCA with L=120, b=2 and γ_{ss-r}=20dB

[1] In this paper, we take the [3,4,3] STBC code given in [16] (pp. 2485, Eqn. (99)). Therefore, the rate R is 3/4.

Fig. 3 shows the case when γ_{ss-r} decreases to 15dB. Here the s-r channel is not good enough and therefore the performance of FCA deteriorates rapidly due to the effect of error propagation. When SNR is high which indicates a good s-d channel, FCA even gets a worse throughput than the truncated ARQ scheme. In contrast, SCA still achieves the highest throughput among all the schemes and a significant gain can be observed.

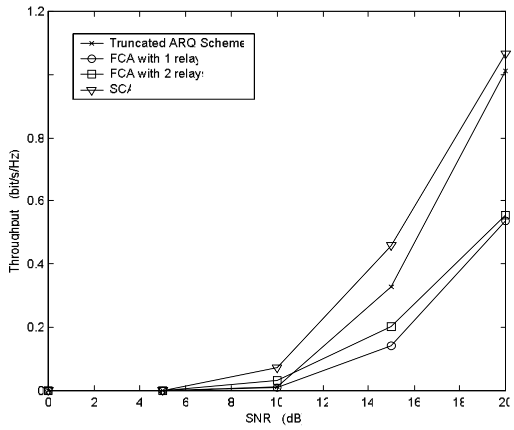

Fig. 3: Throughput curves of the truncated ARQ scheme, FCA with 1 relay, FCA with 2 relays and SCA with L=120, b=2 and γ_{ss-r} =15dB

From the above discussion, we can conclude that SCA can always achieve a significant throughput gain irrespective of whether the s-r channel is good or not. In contrast, the performance of FCA largely depends on the quality of the s-r channel. It can improve the throughput only when the s-r channel is perfect. Otherwise, the performance will deteriorate rapidly due to error propagation and may be even worse than the pure truncated ARQ scheme. This can be more clearly seen in Fig. 5, where the average SNR per symbol of the s-d channel γ_{sd} is fixed to be 15dB. Here the x-axis is given by $\rho = \gamma_{ss-r} / \gamma_{sd}$. It can be seen that FCA can achieve a higher throughput than the truncated ARQ scheme only when ρ increases to 2. This can give us some insights on the selection of cooperation region when fixed cooperative diversity is adopted. SCA again achieves the highest throughput and substantial gains can be observed for all the values of ρ.

V. CONCLUSIONS

In this paper, we proposed a cross-layer design method for combing truncated ARQ at the link layer and cooperative diversity at the physical layer, which has been shown to be able to greatly improve the system throughput. The throughput expressions of the proposed SCA scheme, FCA scheme and the pure truncated ARQ scheme are derived and the comparison of these three schemes showed that the proposed SCA scheme can always achieve the highest throughput and effectively avoid error propagation.

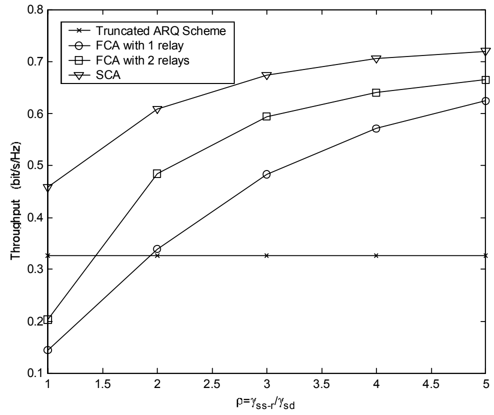

Fig. 4: Throughput curves of the truncated ARQ scheme, FCA with 1 relay, FCA with 2 relays and SCA with L=120, b=2 and γ_{sd} =15dB

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