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ORIGINAL CONTRIBUTION

Selection Combining-based Packet Combining Schemes for Multi-path Diversity System

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Abstract In multi-path diversity system, the receiver receives several signals bearing the same information, through distinct and independent fading channels. The packets traversing through independent and distinct paths would undergo different degree of fading. Thus, even if the copy of the packet is distorted badly in one path, the copy received from other paths might be lesser distorted; so by combining the copies of the packet, the correct copy of the packet could be retrieved. In this paper, selection combining-based packet combining scheme for multi-path diversity system have been proposed. In the proposed scheme, a packet is transmitted to the receiver via m different paths, where $m \geq 2$. At the receiver, erroneously received copies of the packet are combined to recover the correct copy of the packet. The proposed selection combining-based packet combining scheme is analyzed and studied using simulation on MatLab. It was observed experimentally that proposed scheme has superior performance than that of conventional packet combining schemes. The superior performance of the proposed scheme with selection combining scheme can be attributed to diversity achieved using multi-path transmission.

Keywords Packet combining · Majority packet combining · Aggressive packet combining · Multipath diversity · Selection combining · Error control

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Introduction

In multi-path diversity system, the receiver receives several signals bearing the same information, through distinct and independent fading channels. The probability that all the signals are simultaneously in deep fade is low [1–4]. The packets traversing through different paths would undergo different degree of fading [5], which would cause different link error syndrome in each path. Thus, even if the copy of the packet is distorted badly in one path, the copy received from other paths might be lesser distorted. Traditionally distorted or erroneous packets are rejected by the receiver, and error correction is done using retransmission of the packets. However, the erroneous packet may contain correct bits in addition to erroneous bits, so by combining the copies of the packet received from distinct and independent paths, the correct copy of the packet could be retrieved [6–9]. This would reduce the number of retransmissions and would reduce packet error rate to make the wireless communication system more reliable and throughput efficient. In this paper, a selection combining based aggressive packet combining scheme is proposed for multipath diversity system. The proposed model for the proposed scheme is discussed in Sect. 2. Section 3 discusses the proposed scheme in detail, followed by the analysis and simulation result in Sects. 3, and 4 concludes the paper.

Proposed Model

The proposed system for selection combining-based packet combining (SC + PC) scheme and/or selection combining-based aggressive packet combining (SC + APC) scheme is shown in Fig. 1. Let m_1, m_2, …., m_m be the distinct and independent $'m'$ paths between the transmitter and the

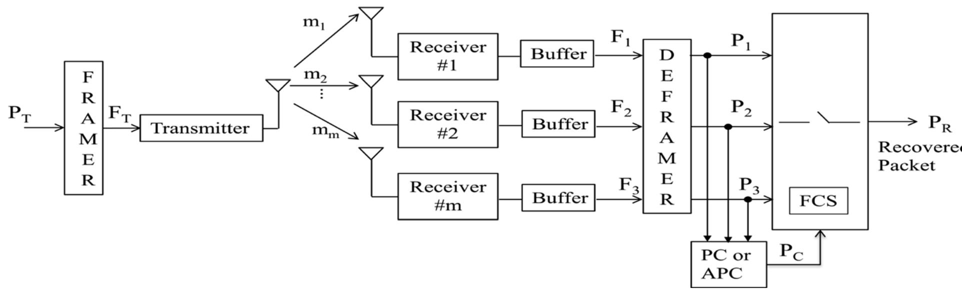

Fig. 1 Simplified model for the SC + PC scheme and SC + APC scheme for multipath diversity system

receiver. Each path is used to transmit a frame (F_T) which contains data (P_T), corresponding header and frame check sequence (FCS) for error detection. At the receiver, each frame (F_T) received is de-framed into packet (P_T) and are buffered. In the receiver, error correction is performed in two steps, namely: selection combining (SC) and packet combining (PC) scheme / aggressive packet combining (APC) scheme.

In SC, each received and buffered packet is individually processed. A transmission is declared successful, if at least a copy of a transmitted packet is received without detectable errors. After the successful transmission of a packet, the buffered copies of the packet are flushed from the buffer; correct copy of the packet delivered to the end user; and its corresponding ACK is sent to the transmitter by the receiver for transmission of the next packet if any. If SC scheme fails, then packet combining is performed using the received erroneous copies of the transmitted packet. In multi-path diversity system, m number of copies of a packet are received from m distinct and independent paths, where $m \geq 2$. Accordingly we have considered two scenarios: two-path diversity scenario where $m = 2$, i.e., copies of packets are received from two different paths and multi-path diversity scenario where $m \geq 3$, i.e., copies of the packet are received from more than two paths. The two-path diversity system is discussed next in detailed.

SC-PC Scheme for Two-Path Diversity System

Let two copies of the transmitted packet are received at the receiver via two paths: m_1 and m_2. Let the bit error rate (BER) in paths m_1 and m_2 be α_1 and α_2, respectively, and $'n'$ be the packet size in bits. The two copies of the packet received from the two distinct and independent paths, m_1 and m_2, are buffered and are processed separately. In the first step, named selection combining, error detection is performed using each received copy separately. If at least a copy is received without any detectable errors, then the transmission is considered successful and this copy is accepted as the correct copy of the packet. Let the probability that the correct copy is obtained using SC scheme be Q_{SC}. The probability of successful transmission using SC scheme is:

$$Q_{SC} = 1 - [(1 - (1 - \alpha_1)^n)(1 - (1 - \alpha_2)^n)] \quad (1)$$

If the first step fails, the receiver performs PC scheme. In PC scheme, the receiver combines the received two erroneous copies of the packet using XOR operation in order to locate the position of erroneous bits; the located erroneous bits are bit inverted in an attempt to obtain the corrected packet [10]. Let the probability that correct copy would be recovered from received erroneous copies of the packet by using packet combining (PC) scheme after SC scheme has failed be $Q_{PC|\overline{SC}}$. Let $SC + PC$ be the event that the packet is corrected using SC scheme and/or PC scheme and $\overline{SC + PC}$ be the event that the packet is not corrected using neither SC nor PC scheme. Therefore,

$$P(\overline{SC + PC}) = P_{SC+PC} = 1 - \left[Q_{SC} + Q_{PC|\overline{SC}}\right] \quad (2)$$

The PC scheme is invoked when SC scheme fails; PC scheme fails to correct when at least an error occurs in the same bit position of the received erroneous copies. The probability of double bit error at the same bit location is $(\alpha_1\alpha_2)$. Further, the correction capability of PC scheme is bounded by the computational complexity of the system [10, 11], let $N_{\max}$ be the total number of erroneous bits that could be corrected using PC scheme. The probability of successful transmission in kth path and error in the remaining path is $(1 - \alpha_k)(\alpha_1\alpha_2/\alpha_k)$, where $k = 1$ or 2. Thus, the corresponding probability of a successful transmission using PC scheme is:

$$Q_{PC|\overline{SC}} = \sum_{k_1}^{N_{\max}-1} \binom{n}{k_1} \alpha_1^{k_1} (1 - \alpha_1)^{n-k_1} \times (1 - \alpha_1)^{k_1} \sum_{k_2}^{N_{\max}-k_1} \binom{n-k_1}{k_2} \alpha_2^{k_2} (1 - \alpha_2)^{n-k_2}$$

Rewriting the equation

$$Q_{PC|\overline{SC}} = \sum_{k_1}^{N_{\max}-1} \sum_{k_2}^{N_{\max}-k_1} \binom{n}{k_1} \binom{n-k_1}{k_2} \alpha_1^{k_1} \alpha_2^{k_2} (1-\alpha_1)^n (1-\alpha_2)^{n-k_1-k_2} \quad (3)$$

Substituting (1) and (3) into (2),

$$P_{SC+PC} = [(1-(1-\alpha_1)^n)(1-(1-\alpha_2)^n)] - \sum_{k_1}^{N_{\max}-1} \sum_{k_2}^{N_{\max}-k_1} \binom{n}{k_1} \binom{n-k_1}{k_2} \times \alpha_1^{k_1} \alpha_2^{k_2} (1-\alpha_1)^n (1-\alpha_2)^{n-k_1-k_2} \quad (4)$$

Packet throughput of SC + PC scheme is:

$$T_{SC+PC} = 1 - P_{SC+PC} \quad (5)$$

If PC scheme also fails, the receiver sends NAK to the transmitter for retransmission of the packet. Otherwise, if the correct copy of the packet is retrieved, ACK is sent to the transmitter for the transmission of the next packet.

SC-APC Scheme For Multi-Path Diversity System

In the multi-path diversity system, the receiver receives multiple (≥ 3) copies of the transmitted packet from $m \geq 3$ distinct and independent paths. From among the multiple received copies of the packet, the receiver selects three copies of the packet that were received through paths with higher signal-to-noise (SNR) ratio. Let m_1, m_2, m_3 be the established paths, with higher SNR, between the transmitter and the receiver and let their channel error rates be α_1, α_2 and α_3, respectively. The receiver receives three copies of the packet. The receiver applies SC scheme by checking for errors in the each received copy separately. If any of the copy of the packet is received without errors, the receiver accepts the copy, flushes the buffer and requests for transmission of the next packet by sending an ACK to the transmitter. If SC scheme fails, the receiver performs APC scheme [11, 12] using the received three erroneous copies. If the corrected copy of the packet is obtained using APC scheme, the receiver accepts the copy, flushes the buffer and request for transmission of the next packet by sending an ACK to the transmitter. Otherwise, the receiver requests for retransmission of the packet by sending NAK to the transmitter.

Let $(SC + APC)$ be the event that the packet is corrected using SC scheme and/or APC scheme and P_{SC+APC} be the probability that the packet is in error in SC-APC scheme, i.e., the packet is not corrected using SC scheme and/or APC scheme. Thus as shown in (2), P_{SC+APC} can be obtained as:

$$P_{SC+APC} = 1 - \left[Q_{SC3} + Q_{APC|\overline{SC}}\right] \quad (6)$$

whereQ_{SC3} is the probability of a successful transmission using SC scheme in multi-path diversity system and $Q_{APC|\overline{SC}}$ is the probability of a successful packet transmission when APC scheme is activated after SC scheme failed. SC scheme is considered successful if at least a copy is received without any detectable errors; therefore,

$$Q_{SC3} = 1 - [(1-(1-\alpha_1)^n)(1-(1-\alpha_2)^n)(1-(1-\alpha_3)^n)] \quad (7)$$

APC scheme is applied when SC scheme fails. APC scheme can correct single bit error and double bit error even if error occur in the same bit location of two erroneous copies [13–16], but correction of double bit error is limited by the computational complexity (number of least reliable bits in the combined packet) involved in the search of correct bit pattern. Let A be the maximum number of allowed least reliable bits in the combined packet. The probability that correct copy of the packet will be retrieved by APC scheme after SC scheme has failed is equal to the probability of single bit error and probability of double bit error (bit error at the same bit location of two erroneous copies) up to maximum of A. Let the probability of single bit error and double bit error corrected by SC-APC scheme be Q_{Sbit} and Q_{Dbit}, respectively. Then the probability of correction using APC scheme after SC scheme has failed is:

$$Q_{APC|\overline{SC}} = Q_{Sbit} + Q_{Dbit} \quad (8)$$

where

$$Q_{Sbit} = \sum_{k_1=1}^{n-2} \binom{n}{k_1} \alpha_1^{k_1} (1-\alpha_1)^{n-k_1} \times (1-\alpha_1)^{k_1} \sum_{k_2=1}^{n-k_1-1} \binom{n-k_1}{k_2} \alpha_2^{k_2} (1-\alpha_2)^{n-k_1-k_2} \times (1-\alpha_2)^{k_2} \sum_{k_3=1}^{n-k_1-k_2} \binom{n-k_1-k_2}{k_3} \alpha_3^{k_3} (1-\alpha_3)^{n-k_1-k_2-k_3}$$

Rewriting the equation for Q_{Sbit}

$$Q_{Sbit} = \sum_{k_1=1}^{n-2} \sum_{k_2=1}^{n-k_1} \sum_{k_3=1}^{n-k_1-k_2} \binom{n}{k_1} \binom{n-k_1}{k_2} \binom{n-k_1-k_2}{k_3} \alpha_1^{k_1} \alpha_2^{k_2} \alpha_3^{k_3} (1-\alpha_1)^n (1-\alpha_2)^{n-k_1} (1-\alpha_3)^{n-k_1-k_2-k_3} \quad (9)$$

And the probability that there is an erroneous at the same bit location of two out of three erroneous copies is $(1-\alpha_k)(\alpha_1\alpha_2\alpha_3/\alpha_k)$, where $k = 1$ or 2 or 3. Thus, the probability of occurrence double bit error in the same location of two out of three erroneous copies is:

$$Q_{Dbit} = \sum_{k_1=1}^{n-1} \binom{n}{k_1} \alpha_1^{k_1} \alpha_2^{k_1} (1-\alpha_1)^{n-k_1} (1-\alpha_2)^{n-k_1} \times (1-\alpha_1)^{k_1} (1-\alpha_2)^{k_1} \sum_{k_2=1}^{n-k_1} \binom{n-k_1}{k_2} \alpha_3^{k_2} (1-\alpha_3)^{n-k_1-k_2}$$

Rewriting the equation for Q_{Dbit}

$$Q_{Dbit} = \sum_{k_1=1}^{n-1} \sum_{k_2=1}^{n-k_1} \binom{n}{k_1} \binom{n-k_1}{k_2} \alpha_1^{k_1} \alpha_2^{k_1} \alpha_3^{k_2} (1-\alpha_1)^n (1-\alpha_2)^n (1-\alpha_3)^{n-k_1-k_2} \tag{10}$$

Therefore, substituting (9) and (10) into (8),

$$Q_{APC|\overline{SC}} = \left[\sum_{k_1=1}^{n-2} \binom{n}{k_1} \binom{n-k_1}{k_2} \binom{n-k_1-k_2}{k_3} \alpha_1^{k_1} \alpha_2^{k_2} \alpha_3^{k_3} (1-\alpha_1)^n \times (1-\alpha_2)^{n-k_1} (1-\alpha_3)^{n-k_1-k_2-k_3} \right] + \left[\sum_{k_1=1}^{n-1} \sum_{k_2=1}^{n-k_1} \binom{n}{k_1} \binom{n-k_1}{k_2} \alpha_1^{k_1} \alpha_2^{k_1} \alpha_3^{k_2} \right] (1-\alpha_1)^n (1-\alpha_2)^n (1-\alpha_3)^{n-k_1-k_2} \tag{11}$$

Thus substituting (7) and (11) into (6), the probability that the packet is in error using SC-APC scheme is:

$$P_{SC+APC} = (1-(1-\alpha_3)^n)^3 - \left[\sum_{k_1=1}^{n-2} \binom{n}{k_1} \binom{n-k_1}{k_2} \binom{n-k_1-k_2}{k_3} \alpha_1^{k_1} \alpha_2^{k_2} \alpha_3^{k_3} (1-\alpha_1)^n (1-\alpha_2)^{n-k_1} (1-\alpha_3)^{n-k_1-k_2-k_3} \right]. - \left[\sum_{k_1=1}^{n-1} \sum_{k_2=1}^{n-k_1} \binom{n}{k_1} \times \binom{n-k_1}{k_2} \alpha_1^{k_1} \alpha_2^{k_1} \alpha_3^{k_2} (1-\alpha_1)^n (1-\alpha_2)^n (1-\alpha_3)^{n-k_1-k_2} \right] \tag{12}$$

And the packet throughput of SC-APC scheme is

$$T_{SC+APC} = 1 - P_{SC+APC} \tag{13}$$

If APC scheme also fails, the receiver sends NAK to the transmitter for retransmission of the packet. Otherwise, if the correct copy of the packet is retrieved, an ACK is sent to the transmitter for the transmission of the next packet.

Simulation Results

The proposed SC-PC scheme and SC-APC scheme for multi-path diversity system were simulated using MATLAB R2012b in a windows-8 environment on an Intel based 1.70 GHz PC having 4 GB RAM.

Experiments were conducted to compare the performance of SC-PC scheme, APC scheme, SC-APC scheme and selection combining with majority combining (SC-MC) proposed in [8]. The packet error rates of APC scheme (P_{APC}), SC-PC scheme (P_{SC+PC}), SC-MC scheme (P_{SC+MC}) and SC-APC scheme (P_{SC+APC}) for packet size $n = 56$, $N_{max} = 6$, $A = 6$ and BER ranging from 10^{-3} to 0.12 for path m_1 and BER ranging from 10^{-3} to 0.11 for path m_2 and BER ranging from 10^{-3} to 10^{-1} for path m_3 were plotted and are shown in Fig. 2. And the packet throughput of APC scheme (T_{APC}), SC-PC scheme (T_{SC+PC}), SC-MC scheme (T_{SC+MC}) and SC-APC scheme (T_{SC+APC}) for packet size $n = 56$, $N_{max} = 6$, $A = 6$ and BER ranging from 10^{-3} to 0.12 for path m_1 and BER ranging from 10^{-3} to 0.11 for path m_2 and BER ranging from 10^{-3} to 10^{-1} for path m_3, were plotted and are shown in Fig. 3. It can be observed in Fig. 2 that the performance of APC scheme, SC-PC scheme, SC-MC scheme and SC-APC scheme deteriorates with increasing BER. However, the packet error rate of SC-APC scheme is better than those of other schemes. The superior performance of SC-APC scheme can be attributed to the fact that SC-APC scheme uses more redundancies compared to SC-PC and SC-APC scheme further exploits the information present in erroneously received copies compared to SC-MC scheme. Due to this, the error correction capability of SC-APC scheme is improved. In Fig. 3, it was observed that the throughput of APC scheme, SC-PC scheme, SC-MC scheme and SC-APC scheme deteriorates with increasing BER. Further, the throughput of SC-APC scheme is better than that of APC scheme, SC-PC scheme and SC-MC scheme. The superior performance of SC-APC scheme can be attributed to the superior error correction capability of SC-APC scheme, due to which the retransmissions are reduced and throughput is enhanced.

Further, the experiments were conducted to compare the performance of SC-PC scheme, APC scheme, SC-APC scheme and SC-MC scheme for the same channel condition in all three paths assuming that there is at-least a bit in error in each received copy of the packet, that is the bit error rate in all three paths were same ($\alpha_1 = \alpha_2 = \alpha_3$) and the range of BER considered was from 10^{-3} to 10^{-1} with packet size $n = 32$, $N_{max} = 4$, $A = 4$, and the results of the experiment are plotted in Figs. 4 and 5. It can be observed from Fig. 4 that the packet error rate of APC scheme and SC-APC scheme are same when the channel condition of all

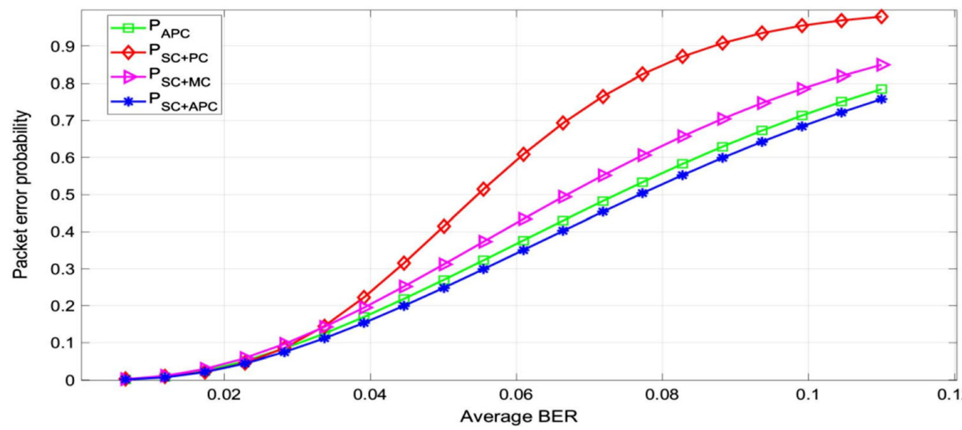

Fig. 2 Packet Error rate comparison, when packet size n = 56, NMAX = 6 and A = 6

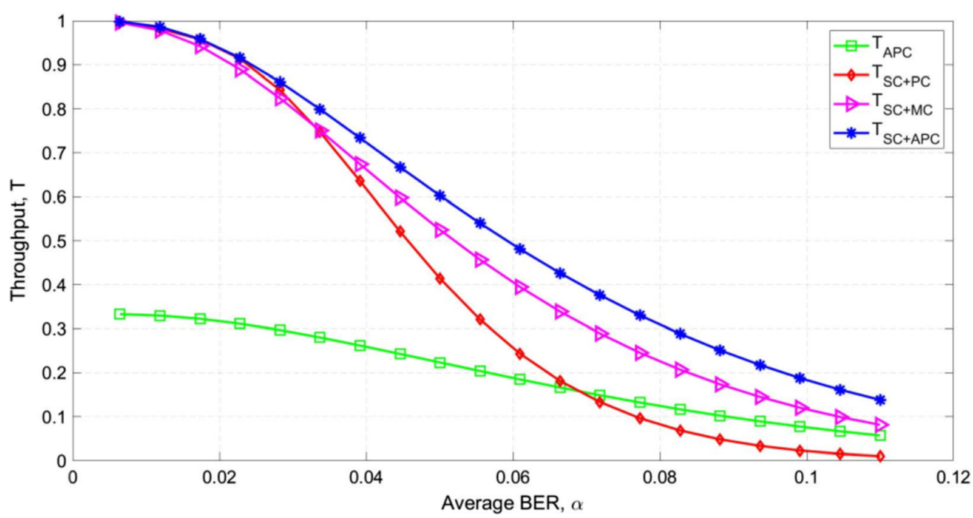

Fig. 3 Packet Throughput, when packet size n = 56, NMAX = 6 and A = 6

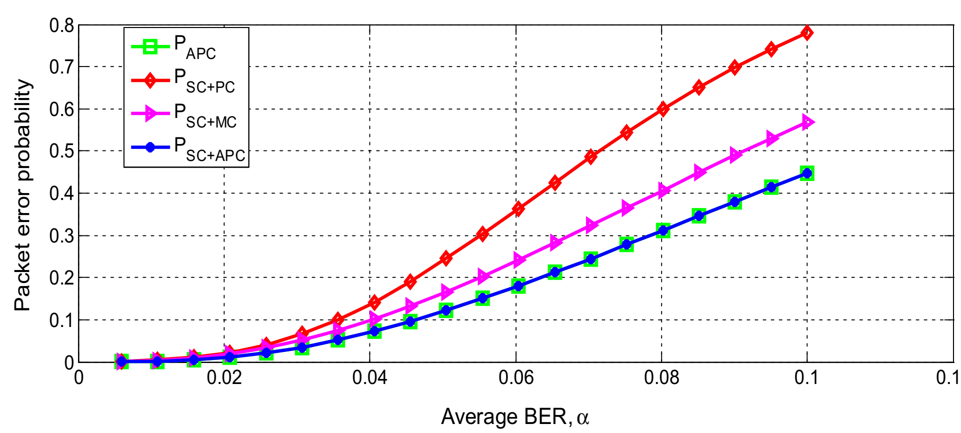

Fig. 4 Packet error rate comparison, when packet size *n* = 32, NMAX = 4 and *A* = 4

the paths is assumed to be same and there is at least a bit in error in each received copy of the packet. The PER rate of APC scheme (P_{APC}) and SC-APC scheme (P_{SC+APC}) is lower than of SC-PC scheme (P_{SC+PC}) and SC-MC scheme (P_{SC+MC}) as expected. The packet throughputs of APC scheme (T_{APC}), SC-PC scheme (T_{SC+PC}), SC-MC scheme (T_{SC+MC}) and SC-APC scheme (T_{SC+APC}) are compared in Fig. 5. As expected, the packet throughput of APC scheme (T_{APC}) is lowest as three copies of packet are transmitted, due to which the best packet throughput that could be achieved with APC scheme is 33.33% only. Since in multipath diversity system, only a copy of packet is transmitted via different paths, the packet throughput of 100 % could also be achieved as correct copy of the packet

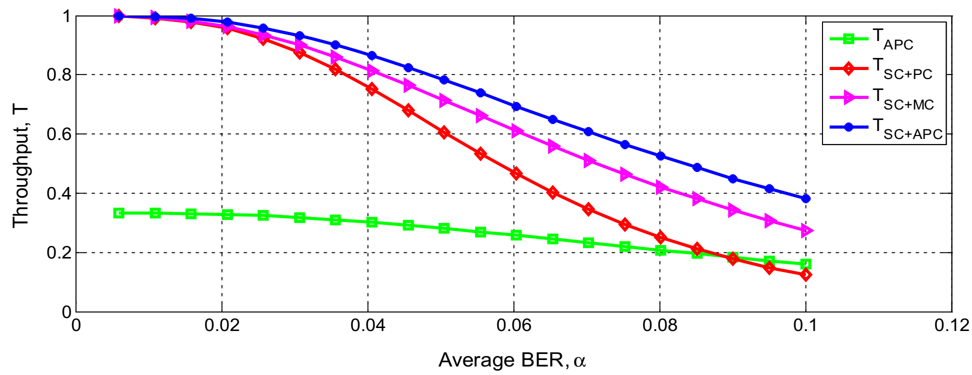

Fig. 5 Packet throughput comparison, when packet size $n = 32$, NMAX = 4 and $A = 4$

could be retrieved using packet combining scheme at the receiver. As the correction rate of SC-APC scheme is highest as seen from Fig. 4; thus, the number of retransmission is lowest in SC-APC scheme, which cause the packet throughput of SC-APC scheme to be higher as illustrated in Fig. 5.

Conclusion

In this paper, an attempt was made to improve the reliability and throughput of wireless communication system by incorporating PC scheme with selection combining and APC scheme with selection combining in multi-path diversity system. Accordingly, SC-PC scheme and SC-APC scheme for multi-path diversity system were proposed. The performance of the proposed schemes: SC-PC scheme and SC-APC scheme, were compared with the existing techniques such as APC scheme and SC-MC scheme. From the experimental results, it was observed that the packet error rate increases with increasing bit error rate as expected and throughput decreases when bit error rate increases. It was observed that SC-APC scheme has superior performance than that of PC scheme, APC scheme, SC-PC scheme and SC-MC scheme. The proposed SC-PC scheme and SC-APC scheme perform better than conventional PC scheme and APC scheme, respectively, due to diversity achieved using multi-path transmission. It was also observed that the performance of SC-APC scheme is better than APC scheme, SC-PC scheme and SC-MC scheme. The superior performance of SC-APC scheme can be attributed to the fact that SC-APC scheme uses more redundancies compared to SC-PC and SC-APC schemes further exploits the information present in erroneously received copies compared to SC-MC scheme. Due to this, the error correction capability of SC-APC scheme is improved. The superior performance of SC-APC scheme in terms of throughput can be attributed to the superior error correction capability of SC-APC scheme, due to which the retransmissions are reduced and throughput is enhanced.

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