SOURCE-DESTINATION HYBRID ARQ FOR MULTI-ROUTE CODING IN WIRELESS MULTI-HOP NETWORKS

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ABSTRACT

For reduction in transmission errors on wireless links, we proposed the multi-route coding on multiple routes for wireless multi-hop networks. In the proposed coding, a source node encodes a packet, divides it into sub packets, and transmits them on multiple routes. A destination node combines and decodes the arriving sub packets to get coding and diversity gain. In this paper, we propose a hybrid ARQ scheme for the multi-route coding. In a hybrid ARQ, important information is firstly transmitted, and redundant information is retransmitted later. On the other hand, in the multi-route coding, all sub packets should have the same importance because of efficient diversity combining. We investigate the trade-off between hybrid ARQ and multi-route coding.

I. INTRODUCTION

In wireless multi-hop networks, a packet is transmitted from a source node to a destination node via intermediate nodes even if a source node cannot be directly connected with a destination node. Its route from a source node to a destination node can be constructed flexibly by various ways to select intermediate nodes. Wireless multi-hop networks have drawn much attention for mobile ad-hoc networks, sensor networks and next generation mobile networks [1]–[4].

Because of flexibility of network construction in wireless multi-hop networks, multiple routes can be established by the multi-path routing [5], [6]. They are used for several purposes such as maintaining alternative routes, load balancing, and diminishing the effect of frequent topological changes. For reduction in transmission errors on wireless links, we proposed the multi-route coding on multiple routes [7]. In the proposed coding, a transmitter at a source node encodes a packet, divides it into sub packets, and transmits them on multiple routes. Intermediate nodes on each route relay one of multiple sub packets to a destination node. A receiver at the destination node combines and decodes the receiving sub packets to get coding and diversity gain.

In this coding, each intermediate node relays one of multiple sub packets, that is, only a part of a packet. Therefore, intermediate nodes cannot detect packet errors. Then, we proposed the source-destination ARQ scheme for the multi-route coding [8].

In this scheme, error detection is performed after combining and decoding sub packets at a destination node. If packet errors are detected, a destination node returns a NACK message to a source node. A source node retransmits sub packets after receiving the NACK message. In contrast to the single hop transmission, sub packet propagation time on each route is random variable in wireless multi-hop networks [9]. The arrival time of a sub packet on each route is different. The multi-route coding can also reduce the delay until a successful transmission and it results in the improvement of the throughput.

In this paper, we propose a source-destination hybrid ARQ scheme for multi-route coding. In [8], the same sub packets with the first transmission are retransmitted. The throughput performance will be improved by introduction of a hybrid ARQ scheme. To begin with, important information such as a message sequence is transmitted in a hybrid ARQ scheme. If transmission errors are detected, redundant information such as a parity sequence is retransmitted. This process can improve link efficiency. On the other hand, for the multi-route coding, all sub packets should have the same importance because of efficient diversity combining and reduction of delay [7]. Therefore, we investigate the trade-off between the hybrid ARQ and the multi-route coding.

II. MULTI-ROUTE CODING

A. Network Model

Figure 1 shows a wireless multi-hop network model. Sub packets are transmitted from a source node to a destination node.
Intermediate nodes relay transmitted sub packets. By a certain routing algorithm, \( N \) routes are established. On the \( n \)th route, the number of hops from the source node to the destination node is \( K_n \). In each hop, a sub packet transmission is according to a certain access control protocol. So the delay of sub packet transmission is considered as not only the propagation delay but also the waiting time delay by an access control protocol.

### B. Transmitter Structure of a Source Node

Figure 2 shows a transmitter structure of a source node. A bit sequence of a packet, \( d(i) \in \{+1, -1\}^{L_p} \), is encoded by RCPT code with a coding rate \( 1/M \) and puncture period \( P \), where \( L_p \) is the packet length. The encoded bit sequence, \( b(i) \in \{+1, -1\}^{M/L_p} \), is divided into \( MP/J \) sub packets, and scrambled for \( N \) routes, where \( J \) is a puncturing step. The detail of a RCPT encoder and a scrambler is described in Section III-A. Sub packets are stored at buffers. Each stored sub packet is interleaved, and after modulation, it is transmitted to the next node on the \( n \)th route.

### C. Regenerative Relay at Intermediate Nodes

Intermediate nodes perform regenerative relay. At intermediate nodes, the received signal is demodulated to a hard-valued binary sequence, remodulated, and transmitted to the next node. Note that error correction or error detection are not performed at intermediate nodes.

### D. Receiver Structure of a Destination Node

After \( K_n \) hops, a sub packet arrives at a destination node. Figure 3 shows a receiver structure of a destination node. The received signal is demodulated, hard-decided and deinterleaved to the estimated bit sequence of the \( j \)th transmission of the \( m \)th sub packet, \( \hat{b}^{(m,j)}(i) \).

We introduce a packet combining strategy to enhance packet retransmission effect. The estimated bit sequence of the \( m \)th sub packet is combined with the past (re)transmitted \( m \)th sub packets. Let \( \hat{b}^{(m,j)}(i) \) be the combiner output, it can be expressed as,

\[
\hat{b}^{(m,j)}(i) = L_c^{(m,j)} \cdot \hat{b}^{(m,j)}(i) + \hat{b}^{(m,j-1)}(i),
\]

where \( L_c^{(m,j)} \) is channel information for the \( j \)th transmission of the \( m \)th sub packet. The channel information can be calculated as the log likelihood ratio,

\[
L_c^{(m,j)} = \log \frac{1 - p^{(m,j)}}{p^{(m,j)}},
\]

where \( p^{(m,j)} \) is the bit error rate of the \( j \)th transmission of the \( m \)th sub packet. The estimation scheme of \( p^{(m,j)} \) is discussed in [10], [11]. The combiner output, \( \hat{b}^{(m,j)}(i) \), is stored at the buffer.

Sub packets stored at buffers are descrambled, composed, and decoded to the bit sequence of the recovered packet by the iterative decoder. The recovered packet is error-detected, and an ACK/NACK message is returned to a source node. This process is described in Section III-B.

### III. Source-Destination Hybrid ARQ for Multi-Route Coding

In this section, we describe the source-destination hybrid ARQ for the multi-route coding.

#### A. RCPT Encoder and Scrambler

A structure of a RCPT encoder is shown in Figure 4. Generally, it can generate multiple codes of rates,

\[
R_t = \frac{P}{P + l} \quad (l = 0, 1, \ldots , (M - 1)P),
\]
from a unique turbo encoder [12]. A RCPT encoder consists of a rate $1/M$ turbo encoder and puncturing with a period $P$. The sequence encoded by a turbo code is punctured according to multiple puncture matrices, which are $(M \times P)$ matrices. The first column of puncture matrices indicates the puncture pattern of a message sequence, and the other columns show those of parity sequences.

To apply a RCPT code to the multi-route coding, it is slightly modified. The highest coding rate of a RCPT is 1. The code with a coding rate 1 corresponds to a message sequence, and the 1st column of its puncture matrix is all-one. In the multi-route coding, it is possible to make a sub packet which consists of a part of a message sequence. Then, the highest code rate becomes more than 1. To make such high code rate, we modify puncture matrices in which the number of 1’s increases from 0 to $MP$, that is, the $i$th puncture matrix has $i$ 1’s. For example, the puncture matrix for $M = 3$ and $P = 2$ is,

$$
\begin{bmatrix}
A(0) & A(1) & A(2) & A(3) & A(4) & A(5) & A(6) \\
00 & 10 & 11 & 11 & 11 & 11 & 11 \\
00 & 00 & 00 & 10 & 10 & 11 & 11 \\
00 & 00 & 00 & 00 & 01 & 01 & 11 \\
\end{bmatrix}
$$

Note that assigning 1 to the first column of puncture matrices is given priority. A message sequence is more important than parity sequences [13]. Therefore, a message sequence is firstly transmitted for an efficient hybrid ARQ.

Each sub packet is constructed from these puncture matrices. Let $J$ be a puncturing step, then the $m$th sub packet is made by puncturing a turbo-encoded sequence according to the puncture matrix $B(m) = A(m \cdot J) - A((m - 1) \cdot J)$. As a result, $MP/J$ sub packets are generated. These $MP/J$ sub packets are transmitted every $N$ sub packets on $N$ routes. Since $N$ sub packets are simultaneously transmitted at the first transmission, these should have a whole message sequence. The first $P/J$ sub packets have a message sequence. So the condition $P/J \leq N$ should be satisfied.

If $P/J$ is less than $N$, not only a message sequence but also a part of parity sequences are simultaneously transmitted at the first transmission. So as to enhance the diversity effect, a message sequence has to be spread uniformly on $N$ sub packets. As shown in Figure 4, $N$ sub packets are scrambled at bit level.

As described in Section I, the proposed scheme has the relationship between the hybrid ARQ and the multi-route coding. The degree of the multi-route coding depends on the number of routes $N$. On the other hand, the number of transmissions for the hybrid ARQ is $MP/JN$. By changing these parameters, the trade-off between the hybrid ARQ and the multi-route coding can be investigate.

### B. ARQ Procedure

Figure 5 shows the (re)transmission procedure for the source-destination hybrid ARQ for the multi-route coding.

At first, a source node transmits the first $N$ sub packets among $MP/J$ sub packets. Since propagation time on each route is random variable, the arrival time of a sub packet on each route is different [9]. A destination node checks whether packet transmission is succeed or not every time a sub packet arrives. If a destination node does not detect packet errors, an ACK message is returned to a source node. Note that a NACK message does not have to be returned every error detection [8]. In this paper, a NACK message is returned only when all $N$ sub packets arrive. An ACK/NACK message is transmitted on one of multiple routes.

When a source node receives a NACK message, it transmits the next $N$ sub packets on $N$ routes. If all sub packets are sent, the first $N$ sub packets are retransmitted. This process is repeated until a packet is transmitted successfully.

### IV. PERFORMANCE EVALUATION

The performance of the proposed scheme is evaluated in this section. Operating parameters are shown in Table 1 and employed puncture matrices are described in Appendix. The number of routes is set at $N = 3$. The number of hops is identical on each route and set at $K_n = 3$. The Rayleigh fading environment is assumed on each wireless link. The fading loss is

1If some sub packets are lost and does not arrive at a destination node, a destination node cannot know it. In this case, a source node should retransmit them after a timeout.
Table 1: Operating parameters.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>packet length $L_p$</td>
<td>exponentially distributed with average $L_p = 1,000$ bits</td>
</tr>
<tr>
<td>turbo code</td>
<td>coding rate $1/M=1/3$, (37,21) RSC, 5 iteration decoding</td>
</tr>
<tr>
<td>puncture period $P$</td>
<td>$1, 2, 3$</td>
</tr>
<tr>
<td>puncturing step $J$</td>
<td>$1$</td>
</tr>
<tr>
<td>modulation scheme</td>
<td>BPSK</td>
</tr>
<tr>
<td>wireless link model</td>
<td>Rayleigh fading</td>
</tr>
<tr>
<td>number of routes $N$</td>
<td>$3$</td>
</tr>
<tr>
<td>number of hops $K_n$</td>
<td>$3$</td>
</tr>
</tbody>
</table>

constant during a sub packet transmission, and independently varies at each sub packet transmission.

A. Packet Error Rate

Figure 6 shows the simulation results of packet error rate for $E_b/N_0 = 12$ dB, where $E_b$ is bit energy and $N_0/2$ is two side power spectral density. The horizontal axis indicates the amount of arriving sub packets normalized by packet length, which can be derived by $P_{k}^{k}$, where $k$ is the number of sub packets arriving at a destination node. When this amount is equal to 1, total amount of arriving sub packets is equal to one packet.

From this figure, we can find that the packet error rate can be improved as a puncture period becomes longer. To lengthen a puncture period increases the number of sub packets, $MP/J$. It results in enlarging the time-diversity gain for the hybrid ARQ. We also find that the scrambler for the multi-route coding can improve the packet error rate.

B. Link Efficiency

In this sub section, we evaluate the link efficiency of the proposed scheme. We define the link efficiency as $\eta = 1/\pi$, where $\pi$ is the average amount of total sub packet transmissions until a packet is transmitted successfully. If link efficiency $\eta$ is equal to 1, a packet transmission is succeed when only a message sequence is transmitted.

The simulation results of link efficiency are shown in Figure 7. The longer a puncture period is, the larger the link efficiency becomes. The hybrid ARQ can improve the link efficiency because transmissions of parity sequences can be reduced when $E_b/N_0$ becomes high. On the other hand, the contribution of the multi-route coding to the improvement in link efficiency is small since a message sequence and parity sequences are simultaneously transmitted. For $P = 1$, the coding rate of the first transmission becomes $1/3$. So the link efficiency comes closed to $1/3$. That for $P = 2$ comes closed to $2/3$ since the coding rate of the first transmission is $2/3$.

C. Delay and Throughput

Since the link efficiency does not consider the usability for users, we evaluate delay and throughput performances.

The delay is defined as the elapsed time from the occurrence of a transmission request to its successful transmission. The average delay is derived by using the analytical method explained in [8]. In this method, each wireless link is modeled as an $M/M/1$ queue with traffic intensity $\rho$. In order to consider the increase in traffic intensity due to transmissions of parity sequence and sub packet retransmissions, traffic intensity is assumed to increase proportional to the average amount of total sub packet transmissions. It may be expressed as $\rho = \rho_0$, where $\rho_0$ is the traffic intensity of newly generating packets. The average delay is calculated by this queuing model of a wireless link and a packet error rate. The throughput is defined as the time ratio of a packet transmission to the elapsed time until its successful transmission in each wireless link. Let $\bar{D}$ be the average delay normalized by a packet length. Then, the normalized throughput is obtained by [8]

$$S = \frac{1}{\bar{D}/K_n}.$$  \hspace{1cm} (4)

Figure 8 shows the average delay normalized by a packet length, and Figure 9 shows the normalized throughput. In both figures, we set $\rho_0 = 0.1$. Except for low $E_b/N_0$, the case
In this paper, we have proposed the source-destination hybrid ARQ scheme for the multi-route coding in wireless multi-hop networks. To apply a RCPT code to the multi-route coding, it has been slightly modified. By adjusting a puncture period, we have investigated the trade-off between the hybrid ARQ and the multi-route coding. As a result, we can find that the combination of the multi-route coding and the hybrid ARQ is effective in terms of the delay and the throughput performance although the link efficiency cannot be maximized.

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REFERENCES


APPENDIX: PUNCTURE MATRICES

\[ M = 3, P = 1, J = 1; \]
\[
\begin{bmatrix}
B(1) \\
B(2) \\
B(3)
\end{bmatrix} = 
\begin{bmatrix}
1 & 0 & 0 \\
0 & 1 & 0 \\
0 & 0 & 1
\end{bmatrix}
\]

\[ M = 3, P = 2, J = 1; \]
\[
\begin{bmatrix}
B(1) \\
B(2) \\
B(3) \\
B(4) \\
B(5) \\
B(6)
\end{bmatrix} = 
\begin{bmatrix}
10 & 0 & 0 & 0 & 0 & 0 \\
0 & 01 & 0 & 00 & 0 & 00 \\
00 & 00 & 10 & 00 & 01 & 00 \\
00 & 00 & 00 & 00 & 00 & 10 \\
00 & 00 & 00 & 00 & 00 & 00 \\
00 & 00 & 00 & 00 & 00 & 10
\end{bmatrix}
\]

\[ M = 3, P = 3, J = 1; \]
\[
\begin{bmatrix}
B(1) \\
B(2) \\
B(3) \\
B(4) \\
B(5) \\
B(6) \\
B(7) \\
B(8) \\
B(9)
\end{bmatrix} = 
\begin{bmatrix}
100 & 010 & 001 & 000 & 000 & 000 & 000 & 000 \\
000 & 000 & 000 & 001 & 000 & 000 & 000 & 000 \\
000 & 000 & 000 & 000 & 000 & 010 & 000 & 000 \\
000 & 000 & 000 & 000 & 000 & 000 & 010 & 000 \\
000 & 000 & 000 & 000 & 000 & 000 & 000 & 000 \\
000 & 000 & 000 & 000 & 000 & 000 & 000 & 000 \\
000 & 000 & 000 & 000 & 000 & 000 & 000 & 000 \\
000 & 000 & 000 & 000 & 000 & 000 & 000 & 000
\end{bmatrix}
\]