Multi-Route Coding in Wireless Multi-Hop Networks

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SUMMARY Wireless multi-hop networks have drawn much attention for the future generation mobile communication systems. These networks can establish multiple routes from a source node to a destination node because of flexible construction of network topology. Transmissions by multiple routes have enough capability to achieve reliable communication because we can expect to obtain diversity gain by multiple routes. In this paper, we propose the multi-route coding scheme. At first, we discuss a channel model in multi-hop networks employing regenerative relay, which we named the virtual channel model. By using the virtual channel model, a packet is encoded on multiple routes as follows; a bit sequence of a packet is encoded and divided into subpackets, and each subpacket is transmitted on each route. We evaluate its packet error rate performance, and clarify effectiveness of the proposed scheme. In general, we should face degradation of a route condition such as the case when a subpacket does not reach a destination node. Hence, we have to consider the influence of subpacket loss. We also investigate it, and show tolerance of the proposed scheme over that.

key words: multi-route coding, turbo code, multipath dynamic source routing, wireless multi-hop network

1. Introduction

For the future generation mobile communication systems, it is required to realize much higher data rate transmission. One of the ways to satisfy this requirement is to have smaller cell size such as a micro or pico cell. But it is difficult to construct a large number of wired base stations for its high cost. Wireless multi-hop networks are useful strategies to solve this difficulty, and have much attention among a lot of researches [1], [2]. In wireless multi-hop networks, a packet generated by a source node is relayed by some wireless intermediate nodes, and finally arrives at a destination node. Intermediate modes usually have simple structure compared with wired base stations, and can construct wireless networks in small cell environment.

Wireless multi-hop networks can establish a route from a source node to a destination node flexibly by various ways to select intermediate nodes. So, multiple routes can be also established by using multi-path routing protocols [3]–[9]. They are used for several purposes such as maintaining alternative routes, load balancing, and diminishing the effect of frequent topological changes.

If a packet is divided into subpackets, transmitted via multiple routes and diversity-combined effectively at a destination node, it is expected to get diversity gain and reduce packet errors. Furthermore coding on multiple routes may bring about additional improvement. In wireless multi-hop networks, regenerative relay is usually employed because a header of a subpacket has to be demodulated. Then a received subpacket is demodulated to a binary sequence, regenerated and relayed to the next node at intermediate nodes. A destination node can make use of only hard (binary) values of subpackets transmitted via multiple routes since soft values cannot be transmitted beyond intermediate nodes. Therefore, we have to develop a diversity and coding scheme based on hard values for multiple routes in wireless multi-hop networks.

In multi-hop networks, we may face subpacket loss due to topological change and/or recognizing failure at an intermediate node, where a link availability model was discussed in [10]. Furthermore, congestion might occur at an intermediate node, and a subpacket could not arrive at a destination node within tolerable delay time. These situations result in losing a part of a packet and this influence could not be ignored.

In this paper, we propose the multi-route coding in wireless multi-hop networks. At first, we discuss a channel model in multi-hop networks employing regenerative relay, which is named the virtual channel model. By using the virtual channel model, a packet is encoded on multiple routes. We employ a turbo code as the route coding scheme because it can realize very low bit error rate performance. Furthermore, we expect that degradation due to subpacket loss may be mitigated by iterative decoding of the turbo code. We evaluate its packet error rate performance, and clarify effectiveness of the proposed scheme.

This paper is organized as follows. In Sect. 2, we describe the concept of the virtual channel model. The proposed route coding scheme is described in Sect. 3. In Sect. 4, we introduce some numerical examples and show effectiveness of the proposed scheme. Finally, we conclude this paper in Sect. 5.

2. Concept of Virtual Channel

In this section, we explain the virtual channel in multi-hop networks employing regenerative relay.

Before discussing the virtual channel, we describe the wireless multi-hop network model used in this paper. Wireless multi-hop networks are modeled as Fig. 1. Subpackets are transmitted from a source node to a destination node in this network model. Intermediate nodes relay the transmitted packets. By using a certain routing algorithm, N routes from a source node to a destination node are established. The number of hops from a source node to a destination node on the nth route is denoted by M_n, which is dependent on network topology. In each hop, subpacket transmissions are according to a certain access control protocol such as IEEE802.11.

As described in Sect. 1, we employ regenerative relay at intermediate nodes. Then, soft decision values of a subpacket received at an intermediate node are lost and cannot be transmitted beyond an intermediate node. But hard decision values of that are remodulated and transmitted to a destination node, that is to say, a destination node can make use of hard decision values, which contain hard valued reliability information of every wireless link on a route.

Therefore, we can regard whole wireless links on each route as a virtual binary symmetric channel, and N routes are considered as N virtual channels. Each virtual binary symmetric channel is characterized by the characteristics of all wireless links on each route.

Note that wireless links are not shared each other in Fig. 1. The routing protocols to achieve this condition are discussed in [7]–[9]. Even if some of them are shared, it only results in loss of independence among routes and might bring about a slight degradation of packet error rate. But time diversity gain could be obtained in such a situation be-
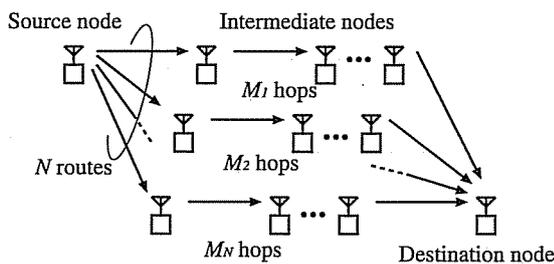
cause subpackets are distinguished and are not transmitted at the same time on the shared wireless link.
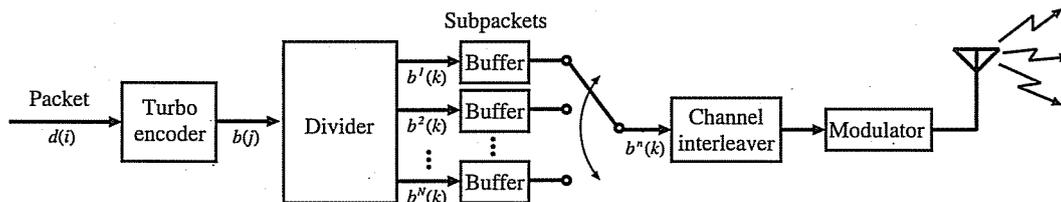
3. Multi-Route Coding

The multi-route coding scheme is explained in this section. In this scheme, a packet is encoded on multiple routes, namely, multiple virtual channels.

3.1 Transmitter Structure of the Source Node

Figure 2 shows a transmitter structure of a source node. It consists of a turbo encoder, a divider, buffers, a switch, a channel interleaver and a modulator. A bit sequence of a packet, $d(i) \in \{+1, -1\}^L$, is encoded to an encoded bit sequence by the turbo code with a coding rate R, where L is packet length. An encoded bit sequence, $b(j) \in \{+1, -1\}^{L/R}$, is divided into N subpackets for multiple routes. Note that an encoded bit sequence of typical turbo code consists of a message sequence, $c^m(i)$, and parity sequences, $c^{p1}(i), c^{p2}(i)$, and a message sequence is more important than parity sequences [11]. A message sequence has to be spread uniformly on subpackets so as to enhance diversity effect. Let $b^n(k)$ be the kth bit of the subpacket transmitted on the nth route, where $k = 1, 2, \cdots, \lceil L/RN \rceil$ and $\lceil x \rceil$ means the lowest integer value not below x. Then, the divider operates according to the following algorithm.

(a). If $N \cdot R$ is an integer number,

$$b^n(k) = b((k-1)N + (n \oplus_N k) + 1), \qquad (1a)$$

where $a \oplus_N b$ means a remainder of $(a + b)$ divided by N.

(b). Otherwise,

$$b^n(k) = b((k-1)N + n). \qquad (1b)$$

Subpackets are stored at the buffers. Against the influence of time-variant fading, a channel interleaver for subpackets is employed. Each stored subpacket is interleaved, and after modulation, it is transmitted to the next node on the nth route. This operation is repeated until all subpackets are transmitted to the next nodes on N routes.

3.2 Regenerative Relay of the Intermediate Node

Intermediate nodes perform only regenerative relay. At intermediate nodes, the received signal is demodulated to a
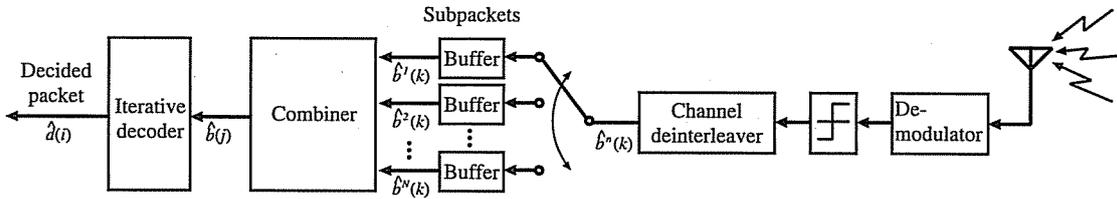

Fig. 1 Wireless multi-hop network model.

Fig. 2 Transmitter structure of a source node.

Fig. 3   Receiver structure of a destination node.

hard-valued binary sequence, remodulated, and transmitted to the next node. Note that error correcting or error detecting are not performed at intermediate nodes because we should reduce the load of intermediate nodes.

3.3 Receiver Structure of the Destination Node

After M_n hops, a subpacket arrives at a destination node. A receiver structure of a destination node is shown in Fig. 3. It consists of a demodulator, a channel deinterleaver, a switch, buffers, a combiner, and an iterative decoder. The received signal transmitted via the nth route is demodulated, hard-decided and deinterleaved to an estimated bit sequence of a subpacket, $\hat{b}^n(k)$. It is stored at the buffer. After receiving all N subpackets or wasting tolerable delay time, they are combined and reordered according to the inverse algorithm of (1). As described in Sect. 1, subpackets might be lost. If the subpacket on the nth route is lost, the estimated bit sequence of the subpacket $\hat{b}^n(k)$ is assumed to be all-zero sequence. Finally, a bit sequence of the combined and reordered packet, $\hat{b}(j)$, is decoded to a decided bit sequence of a packet, $\hat{d}(i)$, by the iterative decoder.

In the following section, we describe the iterative decoder.

3.4 Iterative Decoder

In our proposed scheme, N routes are regarded as N binary symmetric channels, and each channel will have the different characteristic (bit error rate) from the other channels. The iterative decoder should be designed in consideration of these properties. In this section, we explain the Soft Output Viterbi Algorithm (SOVA) in the iterative decoder for our proposed scheme. Each channel characteristic, that is a bit error rate (BER) of whole wireless links on each route, is employed so as to calculate a reliability value of a channel for the SOVA. The estimation scheme of a BER on each route is discussed in [12].

Let us take the typical iterative decoder to explain the SOVA for multiple virtual binary symmetric channels. Figure 4 shows a block diagram for the typical iterative decoder. The decoder consists of two SOVA decoders, interleavers and a deinterleaver. We denote $L_a[d(i)]$ as the a priori value for the ith bit, $L_e[d(i)]$ as an extrinsic information and L_c as a reliability value of a channel. For turbo decoding, Log Likelihood Ratio (LLR) of a bit sequence $d(i)$ is expressed as,
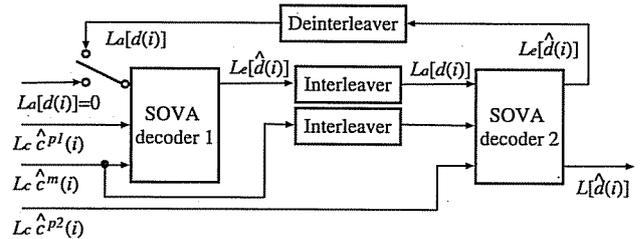

Fig. 4   Block diagram of a typical iterative decoder.

$$L[\hat{d}(i)] = L_c \cdot \hat{c}^m(i) + L_a[d(i)] + L_e[\hat{d}(i)], \qquad (2)$$

where $\hat{c}^m(i)$ is the estimated message sequence.

An extrinsic information $L_e[\hat{d}(i)]$ is derived from a path metric by SOVA decoder. This $L_e[\hat{d}(i)]$ becomes a priori value $L_a[d(i)]$ for the next SOVA decoder. The calculation of these terms is the same with that for conventional SOVA decoder. On the other hand, the calculation of L_c is slightly modified for the proposed scheme. A reliability value of a channel L_c is expressed as,

$$L_c = \log \left(\frac{P(\hat{c}^m(i)|d(i) = 1)}{P(\hat{c}^m(i)|d(i) = -1)} \right). \qquad (3)$$

For a binary symmetric channel, L_c is generally calculated by log likelihood ratio of a BER,

$$L_c = \log \frac{1-p}{p}, \qquad (4)$$

where p is a BER [13]. For the multiple virtual channels, a reliability value of a channel L_c has to differ for every N virtual channel since each virtual channel has a different characteristic. Then, by modifying (4), the reliability value of the nth virtual binary symmetric channel, $L_c^{(n)}$, is calculated by

$$L_c^{(n)} = \log \frac{1 - p^{(n)}}{p^{(n)}}, \qquad (5)$$

where $p^{(n)}$ is the BER of the nth channel. Of course, we could employ received signal power-to-noise power ratio (SNR) at a destination node for calculation of a reliability value of a channel. But it cannot work perfectly on the decoding process because it reflects the condition of only the final hop. We expect that a BER is suitable because a BER reflects both the results of hard decision on intermediate nodes and SNR on routes. Therefore, we employ log likelihood ratio of a BER on each route as a reliability value of a channel.

4. Performance Evaluation

In this section, we evaluate the performance of the proposed scheme in terms of a packet error rate. A packet error rate is a probability that a decided packet $\hat{d}(i)$ has at least one bit error regretfully.

4.1 Case of Two Virtual Binary Symmetric Channels

To begin with, we discuss the basic property of the route coding scheme. As mentioned in Sect. 2, whole wireless links on each route can be regard as a virtual binary symmetric channel. Let us consider two virtual binary symmetric channels, in which the number of routes N is 2. In this paper, we define the BER as the BER on the virtual binary symmetric channel, that is, the total BER of whole wireless links on each route. The BER on the nth route is denoted by $p^{(n)}$ ($n = 1, 2$). The length of a packet L is set at 1000 bits. The code rate of turbo encoder R is $1/3$. It has two $(37, 21)$ RSC element encoders and a random interleaver whose size is equal to L. An encoded sequence is divided into 2 subpackets each of which includes $\lceil 3 \cdot 1,000/2 \rceil = 1,500$ bits. The number of iterations of the iterative decoder is set at 5.

Figure 5 shows the packet error rate in 2 virtual binary symmetric channels in the cases of the conventional reliability value of a channel L_c in (4) and the modified reliability value $L_c^{(n)}$ in (5). The conventional reliability value of a channel is calculated by the average BER, which is derived by $p = (p^{(1)} + p^{(2)})/2$. Ideal estimation of a BER for each channel is assumed since we focus on the effect of the route coding scheme. From this figure, we can obviously find that the packet error rate with the modified reliability value of a channel is superior to that with the conventional one. In particular, the modification of a reliability value brings about a remarkable improvement when the difference between $p^{(1)}$ and $p^{(2)}$ is large. On the other hand, the packet error rate with the conventional reliability value does not decrease even if the BER of one of two routes becomes good.

As described above, the modified reliability value of a channel can improve the packet error rate, but it needs to estimate a BER for each channel and estimation errors will degrade packet error rate. To investigate this, the influence of BER estimation errors on the packet error rate is shown in Fig. 6. We assume estimation errors obey Gaussian distribution with mean zero. Giving the Root Mean Squared Error (RMSE) normalized by a BER of each route, the estimated BER of each route is obtained by the sum of a BER of each route, $p^{(n)}$, and a Gaussian error value whose standard deviation is equal to its RMSE. A reliability value of a channel in (5) is calculated by the estimated BER. From this figure, we can find that the packet error rate is hardly degraded when the normalized RMSE is 0.1. But striking degradation can be found if the normalized RMSE is 0.5. In this case, the packet error rate becomes worse than that of conventional
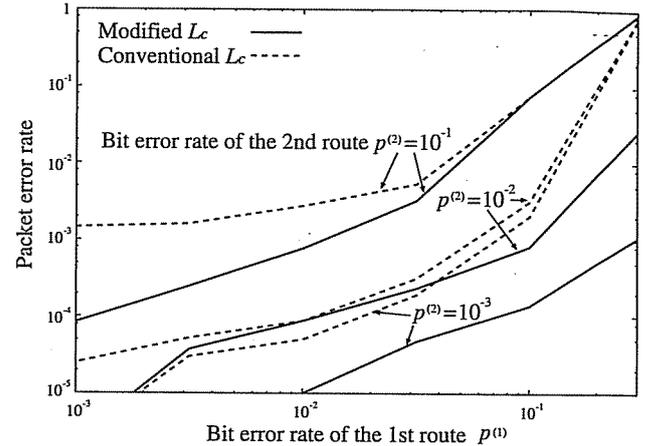

Fig. 5 Packet error rate in two virtual binary symmetric channels.
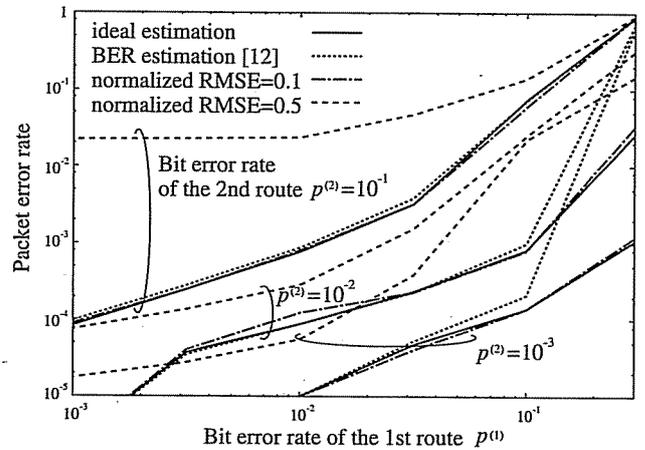

Fig. 6 Influence of BER estimation error on packet error rate.

L_c shown in Fig. 5[†]. So it is required to keep the normalized RMSE below 0.1 in virtual binary symmetric channels. In Fig. 6, we also show the packet error rate by using the BER estimation scheme [12]. From this figure, we can find that the packet error rate comes close to that of ideal estimation case except for $p^{(1)} > 1.0 \times 10^{-1}$. Therefore, the BER estimation scheme can satisfy the required accuracy of BER estimation except for the intolerable wireless link condition.

4.2 Case of Multipath Dynamic Source Routing

Next, we evaluate the performance of the proposed scheme in more practical model. For the numerical examples of this, the Multipath Dynamic Source Routing (MDSR) [7] is employed so as to establish multiple routes. This routing protocol is based on the Dynamic Source Routing (DSR) [14] protocol, and searches multiple possible routes by a single flooding. In the conventional DSR protocol, a destination node returns a route reply message to a source node on only

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[†]The calculation of a conventional reliability value of a channel in (4) also needs to estimate BER for all channels, but ideal estimation is assumed in Fig. 5.

Table 1 Simulation parameters.

area	1,000 m × 1,000 m
number of nodes	300
distribution of nodes	uniform
distance from source node to destination node	500 m
path loss exponent	3.5
standard deviation of lognormal shadowing	7 dB
transmit SNR	80, 85, 90 dB
required link connection SNR	10, 15 dB

a primary route discovered by a flooding. On the other hand, in the MDSR protocol, a destination node replies on more than or equal to one disjoint route which is chosen among all arrival query messages. Therefore, multiple routes can be established by a single flooding and several route reply messages. The cost of the search for multiple routes is only an increase of route reply messages. This cost could be neglected because the construction of multiple routes may reduce the frequency of flooding to recovery a lost route. Further discussion about this is omitted since we focus on the evaluation of the proposed scheme.

Simulation parameters are shown in Table 1. There are 300 nodes distributed uniformly in 1,000 m × 1,000 m area. The distance from a source node to a destination is fixed at 500 m. Assume that every wireless link is statistically independent and there are no shared wireless links on multiple routes. In wireless links, distance dependent path loss, lognormal shadowing, and flat Rayleigh fading are considered. The path loss exponent is set at 3.5, and standard deviation of lognormal shadowing is set at 7 dB. Transmit signal power is identical among all nodes, and transmit SNR is defined as the transmit signal power-to-the received noise power ratio. The transmit SNR is set at 80, 85 and 90 dB, which corresponds to the cases in which received SNR at a distance 100 m is 10, 15 and 20 dB, respectively, if only distance dependent path loss is considered. We assume lognormal shadowing loss is constant while its wireless link is held, and define link connectivity SNR as received SNR affected by distance dependent path loss and lognormal shadowing. Wireless links are available if link connectivity SNR is above required link connection SNR, which is set at 10 dB and 15 dB. These available wireless links are candidates for routes. Fading gain is assumed to be constant during a subpacket transmission and vary at each subpacket transmission. QPSK is employed as a modulation scheme, and occurrence of bit errors for each wireless link depends on instantaneous SNR, which considers the effect of distance dependent path loss, shadowing and fading. The packet length, the turbo encoder and the iterative decoder are the same with those in Sect. 4.1, and ideal estimation of a BER for each channel is assumed at a receiver of a destination node.

Figure 7 shows the packet error rate as a parameter of the number of transmitting routes, N. A source node selects N routes among routes established by MDSR in order of arrival time of route reply messages from a destination node. The case for $N = 1$ corresponds to the conventional one in which the proposed route coding scheme is not em-
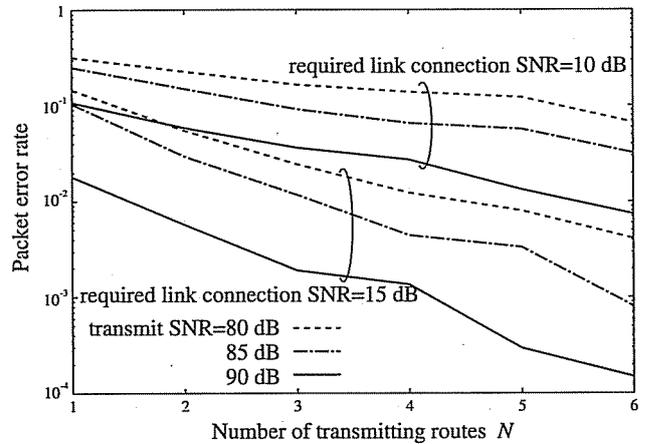
Fig. 7 Packet error rate when MDSR is employed as routing protocol.
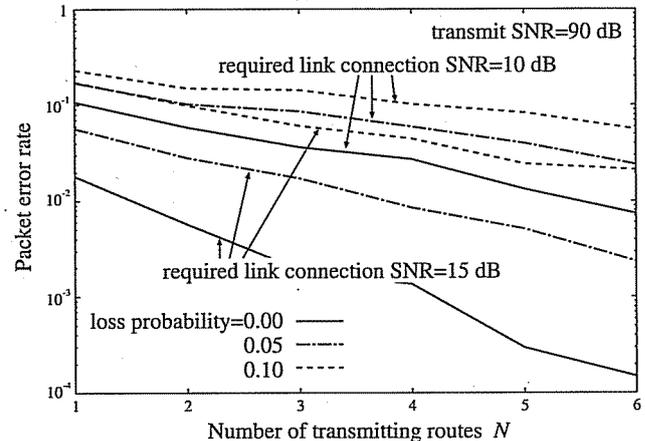
Fig. 8 Influence of lost subpackets on packet error rate.

ployed and an encoded bit sequence is transmitted on a primary route established by the DSR. We can observe that the packet error rate is improved as the number of transmitting routes increases. This means that diversity gain becomes large by increasing transmitting routes.

Lastly, we investigate influence of subpacket loss. Although one of the causes of subpacket loss may be degradation of received SNR, we employ the simple model of an occurrence of subpacket loss to focus on the evaluation of its influence. Let the loss probability be the probability that a subpacket is lost on a route, and we assume subpacket loss happens according to this probability, which does not depend on the received SNR. Setting the loss probability at 0.00, 0.05 and 0.10, the packet error rate is shown in Fig. 8, where transmit SNR is 90 dB. Although subpacket loss degrades the packet error rate, it can be improved by increasing the number of transmitting routes. It follows from this that the proposed route coding scheme can mitigate influence of subpacket loss.

5. Conclusions

In this paper, we have modeled multiple routes as multiple

virtual binary symmetric channels, and proposed the multi-route coding scheme on them in wireless multi-hop networks. In the proposed scheme, a bit sequence of a packet is encoded by a turbo code and divided into multiple subpackets. These subpackets are transmitted on their own virtual channels. We have evaluated the proposed scheme in terms of packet error rate. As a result, we have shown that significant improvement can be obtained by modifying a reliability value of a channel for SOVA decoder. Although this modification can improve packet error rate, it needs to estimate a BER for each channel. By evaluating influence of estimation error, required accuracy of estimation has been clarified. We have also evaluated the proposed scheme in the practical situation and shown improvement of packet error rate by increasing the number of transmitting routes since its diversity gain becomes large. Although the proposed scheme has a relatively simple structure, its improvement is large. This effect can be expected if wireless link conditions probabilistically vary and the averaged performance of them is almost identical. Even if subpacket loss occurs, the proposed route coding scheme can mitigate this influence.

The proposed multi-route coding scheme is based on the virtual binary symmetric channel model which is characterized by properties of all wireless links on a route. This channel model is very simple, and then it can simplify the discussion about the coding scheme to reduce bit errors in wireless multihop networks. It will help us to develop the multi-route coding scheme for future works.

Acknowledgments

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