PERFORMANCE ANALYSIS OF MULTIPLE-ROUTE PACKET COMBINING SCHEME FOR REAL-TIME COMMUNICATIONS IN WIRELESS MULTIHOP NETWORKS

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Abstract - In real-time packet communications, packet retransmission is generally not used because it may produce undesired delays. In this case, however, packet errors caused by a channel may lead to a loss of transmitted information directly. Then, it is necessary to employ a technique which can reduce the influence of packet errors. We propose to employ a multiple-route packet combining scheme in real-time communications on wireless multihop networks. The scheme, which is proposed in [1], can achieve a diversity gain by combining multiple copies of the same packet that are transmitted along different routes. We analyze two characteristics of the proposed system. One is the average packet error probability, which is obtained as a function of elapsed time after transmission requests for copied packets are generated. The other is the required time for achieving a required packet error probability. The results are evaluated from a quality of service (QoS) point of view. From numerical results, it is shown that for a given tolerable delay, there exists a number of multiple routes that minimizes the achievable average packet error probability. Moreover, if the number of multiple routes is selected appropriately, the required time for achieving a required packet error probability can be minimized.

Keywords - Wireless multihop networks, Multiple routing, Packet combining, Real-time communications.

1. INTRODUCTION

Wireless multihop networks [2], [3] consist of wireless nodes that are connected with each other by wireless links. The packets sent by a source node are forwarded toward a destination node by forwarding nodes which exist between the source node and the destination node. Routing protocols determine which nodes are selected as forwarding nodes. Wireless ad-hoc networks [4] and wireless sensor networks [5] are typical examples of wireless multihop networks.

In this paper, we consider real-time packet communications in wireless multihop networks. In packet communications; when a packet is received with errors, the packet is retransmitted. Packet retransmissions may cause excessive delays and large delay jitters which are not desirable for delay-sensitive communications. Therefore, packet retransmission techniques are generally not used in real-time communications. In this case, however, packet errors caused by a channel may lead to a loss of transmitted information directly. Then, it is necessary to employ a technique which can reduce the influence of packet errors.

By using multipath routing, multiple routes can be established between a source node and a destination node. Multiple routes are used for various purposes such as maintaining alternative routes [6], load balancing [7], [8], and diminishing the effect of frequent topological changes [9]. In [1], a multiple-route packet combining scheme is proposed to reduce bit errors on wireless channels. In this scheme, multiple copies of a packet are sent by a source node. Each copied packet is transmitted along different routes. At a destination node, the received copies are combined by a soft-output combiner. To combine multiple copies of the same packet provides a diversity gain. This scheme is suitable for real-time communications because of the ability to reduce the influence of packet errors on quality of service without causing additional delays.

We propose to employ the multiple-route packet combining scheme in real-time communications on wireless multihop networks. To support delay-sensitive traffic, a decoding and combining process needs finishing within a given tolerable time interval. Since packet delays of each route are random variables, not all the copied packets can be received and combined within the interval. This case is not considered in [1]. The number of combined packets increases as time elapses after a source node sends copies of a packet. Since the more copied packets are combined, the more the diversity gain is achieved, the packet error probability may be a function of a elapsed time.

In this paper, we analyze the performance of the multiple-route packet combining scheme for real-time communications in wireless multihop networks. We derive two characteristics. One is the average packet error probability, which is obtained as a function of elapsed time after transmission requests of copied packets are generated. The other is the required time for achieving a required packet error probability. The derivation is done based on a queuing theory. The results are evaluated from a QoS point of view.
II. NETWORK MODEL

We consider a wireless multihop network which consists of wireless nodes which are connected with wireless links. Assume that all the source-destination pairs in the network have the same number of routes that are established by a multipath routing protocol. A network model for any source-destination pair in the network is shown in Fig. 1. \( N \) mutually disjoint routes exist between the source node and the destination node. The \( n \)-th route consists of \( M_n \) wireless links and \( M_n - 1 \) forwarding nodes. The network topology is assumed not to change during packet transmissions.

III. MULTIPLE-ROUTE PACKET COMBINING SCHEME

The transmitter structure of the source node is shown in Fig. 2. A information packet that is generated in the source node is coded by the convolutional encoder. The coded packet is interleaved on a bit-by-bit basis. The output of the interleaver is fed into the modulator. Binary phase shift keying (BPSK) is used as the modulation method. The modulated packet is sent toward the destination node.

There exist \( N \) multiple routes between the source node and the destination node. The packet sent by the source node is received by \( N \) forwarding nodes which are the first node on the routes. The decoding and reencoding process is not performed in forwarding nodes. Each forwarding node sends the received packet to the next node on the route. Therefore, \( N \) copies of the same packet are transmitted along \( N \) routes.

The multiple copies of the packet are received by the destination node. The receiver structure of the destination node is shown in Fig. 3. A received copy is demodulated to a binary sequence and stored to the buffer. After some copies are received, the stored packets are fed into the combiner simultaneously. The combiner calculates likelihood information for each bit of the packet from its copies. A soft-output combining scheme proposed in [1] is employed in the combiner. The output of the combiner is fed into the Viterbi decoder.

If the multiple routes between the source and the destination are mutually disjoint and each route consists of independent wireless links, these routes are independent communication channels. Since the receiver combines several copies of the same packet transmitted over independent channels, a diversity gain can be obtained.

IV. PERFORMANCE ANALYSIS

A. Assumptions and Modeling

Each node can transmit and receive a packet independently. Each node is allowed to transmit and receive only one packet simultaneously. It is assumed that every packets sent from nodes are received without collisions. This assumption is valid if an optimum medium access control protocol is employed. Let us consider a set of nodes that includes all the neighboring nodes of a node, say \( A \). The protocol controls packet transmissions from all the nodes in the set. It is assumed that each node in the set can detect transmissions of the other nodes. When a request for transmitting a packet to \( A \) is generated in one of the neighbors, say \( B \), \( B \) is allowed to transmit the packet if none of the other neighbors are not transmitting a packet to \( A \). If one of the other neighbors is transmitting a packet to \( A \), \( B \) has to wait. When the transmission is finished, a node that has the earliest generated request is allowed to transmit the packet.

When packet transmissions are controlled as described above, transmission request arrival process at any wireless node is modeled as a queue. Generations of transmission requests correspond to arrivals of packets at the queue. The time between the start of a transmission and the end of it corresponds to the service time of the queue.

For each wireless node, the generation process of transmission requests from all its neighbors is assumed to be modeled as an independent Poisson process with mean \( \lambda^{-1} \). Then, the packet arrival process at the queue is also Poisson with mean \( \lambda^{-1} \). Moreover, the length of a information packet is assumed to be exponential with mean \( T_b \). When a
When the convolutional encoder with rate $k/n$ and constraint length $K$ is employed, the duration of a coded packet is also exponential with mean:

$$T_c = \frac{n}{kR} \sum_{k=0}^{K-1} e^{k(K-1)/T_c},$$  \hfill (1)$$

where $R$ is the transmission rate. According to the assumptions described above, each wireless link is modeled as an $M/M/1$ queue. The arrival process for each queue is Poisson with mean $\lambda^{-1}$. The service time distribution is exponential with mean $\mu^{-1} = 1/T_s$. The time between the generation of a transmission request and the end of its transmission equals the waiting time of the queue plus its service time.

### B. Analysis of the Average Packet Error Probability as a Function of Elapsed Time

According to the above model, we derive the average packet error probability as a function of elapsed time after transmission requests of copied packets are generated. Let us consider the $n$th route of the $N$ multiple routes. This route consists of $M_n$ wireless links. When each wireless link is modeled as the $M/M/1$ queue, the probability density function for the packet delay distribution of the $m$th wireless link is exponential and given by

$$f_{w_{m,n}}(t) = \mu(1-\rho)e^{-\mu(1-\rho)t},$$ \hfill (2)$$

where $\rho = \lambda/\mu$ is the traffic intensity. Since wireless links on a route are statistically independent and have the same service time distribution, the probability density function for the packet delay of the $n$th route $w_n$ is derived by $M_n$-fold convolution of Eq. (2) and given by

$$f_{w_{n,n}}(t) = \frac{\mu(1-\rho)}{(M_n-1)!} e^{-\mu(1-\rho)t}. \hfill (3)$$

Consider $N$ multiple copies of a packet whose transmission requests are generated at $t = 0$ by the source node. The $n$th copied packet is assumed to be transmitted along the $n$th route. The packet combining process at the destination is started when some time elapses after the transmission requests are generated. Let the time to be $t$. If the packet delay of the $n$th copied packet is less than $t$, the packet is received by the destination before the start of packet combining. Then, the probability that the packet transmitted along the $n$th route has already been received at the elapsed time $t$ is given by

$$p_n(t) = \Gamma(M_n) - \Gamma(M_n, \mu(1-\rho)t), \hfill (4)$$

where $\Gamma(z)$ is the gamma function and $\Gamma(a,z)$ is the incomplete gamma function. When all the routes between the source and the destination are of equal length, that is, $M_n = M$ for all $n$, the probability $p_n(t)$ is given by

$$p_n(t) = p(t) = \frac{\Gamma(M) - \Gamma(M, \mu(1-\rho)t)}{(M-1)!}. \hfill (5)$$

Then, the probability that the number of received packets at $t$ equals $k$ is given by

$$P[N(t) = k] = \binom{N}{k} p(t)^k [1 - p(t)]^{N-k}. \hfill (6)$$

Equation (6) represents the probability that the number of combined packets at the elapsed time $t$ equals $k$.

Using Eq. (6), the average packet error probability at the elapsed time $t$ is given by

$$Q_e(t) = \sum_{k=0}^{N} P_n(k, M) P[N(t) = k], \hfill (7)$$

where $P_n(k, M)$ is the packet error probability when the number of combined packets is $k$ and the lengths of the routes equal $M$. This probability is obtained by computer simulation.

When the lengths of the routes are different each other, $Q_e(t)$ is not represented by a simple form. Therefore, the derivation is excluded here.

### C. Analysis of the Required Time for Achieving a Packet Error Probability

In this section, we obtain the required time for achieving a packet error probability. To analyze the performance, we first derive the probability density function of the time required to be received $k$ copied packets by the destination node. It is assumed that all the routes between the source and the destination node are of equal length, that is, $M_n = M$ for all $n$. Therefore, the probability density of the packet delay of the $n$th route is expressed as

$$f_{w_{n,k}}(t) = f_{w_{n}}(t) = \frac{\mu(1-\rho)^{M_n}}{(M_n-1)!} e^{-\mu(1-\rho)t}. \hfill (8)$$

Let $w_{(k)}$ be defined the time required to be received $k$ copied packets. Then, the probability density function of $w_{(k)}$ is given by

$$f_{w_{(k)}}(t) = \frac{\mu(1-\rho)^{M}}{(M-1)!} e^{-(M-1)t} = \frac{N!}{(k-1)!(N-k)!} F_{w_{(k)}}(t)[1 - F_{w_{(k)}}(t)]^{N-k} f_{w_{(k)}}(t), \hfill (9)$$

where $F_{w}(t)$ is the cumulative distribution function of the packet delay of any route and obtained by

$$F_{w}(t) = \frac{\Gamma(M) - \Gamma(M, \mu(1-\rho)t)}{(M-1)!}. \hfill (10)$$

For given $k$ and $M$, the probability $P_e(k, M)$ can be uniquely determined. Hence, Eq. (9) represents the required time for achieving the packet error probability $P_e(k, M)$.
V. NUMERICAL RESULTS

In this section, we evaluate the performance of the proposed system. It is assumed that the information packet length is exponential with mean \( L_s = 500 \) bits. A convolutional encoder with \( b_1/n_0 = 1/2, K = 7 \) is employed. All the wireless links are assumed to be mutually statistically independent and identical Rayleigh fading channels. A packet in a wireless link is corrupted by an additive white Gaussian noise process. All packets are assumed to be received with equal power. All the multiple routes are of equal length and assumed to be 5 hops.

In order to evaluate Eqs. (7) and (9) numerically, we first obtain the packet error probability \( P_e(k, M) \) by computer simulation. Then, the average packet error probability and the required time for achieving a packet error probability are evaluated. To consider the effect of the increase in transmitted packets on the amount of traffic, it is assumed that the traffic intensity for each wireless link is proportional to the number of multiple routes and defined by \( \rho = 0.1N \). Moreover, the \( E_b/N_0 \) is assumed to be 9 dB, where \( E_b \) is the energy per bit and \( N_0/2 \) is the two-sided spectral density of the additive white Gaussian noise process.

A. Average Packet Error Probability as a Function of Elapsed Time

Figure 4 represents the average packet error probabilities for different numbers of multiple routes as a function of the elapsed time. The time axis is normalized by the mean duration of the coded packet \( T_c \). It is observed that for any \( N \), the average packet error probability decreases and approaches a constant value as the time elapses. This is because the probability that all the copied packets sent by the source node are received at the destination node tends to 1 as the time elapses. Actually, the minimum achievable value for each \( N \) equals \( P_e(N, M) \), which is the packet error probability when all the copied packets are combined.

At a small elapsed time, the achievable value does not decrease when \( N \) exceeds a certain value. For example, at \( t/T_c = 30 \), the achievable value decreases as the number of the multiple routes increases from \( N = 1 \) to \( N = 7 \). However, when \( N \) increases from \( N = 7 \) to \( N = 9 \), the achievable value increases. The packet delay of each route increases as the number of copied packets increases. When the packet delay of each route increases, the number of received and combined packets at a specific elapsed time decreases. The packet error probability decreases as the number of combined packets decreases. Therefore, if \( N \) exceeds a certain value, the average packet error probability at a specific time decreases.

It is interesting to evaluate these results from a QoS point of view. Assumed that a tolerable delay is 30 and a required packet error probability is \( 10^{-2} \). In this case, the packet error probability is minimized when \( N = 7 \). However, since the required packet error probability is \( 10^{-2} \), the requirements can be satisfied at \( N = 6 \). This implies that the number of multiple routes should be selected based on QoS requirements.

B. Required Time for Achieving a Packet Error Probability

Figures 5–8 illustrate the complimentary cumulative distributions of \( f_{\omega}(t) \). These figures represent the required time for achieving the packet error probabilities \( P_e(1, 5) = 9.9 \times 10^{-1}, P_e(5, 5) = 5.7 \times 10^{-2}, P_e(6, 5) = 6.0 \times 10^{-3} \) and \( P_e(7, 5) = 7.0 \times 10^{-4} \), respectively. In the figures, the time axis is normalized by \( T_c \).

We evaluate the time required to achieve \( P_e(k, M) \) with probability 0.99. In Fig. 5, the required time decreases as the number of routes increases from \( N = 1 \) to \( N = 3 \). The minimum value is attained at \( N = 3 \). However, when \( N \) increases from \( N = 3 \) to \( N = 9 \), the required time increases. Such property can also be seen in Figs. 6 and 7. However, in these figures, the amount of the reduction is small compared to Fig. 5. Besides, in Fig. 8, the required time does not reduce at all. These results illustrate that the reduction of the required time for achieving a packet error probability can be obtained by increasing the number of multiple routes. However, the reduction is limited to the small values of \( k \).

We evaluate these results from a QoS point of view. Assume that the required packet error probability is \( 10^{-1} \). In this case, it is necessary to be received and combined \( k = 5 \) packets by the destination at \( E_b/N_0 = 9 \) dB. Then, \( k = 5 \) packets should be sent by the source node to satisfy the requirement, provided that all the transmitted packets are received. However, if \( k = 6 \) packets are sent by the source, the time needed to satisfy the required packet error probability can be reduced as shown in Fig. 6.

VI. CONCLUSIONS

In this paper, we have proposed to employ the multiple-route packet combining scheme to improve the performance of real-time communications in wireless multihop networks. We have analyzed two characteristics. One is the average packet error probability, which is obtained as a function of elapsed time after transmission requests of copied packets are generated. The other is the required time for achieving
A required packet error probability. The results have been evaluated from a QoS point of view.

From numerical results, it has been shown that for a given tolerable delay, there exists a number of multiple routes that minimizes the achievable average packet error probability. Moreover, if the number of multiple routes is selected appropriately, the required time for achieving a required packet error probability can be minimized. These results indicate that the selection of the number of multiple routes, that is, the number of transmitted copies have to be done based on QoS requirements.

Acknowledgments
This work is supported in part by the Ministry of Education, Culture, Sports, Science and Technology in Japan and the Ministry of Public Management, Home Affairs, Posts and Telecommunications in Japan.

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