Cross-Layer Resource Allocation with Multipath Routing in Wireless Multihop and Multichannel Systems

Bongjhin Shin, Jinwoo Choe, Byoungik Kang, Daehyoung Hong, and Youngsuk Park

Abstract: **A joint multipath routing algorithm and channel allocation and scheduling for wireless multihop and multichannel systems is discussed. In packet transmission, distribution of packets to multiroutes makes it possible to reduce the transmission cost of the channels. Cross-layer cooperation of routing, channel allocation, and scheduling is an effective method of packet distribution. As a framework for the cooperation, we propose a multiroute distance vector routing (MDVR) scheme. In the MDVR scheme, the routing table is logically placed in between the routing and link layers, and the table plays the role of a service access point between these two layers. To evaluate the performance of MDVR, simulation is performed in a multichannel, multihop environment. The simulation results show that the MDVR framework can be efficiently implemented in the form of a distributed routing algorithm. It is also shown that in MDVR, the system-wise channel efficiency is almost 25% higher than that in a conventional single-route routing approach.**

Index Terms: **Cross layer, joint resource allocation, multiroute routing, multiuser diversity, scheduling.**

I. INTRODUCTION

Improving spectral efficiency has been an important objective in the field of wireless communication. Till date, several multichannel systems have been developed and investigated for this purpose. In multichannel systems such as orthogonal frequency division multiplexing (OFDM) [1] and multi-input multi-output (MIMO) [2], [3] systems, a data stream is transmitted over a set of multiple channels divided on the basis of frequency or time, and a set of channels may be used simultaneously or in sequence.

In multichannel systems, for maximization of channel efficiency, channels may be allocated in the decreasing order of transmission cost. Therefore, if the number of packets increases, some packets are allocated to high-cost channels, and the overall cost is increased even in a single-route transmission. Distributing the packets to multiple routes helps reduce the number of transmitted packets per route; consequently, the transmission cost can be lowered. To allocate a packet to the route that incurs the lowest transmission cost is one of the methods for maximizing the gain of this packet distribution. The gain from this route selection is referred to as multiroute channel allocation (MR-CA) diversity gain.

The diversity gain obtained by multiple-route transmission has been studied in the literature. In [4] and [5], cooperative relaying methods for obtaining multiroute diversity gain in wireless relay systems have been proposed. In wireless multihop systems with cooperative relays, data transmitted by a source node are received simultaneously at several relay nodes. Then, the relays transmit the data to a destination node by opportunistic ways to obtain multiuser diversity gain. Another type of diversity gain, MR-CA diversity gain, has been proposed in [6] and [7]. In these papers, the concept of dispersity routing has been introduced: A message transmitted to a destination node is divided into several sub-messages; then, the sub-messages are transmitted via several different routes that connect a source node to the destination node.

Change in the wireless link state of each route that connects a source node to a destination node is important for achieving MR-CA diversity gain. In order to obtain diversity gain from routing, the link states must be changed in a routing process. In [8] and [9], cross-layer schemes for joint resource management and routing have been defined as optimization problems, and heuristic algorithms used to solve the problems have been proposed; however, only an unstable feature caused by fading channels is considered as a reason for the change of link states. The link states also can be changed during scheduling and channel allocation (SCA) by applying multiuser diversity. In this paper, we propose a multipath routing scheme, in which the link state is changed during SCA in the routing process.

Multipath routing schemes have been widely reported in the literature. A multipath routing scheme for video transmission in wireless mesh networks is proposed in [10] and [11]. In these studies, the purpose of applying multipath routing was to guarantee stable and delay-tolerant transmission. However, MR-CA diversity gain was not considered in these studies. On the other hand, the present study focuses on multipath routing to maximize the MR-CA diversity gain.

Previously, we studied the performance of a multichannel system. In [12], we proposed a resource allocation scheme for a multichannel system and in [13], we propose a joint resource allocation and scheduling scheme for multichannel and multihop systems. In the present study, we deal with the cross-layer cooperation of routing, channel allocation, and scheduling in multichannel and multihop systems on the basis of the proposed multipath routing scheme.

In this paper, we introduce a multiroute distance vector routing (MDVR) scheme as a framework for cooperative routing/SCA. MDVR is a distance vector routing scheme (i.e., only neighboring nodes exchange their routing information in the form of a distance vector), in which multiple routes are established and maintained for each destination node. MDVR does

---

Manuscript received August 13, 2009; approved for publication by Christos Douligeris, Division II Editor, October 7, 2010.

This research was supported by in part Samsung Electronics Co., Ltd.

B. Shin and D. Hong are with the Department of Electronic Engineering, Sogang Univ., Korea, email: {bjshin, dhong}@sogang.ac.kr.

B. Kang and Y. Park are with the Samsung Electronics, Suwon, Korea, email: kbi83@sogang.ac.kr, dryspark@gmail.com.

1229-2370/11/$10.00 © 2011 KICS

not dynamically establish/terminate routes to adapt to changes in the link/channel conditions and traffic load; rather, this scheme dynamically shifts traffic load from one route to another and helps reduce the transmission cost and thus improve channel resource efficiency. In MDVR, cooperation between routing and SCA functions is facilitated by modifying the logical position and structure of the conventional routing table; as a result channel resource efficiency is improved.

The rest of this paper is organized as follows. The following section illustrates how traditional routing approaches may cause system-wise inefficiency in wireless networks. In addition, cooperation between routing and SCA functions is suggested as a solution to the efficiency degradation problem. In Section III, a simplified network model that provides a perspective of a wireless network from the viewpoint of a single node is presented. Section IV describes the architecture and mechanism of MDVR in detail and provides an implementation example of MDVR. In Section V, the performance of an exemplary implementation of MDVR is demonstrated through a set of numerical experiments. Finally, Section VI provides concluding remarks.

II. MULTIROUTE CHANNEL ALLOCATION DIVERSITY GAIN

A. Impact of Scheduling and Channel Allocation

In this paper, the marginal transmission cost is defined as the change in the total amount of channel resources allocated to a data stream that arises when the required traffic rate (i.e., load) of the data stream changes by one data unit. Moreover, the average transmission cost is defined as the ratio of the total amount of channel resources allocated to a data stream to the traffic rate of the data stream. The marginal (or average) channel resource efficiency is simply the reciprocal of the marginal (or average) transmission cost.

In wired networks, the channel resource efficiency (i.e., the amount of data carried by a single channel unit) over a link or a route is usually time-invariant and is determined independently of the traffic load. On the other hand, in wireless networks, the efficiency is usually time-varying because the channel quality changes with time for various factors. Furthermore, the efficiency may depend on the offered traffic load because each channel allocated to a data stream may be in a different condition (and hence may have a different capacity). The actual relationship between the efficiency (of channel resources) and the traffic load in a wireless network will be determined by the SCA scheme adopted by individual nodes or by the entire network.

In wireless systems with opportunistic SCA schemes, channels will be additionally allocated to the data stream when the traffic load of a data stream is increased. Generally, the additionally allocated channels will be of lower quality (i.e., less appreciated by the data stream) than the channels that have already been allocated. In other words, channel resources will be allocated to a data stream (or user) in the decreasing order of quality (with respect to the data stream or user) as the traffic load increases. Fig. 1 illustrates an example of such a channel allocation in a simple scenario. A link is established between two nodes over multiple wireless channels of different qualities. An opportunistic SCA scheme is assumed to be adopted by the origin node. As the amount of traffic from node i to node k increases, the number of channels allocated to the link SCA scheme. In the SCA scheme, the best-quality channel is allocated when the traffic load is minimal. As the load increases, the best of the available channels is continuously allocated. Consequently, the order of allocation will be the same as the order of quality, as shown in the figure, and the marginal efficiency (cost) will decrease (increase) as the traffic load increases.

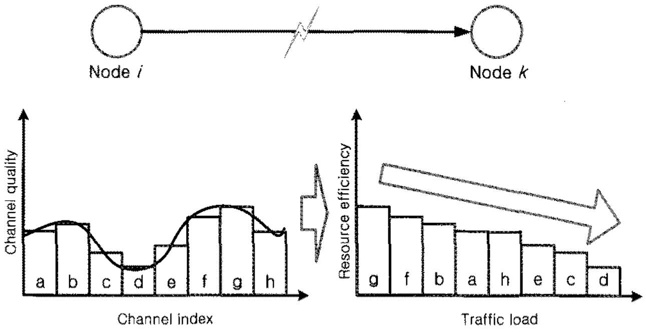


Fig. 1. Illustration of decreasing marginal channel efficiency with increasing traffic load.

B. Multiroute Channel Allocation Diversity Gain

In this section, we explain the concept of MR-CA diversity gain, which is generated by applying the multiuser diversity concept to routing. In addition, we show how cooperation between the routing and the SCA functions can help improve the system-wise efficiency of channel resources.

Consider a simple wireless network, as shown in Figs. 2(a) and 2(b), that consists of four nodes and four wireless links. Nodes 1 and 4 are the source and sink nodes, respectively, and there are two routes (A and B) between them. We assume that disjoint sets of channels are allocated to individual links. We also assume that the quality of channels over route A is better than that of the channels over route B and that an opportunistic SCA scheme is adopted by all the nodes. The marginal transmission cost of both routes increases as the traffic load increases; however, the transmission cost of route B is higher than that of route A at any given traffic load, as shown in Figs. 2(c) and 2(d). A conventional routing scheme that takes into account the efficiency of channel resources would choose route A because this route can accommodate the given traffic load with a smaller set of channels than does route B. Once route A is established (Fig. 2(a)), the entire traffic load will be imposed on this route A, and the total transmission cost of the network will be given by the area covered by the shaded blocks in Fig. 2(c). In Figs. 2(c) and 2(d), each shaded block corresponds to a unit of traffic load, regardless of its size, and the area of the block represents the transmission cost of the associated unit of the traffic load. When the fourth unit of the traffic load is carried by route A, the marginal cost exceeds the cost that would be paid if the unit were carried by route B. Since the transmission cost of route A increases with the traffic load, the transmission cost of this route will exceed that of route B from a certain load. To solve this problem in the conventional routing scheme, a part of the traffic load should be shifted to route B, as shown in Figs. 2(b)

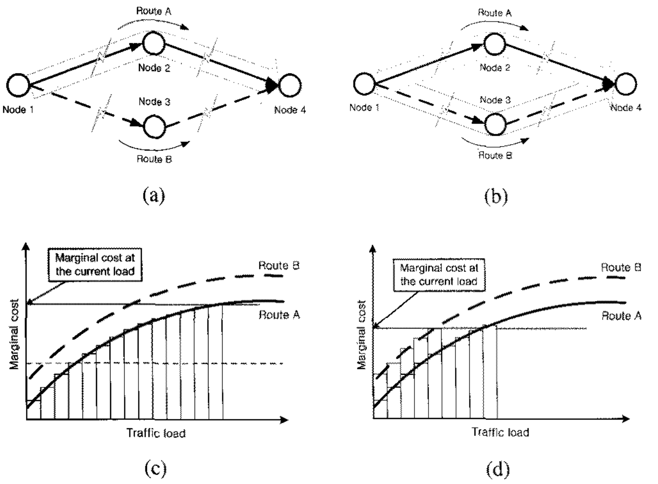


Fig. 2. Comparison of a conventional routing scenario and an optimal routing scenario: (a) Single-route routing, (b) multiroute routing, (c) single-route channel allocation, and (d) multiroute channel allocation.

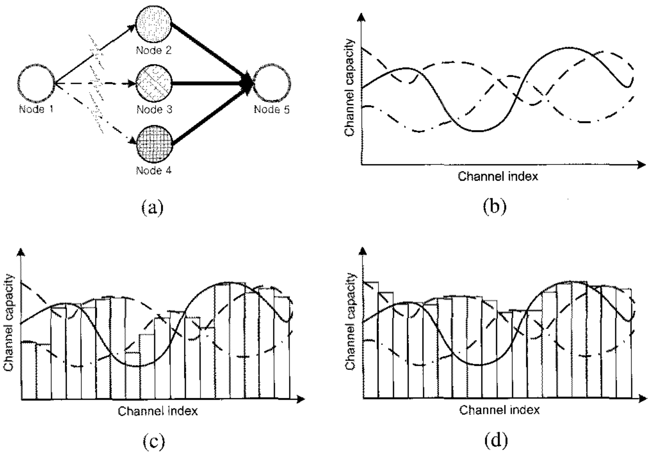


Fig. 3. MR-CA diversity as an extended notion of multiuser diversity: (a) An example of three routes, (b) channel quality of three links, (c) uniform traffic distribution, and (d) optimal traffic distribution.

and 2(d).

Multiroute transmission can help reduce the transmission cost. As shown in Figs. 2(c) and 2(d), the marginal costs of routes A and B (for the given traffic load distribution) are similar to each other but lower than the marginal cost of route A (Fig. 2(c)); this figure shows the result of conventional routing. The difference between the marginal costs in Figs. 2(c) and 2(d) may be considered the MR-CA diversity gain achieved by optimal distribution of the network traffic over multiple routes. The MR-CA diversity gain in terms of the total (i.e., system-wise) transmission cost is given by the difference between the total areas of the shaded blocks in Figs. 2(c) and 2(d). To achieve MR-CA diversity gain, routing should take place for individual fine threads of the traffic and not for the entire traffic. Multiple routes between a pair of source and sink nodes must be dynamically adjusted to the distribution of traffic load over multiple routes after establishing these multiple routes at the beginning. Thus, the routing function will keep referring to the marginal costs of different links or routes, which should be provided by the lower layers, as a result of opportunistic SCA. For a significant MR-CA diversity gain, optimal distribution of the traffic load over multiple routes by making use of the dynamic cooperation between the routing and SCA functions is necessary.

Consider an example of a network that consists of five nodes and six wireless and wired links, as shown in Fig. 3(a). Nodes 1 and 5 are the source and sink nodes, respectively, and three intermediate nodes (i.e., nodes 2, 3, and 4) are connected to the source node through wireless links and to the sink through wired links. Therefore, there are three routes from the source to the sink, each of which is composed of one wireless link and one wired link. It is assumed that three wireless links from the source node to the intermediate nodes share a set of channels and that an opportunistic SCA scheme is adopted by the source node. The channel quality may be different for different links; therefore, a same channel may yield different capacities when allocated to different links. Fig. 3(b) shows an example of such link-dependent channel capacity. The channel capacities for three different links are plotted in the figure. We assume that the transmission costs over three routes are mainly determined by the transmission costs of the wireless links. Furthers, we assume that a multiroute routing scheme is used for load balancing and that the traffic load is distributed uniformly over three routes. Fig. 3(c) shows an example of channel allocation at the source node for uniform load distribution. In Fig. 3(c), there are three different types of shaded blocks, and each type of block represents a channel allocated to an associated link. Moreover, the area of a shaded block represents the amount of traffic carried by the associated channel. Because the traffic load is uniformly distributed, channels are allocated by the SCA function in such a manner that the total area covered by all types of shaded blocks is maximized. In this case, all the three types of blocks should have almost the same total size. In this case, some of the channels cannot be allocated to the links that will profit the most from them.

If the routing and SCA functions cooperate dynamically at the source node, the routing function can easily identity the optimal traffic distribution over the three routes. Fig. 3(d) shows an example of opportunistic channel allocation under optimal traffic distribution conditions. Every channel is allocated to the link that will profit the most from it. Consequently, the resulting channel efficiency will be the optimal efficiency that can be obtained under the given situation. This simple example also indicates that the routing function may help the SCA function in improving multiuser diversity gain by increasing the flexibility of channel allocation. In other words, by dynamically adjusting the traffic load distribution over multiple routes, the routing function can relax the constraints that may be imposed on the SCA function when the traffic distribution is fixed and thus help maximize multiuser diversity gain. Therefore, MR-CA diversity may be thought of as an extension of multiuser diversity achievable through cooperation between the routing and SCA functions.

III. MULTIROUTE NETWORK MODEL

In this section, we introduce a simplified view of wireless networks from the viewpoint of a single node. This network model

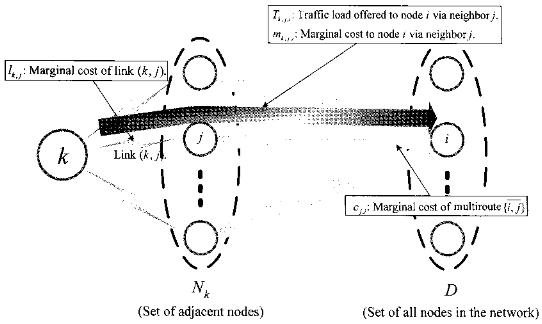


Fig. 4. A simplified view of a wireless network showing a single node.

perspective provides a theoretical basis for MDVR. The cooperative routing/SCA framework is also proposed in the following section. Fig. 4 depicts the network model from the viewpoint of node k. Two sets of nodes are shown in the figure: N_k, the set of nodes neighboring node k; D, the set of all potential sink nodes. Further, there are two different types of connections between nodes; i.e., links between node k and its neighboring nodes, and multiroutes connecting a neighboring node to the node k and a sink node. In fact, we define following three kinds of connections between nodes.

- Link: A direct connection between nodes through a wireless or a wired medium.
- Route: A single- or multihop connection between nodes composed of one or more links.
- Multiroute: A set of routes between an origin node and a destination node.

A link (or route) may be considered a route (or multiroutes) by itself, but the reverse is not true in general. In this paper, a link, route, and multiroutes between two nodes a and b will be denoted by (a,b), $(\overline{a,b})$, and $\{\overline{a,b}\}$, respectively.

Fig. 4 defines a set of quantities associated with (i) links between node k and its neighbors, (ii) multiroutes between N_k and D, and (iii) multiroutes from the node k to D (i.e., all concatenations of a link (k,j) and multiroutes $\{\overline{j,i}\}$ for different $j \in N_k$ and $i \in D$). $T_{k,j,i}$ is the amount of traffic delivered to a sink node $i \in D$ from node k via its neighbor $j \in N_k$ over a unit period of time. Consequently, $S_{k,i}$, the total amount of traffic load transmitted from the node k to sink node i, and $Q_{k,j}$ the total amount of traffic load transmitted from the node k to its neighbor $j \in N_k$, will be given by

$$S_{k,i} = \sum_{j \in N_k} T_{k,j,i} \quad \text{and} \tag{1}$$

$$Q_{k,j} = \sum_{i \in D} T_{k,j,i}, \quad \text{respectively.} \tag{2}$$

All the quantities shown in Fig. 4, except for $T_{k,j,i}$, represent the marginal cost of data transmission over links, routes, and multiroutes. In this network model, it is assumed that the transmission cost of multiroute $\{\overline{j,i}\}$ is determined only by the following two factors: (i) The state (e.g., the quality of wireless channels) of links over every route in $\{\overline{j,i}\}$ and (ii) $T_{k,j,i}$, the traffic load offered to multiroute $\{\overline{j,i}\}$. In other words, the cost $C_{j,i}$ is assumed to be a function of $T_{k,j,i}$ only, i.e.,

$$C_{j,i} = g_{j,i}(T_{k,j,i}) \quad \text{for} \quad j \in N_k \text{ and } i \in D \tag{3}$$

where the function $g_{j,i}$ may be time-varying with the state of links in the multiroutes. We assume that the amount of changes in $C_{j,i}$ is determined mainly by the amount of changes in $T_{k,j,i}$, when (i) the change is fairly small and (ii) the distribution of traffic load in the network that does not appear in the network model is static. The marginal cost $c_{j,i}$ of multiroute $\{\overline{j,i}\}$ is simply given by

$$c_{j,i} = \frac{\partial C_{j,i}}{\partial T_{k,j,i}} = \frac{\partial}{\partial T_{k,j,i}} g_{j,i}(T_{k,j,i}). \tag{4}$$

The second assumption is made for the costs of links $\{(k,j) | j \in N_k\}$. It is assumed that $L_{k,j}$, the cost of the links between node k and its neighbors N_k, is determined only by (i) the quality of the communication channels between k and N_k and (ii) $\vec{Q}_k := [Q_{k,j}]_{j \in N_k}$, the local traffic distribution from node k to its neighbors. In other words, $\vec{L}_k := [L_{k,j}]_{j \in N_k}$, the link cost vector, is given by

$$\vec{L}_k = \vec{r}(\vec{Q}_k) \tag{5}$$

where the function $\vec{r}$ also becomes time-varying as the state of communication channels at node k changes with time. Moreover, $\vec{r}$ reflects the characteristics of the SCA scheme employed by node k, and the link cost $L_{k,j}$ is dependent on the traffic load of other links $\{(k,j') | j' \neq j\}$. This is because an identical set of channels will be allocated disjointly to all links between node k and N_k when the SCA scheme makes use of multiuser diversity. In other words, a change in the traffic load of link (k,j) may cause a change in the sets of channels allocated to other links $\{(k,j') | j' \neq j\}$ and a consequent change in the link costs $\{L_{k,j'} | j' \neq j\}$. To take this cross-influence into account, we define the marginal costs of $\{(k,j) | j \in N_k\}$ are defined differently from those of multiroutes $\{\{\overline{j,i}\} | j \in N_k, i \in D\}$.

$$l_{k,j} := \frac{\partial}{\partial Q_{k,j}} \sum_{j' \in N_k} L_{k,j'} = \sum_{j' \in N_k} \frac{\partial L_{k,j'}}{\partial Q_{k,j}}. \tag{6}$$

Therefore, $l_{k,j}$ is merely the sum of the jth column of the Jacobian matrix

$$\frac{\partial \vec{r}}{\partial \vec{Q}_k} = \left[\frac{\partial r_{j'}}{\partial Q_{k,j}} \right]_{j' \in N_k,\, j \in N_k}.$$

Given the costs of links $\{(k,j) | j \in N_k\}$ and multiroutes $\{\{\overline{j,i}\} | j \in N_k, i \in D\}$, the marginal cost of multiroutes from node k to a sink node $i \in D$ via a neighbor $j \in N_k$ is simply given as

$$m_{k,j,i} = l_{k,j} + c_{j,i}. \tag{7}$$

Now, consider the problem of minimizing the total transmission cost from a viewpoint of node k when the total traffic amount to each sink node is given. In other words, node k knows $S_{k,i}$ for all $i \in D$ and attempts to reduce the total transmission cost by adjusting the traffic load distribution $\mathbf{T}_k := [T_{k,j,i}]_{j \in N_k, i \in D}$. The problem may be formulated mathematically as below.

Minimize:

$$U(\mathbf{T}_k) := \sum_{j \in N_k, i \in D} M_{k,j,i} = \sum_{j \in N_k} L_{k,j} + \sum_{j \in N_k, i \in D} C_{j,i}, \tag{8}$$

under constraints:

$$S_{k,i} = \sum_{j \in N_k} T_{k,j,i} \quad \forall i \in D, \tag{9}$$

$$T_{k,j,i} \geq 0 \quad \forall j \in N_k \text{ and } \forall i \in D. \tag{10}$$

The function g and $\vec{r}$ in (3) and (5) are not usually given in closed form. Therefore, finding the optimum solution of this optimization problem is a challenging task, and search techniques may be an alternative choice to obtain a reasonably accurate solution. To apply a gradient-based (or derivative-based) search technique, we first derive the first-order derivative of the total cost $U(\mathbf{T}_k)$.

$$\begin{aligned}
\frac{\partial}{\partial T_{k,j,i}} U(\mathbf{T}_k) &= \sum_{j' \in N_k} \frac{\partial L_{k,j'}}{\partial T_{k,j,i}} + \sum_{j' \in N_k, i' \in D} \frac{\partial C_{j',i'}}{\partial T_{k,j,i}} \\
&= \sum_{j' \in N_k} \frac{\partial L_{k,j'}}{\partial Q_{k,j}} \frac{\partial Q_{k,j}}{\partial T_{k,j,i}} + \frac{\partial C_{j,i}}{\partial T_{k,j,i}} \\
&\quad \left(\because \frac{\partial C_{j',i}}{\partial T_{k,j,i}} = 0 \quad \forall j' \neq j \right) \\
&= \sum_{j' \in N_k} \frac{\partial L_{k,j'}}{\partial Q_{k,j}} + \frac{\partial C_{j,i}}{\partial T_{k,j,i}} \\
&\quad \left(\because \frac{\partial Q_{k,j}}{\partial T_{k,j,i}} = 1 \right) \\
&= l_{k,j} + c_{j,i} = m_{k,j,i}.
\end{aligned} \tag{11}$$

This equation allows us to express the change in the total cost $U(\mathbf{T}_k)$ resulting from infinitesimally changes in $\mathbf{T}_k$ as below.

$$\begin{aligned}
\Delta U &= \sum_{j \in N_k, i \in D} \frac{\partial U}{\partial T_{k,j,i}} \Delta T_{k,j,i} \\
&= \sum_{j \in N_k} l_{k,j} \sum_{i \in D} \Delta T_{k,j,i} + \sum_{j \in N_k, i \in D} c_{j,i} \Delta T_{k,j,i} \\
&= \sum_{j \in N_k} l_{k,j} \Delta Q_{k,j} + \sum_{j \in N_k, i \in D} c_{j,i} \Delta T_{k,j,i} \\
&= \sum_{j \in N_k, i \in D} m_{k,j,i} \Delta T_{k,j,i}.
\end{aligned} \tag{12}$$

It should, however, be noted that because of constraints (9) and (10), $\Delta \mathbf{T}_k = [\Delta T_{k,j,i}]_{j \in N_k, i \in D}$ cannot be arbitrary but must satisfy the following conditions.

$$\sum_{j \in N_k} \Delta T_{k,j,i} = 0 \quad \forall i \in D, \tag{13}$$

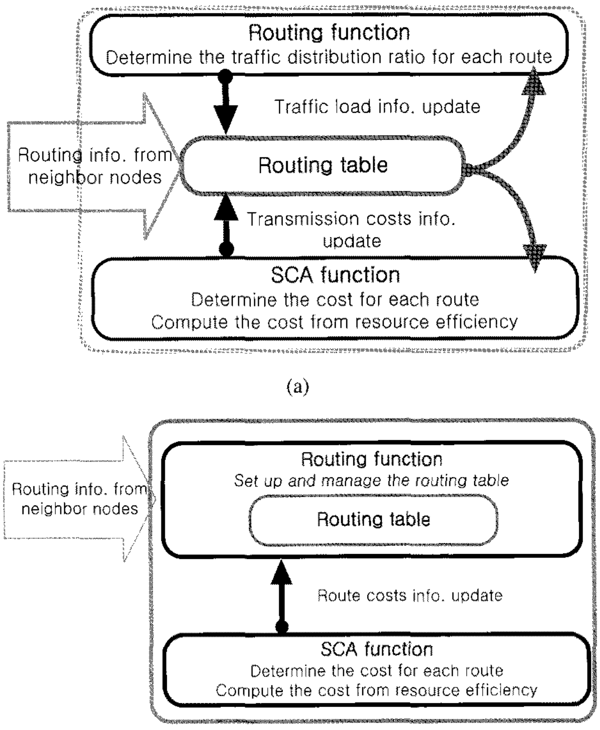
$$\Delta T_{k,j,i} \geq 0 \quad \text{if } T_{k,j,i} = 0, \tag{14}$$

$$\Delta T_{k,j,i} \leq 0 \quad \text{if } T_{k,j,i} = S_{k,i}. \tag{15}$$

Equations (12)–(15) suggest a simple gradient-based search algorithm and help us devise a simple method to search for local optimality. Now, assume that there exists a pair of neighbors $j, j' \in N_k$ such that

$$T_{k,j',i} > 0 \text{ and } m_{k,j,i} < m_{k,j',i} \quad \text{for some} \quad i \in D. \tag{16}$$

Then, one can find a sufficiently small $\epsilon > 0$ such that small changes $\Delta T_{k,j,i} = \epsilon$ and $\Delta T_{k,j',i} = -\epsilon$ (when all the other entries of $\Delta \mathbf{T}_k$ are set to 0) will not result in violation of constraints (9) and (10), while $\Delta U \approx (m_{k,j,i} - m_{k,j',i})\epsilon$ will take a negative value; this implies that there is a high probability of cost minimization. Therefore, if there exists a pair of neighbors $j, j' \in N_k$ that satisfy conditions (16), the current traffic load distribution $\mathbf{T}_k$ cannot be a local optimum, and the total cost U can be reduced simply by shifting a small amount of traffic load from $T_{k,j',i}$ to $T_{k,j,i}$. At the local optimum point, therefore, all the loaded multiroutes to a sink node i established through different neighbors $j \in N_k$ must have the same marginal cost.



(a)

(b)

Fig. 5. Comparison of conventional routing schemes and MDVR: (a) Logical architecture of conventional routing schemes and (b) logical architecture of MDVR.

As will be described later in detail, the MDVR mechanism is simple, and the total cost U may be reduced by iteratively shifting the traffic load from a loaded route with a higher marginal cost to a route with a lower marginal cost until all the loaded multiroutes to a sink node have the same marginal cost.

IV. MULTIROUTE DISTANCE VECTOR ROUTING

In this section, we describe the logical architecture and structure of the MDVR routing table. The parameter update mechanism of the routing table and an implementation example of the traffic-load-shifting algorithm, which shifts the traffic load from one route to another, are also described.

MDVR controls the amount of traffic data loaded on each route of a multiroute set and efficiently maintains the resource efficiency of the multiroute. MDVR collects route cost information about all possible routes that connect a source node to a destination node; then, MDVR distributes and controls the traffic load dynamically on each route on the basis of the cost information. Route cost information includes link costs, route costs, and multiroute costs. The routing table preserves these costs and the amount of traffic load on all possible routes, hence, the form of the routing table should be changed slightly.

The transmission cost depends on the link states and the amount of traffic load on a route. If the cost of a route is increased, a part of the traffic load on this route is shifted to another route that is contained in the common multiroute set, and the overall cost can be reduced if the latter route has a lower cost. To control the amount of the traffic load sent on these routes, cross-layer cooperation between the SCA function (which yields a change in the link/route costs) and the routing function (which determines the amount of traffic load of each routes) is necessary. To facilitate this cooperation, the routing table is located in between the routing and the SCA functions in the logical architecture of MDVR; in conventional schemes, however, the routing table is located within the routing function, as shown in Fig. 5.

A. Logical Architecture of MDVR

The most important feature of the logical architecture of MDVR is that the routing table is located in between the routing and the SCA function. In conventional routing schemes, the routing table is located in the routing function, as shown in Fig. 5(a), and the SCA function does not refer to any route information from the routing table. The SCA function simply provides the link state information from the results of a practical SCA process and sends it to the routing function. The routing function receives this link state information from the SCA function of the same node and the route cost information from the routing function of neighbor nodes. The routing function then calculates the route cost information on the basis of received information, selects a proper route to a destination node, and updates the route cost in the routing table. In other words, the routing function is the only function that refers to the route information in the routing table and updates information about the selected routes in the table. Therefore, it is reasonable that the routing table is located in the routing function.

The SCA function should use the route information to attain MR-CA diversity gains in MDVR. Since the traffic load is another factor that affects the route cost, the SCA function must know the amount of traffic load in order to allocate the channel resource that directly affects the route cost. The SCA function reads the amount of traffic load in the routing table and allocates the channel resources to the routes. Moreover, the route cost provided by the SCA function is updated in the routing table. The SCA function should be able to access the routing table easily in order to read the traffic load and update the route cost in the routing table; therefore, it is reasonable that the routing table is located in between the routing and SCA functions.

Fig. 5(b) shows the logical architecture of MDVR. The routing table is placed in between the routing and SCA functions and is managed by both these functions. The multiroute cost via the neighbor nodes can be directly updated in the routing table of each node. Understanding the structure of the routing table is important for comprehending the operation of MDVR because the routing table is constructed by the interactive cooperation of two functions. The detailed structure of the routing table is described in the following section.

B. Routing Table of MDVR

Fig. 6 describes the routing tables of MDVR and the conventional scheme. In MDVR, the routing table contains three types of costs: Link cost, route cost, and multiroute cost. However, the routing table in the conventional single-route routing scheme only includes route cost information. Hence, MDVR can calculate the route costs of all available routes by compounding the aforementioned three costs; a column for a neighbor node has four sub-columns, and three of them contain these cost values, as shown in Fig. 6(a).

As explained previously, the marginal link cost $l_{k,j}$ is defined as the change in the amount of channel resources used by the link from node k to node j that arises when the traffic load of the link increases by one data unit. It can represent the amount of required channel resources increment for transmitting one unit increment of the data. The marginal link cost depends on the traffic load, channel quality, and SCA scheme, and it can be yielded from the result of a practical SCA process. The marginal route cost $m_{k,j,i}$ is defined as the marginal cost on a route from node k to i via the intermediate node j, and it can be represented in a manner similar to that in the case of the marginal link cost; the route consists of a link from the node k to j and a route from the node j to i. Therefore, the marginal route cost is the sum of the link and the multiroute costs, as shown in (7).

The marginal multiroute cost $c_{k,i}$ denotes the average efficiency of the resources allocated to all available routes from the source node k to the destination node i and is calculated as

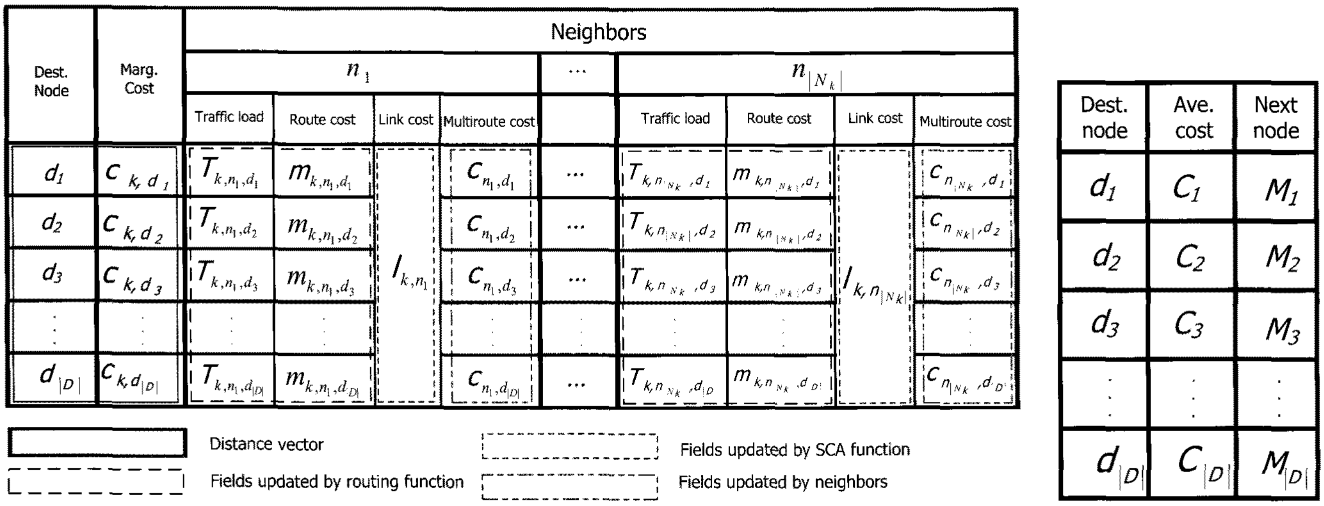
$$c_{k,i} = \sum_{j \in N_k,} \left(\frac{T_{k,j,i}}{\sum_{j \in N_k} T_{k,j,i}} \right) m_{k,j,i} \quad \text{for} \quad i \in D. \qquad (17)$$

This cost is the weighted sum of each marginal route cost, and the relative traffic load on each route is used as the respective weight.

The routing table of MDVR also contains the information about the traffic load; this information is provided in the subcolumn of the neighbor nodes, as shown in Fig. 6(a). The load is varied by changes in the route cost. The traffic load $T_{k,j,i}$ indicates the amount of transmitted data allotted to a route from node k to node i via the intermediate node j. This load can be expressed in bits per second, frames per second, etc and is calculated by the routing function and used by the SCA function. The traffic load is shifted from one route to another depending on the difference in the marginal multiroute costs of the routes. Specific traffic shifting schemes can be created by various manners, and it may affect the performance of the respective schemes in MDVR.

MDVR is based on the distance vector (DV) algorithm. In the conventional DV algorithm, a node sends (or broadcast) its routing table to all the neighbor nodes and updates the route information periodically. In MDVR, a node also sends the route information periodically, but only two columns on the left of the table are sent to the neighbors, and not the entire routing table. Therefore, the overhead resulting from routing table exchange is not increased compared to that of conventional DV.

MDVR is a generic routing algorithm that can be used as a conventional single-route routing method as well. For example,



(a) (b)

Fig. 6. Comparison of routing tables between the conventional routing scheme and MDVR: (a) MDVR routing table and (b) conventional routing table.

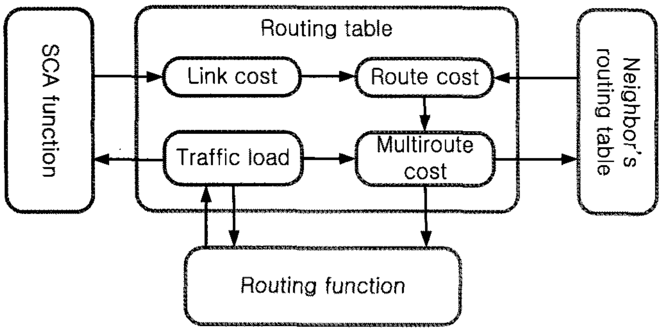


Fig. 7. Parameter update flows in the MDVR routing table.

if all the traffic load values except for one are set to zero, MDVR can operate as a single-route routing algorithm. MDVR can be used in various environments with several algorithms for the routing function, SCA function, traffic shifting, and so on.

The routing table size and the computational complexity of the DV can be changed according to the number of destination nodes and neighbor nodes. When the number of neighbor nodes is increased by N, the routing table size increases by $N(3|D|+1)$, where $|D|$ represents the number of destination nodes. The computational complexity may also increase by $N(3|D|+1)$. When the number of destination nodes is increased by M, the routing table size increases by $M(3|N_k|+2)$, where $|N_k|$ represents the number of neighbor nodes of node k. The computational complexity is also increased by $M(3|N_k|+2)$. The routing table size and the computational complexity of the DV are in direct proportion to the number of destination nodes and neighbor nodes. In order to employ the DV in large-scale networks, therefore, a limit must be imposed on the number of neighbor nodes and destination node.

C. Routing Parameter Update Mechanism

The parameters in the routing table can be managed by the routing function or the SCA function. Fig. 7 describes the update flow of the parameters. Four parameters in the table are updated and referred to three blocks: The SCA function of the node, the routing function of the node, and the routing tables from the neighbor nodes.

The marginal link cost is yielded by the SCA function and used to calculate the route cost. The SCA function reads the traffic load of each route in the routing table and actually allocates channel resources to transmit the traffic load. Then, the link cost is determined as the ratio of the amount of used resources to the data amount transmitted in unit time. In MDVR, various schemes can be used as the SCA function,and the MDVR performance is affected by the schemes. In particular, if multiuser diversity gain can be obtained from the results of the SCA function, the MDVR would attain high performance gain.

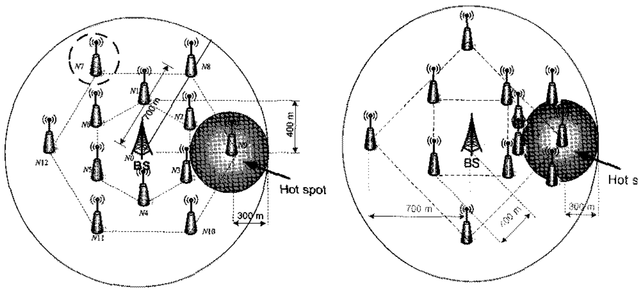
The route cost is calculated by the routing function or the SCA function. The route from node k to node i through the intermediate node j can be divided into a link from the node k to j and multiroutes from node j to node i. The function reads the cost of the link from node k to i in the routing table and receives the multiroute cost information via the neighbor node j; finally, the function calculates the route cost as the sum of the link cost and the multiroute cost, as follows.

$$m_{k,j,i} \leftarrow l_{k,j} + c_{j,i}. \tag{18}$$

Equation (18) is used to calculate $c_{k,i}$ as in (17). The calculated $c_{k,i}$ value is calculated is sent to the neighbor nodes.

D. Traffic-Load-Shifting Algorithm

The main purpose of the traffic-load-shifting algorithm is to reduce the difference in the marginal costs among the available routes at a node in order to avoid inefficient resource usage. There are various traffic-load-shifting algorithm that can be used for MDVR, and the MDVR performance depends on the chosen algorithms. We describe an example of the shifting function as follows. The shifting algorithm involves four steps. First, the algorithm computes the ratio of each traffic load among the neigh-



(a) (b)

Fig. 8. Position of the hot spot and layout of BS/RSs: (a) Symmetric RS topology and (b) asymmetric RS topology.

Table 1. Main simulation parameters.

Parameters	Values	Unit
BS Tx power	43	dBm
RS Tx power	30	dBm
Cell radius	1	km
Hot spot radius	0.3	km
Frame duration	5	ms
Antenna gain	0, Omni	dBi
No. of channels per frame	15 x 36	-
Thermal noise level	-174	dBm/Hz
RS buffer size	3	Mbit
System bandwidth	10	MHz
Routing table update interval	10	frames
α	0.01	-

Table 2. Main simulation models.

Items	Models
Traffic model	Full queue
Schedule	Three-phase scheduler
Path loss model	PL(d)=128.1+37.6log(d)
Delay profile	ITU-R channel model, Ped. A model
Shadowing model	Log normal (8dB)
Multiple access and duplex	OFDMA-TDD downlink
Cell layout	7-cell, hexagonal model

bors, as follows.

$$t_{k,j,i} = \frac{\left(\dfrac{\overline{m_{k,j,i}}}{m_{k,j,i}}\right) T_{k,j,i}(t) + \alpha}{\sum\limits_{j \in N_k} \left(\dfrac{\overline{m_{k,j,i}}}{m_{k,j,i}}\right) T_{k,j,i}(t) + \alpha} \quad \text{for} \quad i \in D \qquad (19)$$

where α is introduced to ensure that $t_{k,j,i}$ is not zero, and $\overline{m_{k,j,i}}$ is the mean route cost over all $j \in N_k$. In the next step, the traffic load ratio is set to zero if it is less than α, which implies that the route is not efficiently used.

$$t_{k,j,i}(t) \leftarrow \begin{cases} t_{k,j,i}(t), & \text{if } t_{k,j,i}(t) \geq \alpha, \\ 0, & \text{if otherwise,} \end{cases} \quad \text{for} \quad i \in D. \quad (20)$$

The traffic load ratio is normalized in the next step.

$$t_{k,j,i}(t+1) = \frac{t_{k,j,i}(t)}{\sum_{j \in N_k} t_{k,j,i}(t)} \quad \text{for} \quad i \in D. \qquad (21)$$

Finally, the updated traffic load is calculated as follows.

$$T_{k,j,i}(t+1) = t_{k,j,i}(t+1) \sum_{j \in N_k} T_{k,j,i}(t) \quad \text{for} \quad i \in D. \quad (22)$$

The total traffic load should remain unchanged after the shifting algorithm is completed; the load decrement in the second step is compensated for in this step.

V. SIMULATIONS

The performance of MDVR is evaluated for various simulation scenarios. The traffic load distribution at increased simulation times is shown to demonstrate that our traffic-load-shifting algorithm converges at a reasonable rate. The system throughput gain yielded by MDVR is compared with that of a single-route routing scheme.

A. Simulation Environments

A multichannel multihop wireless system consisting of a base station (BS) and 12 fixed relay stations (RSs) in a cell is considered for the simulation, as depicted in Fig. 8. Since the MDVR gain is attained by redistributing the traffic load to high-quality routes efficiently, the gain may increase when the initial traffic load is unevenly distributed. For this reason, we create a hot-spot area in which mobile stations (MSs) are densely concentrated. It is assumed that the MSs are uniformly distributed in the hot-spot area. Further, the hot-spot area is assumed to be circular in shape. A detailed description of the hot-spot area is shown in Fig. 8 and Table 1. For comparison, a symmetric RS topology scenario with uniformly distributed MSs is also considered.

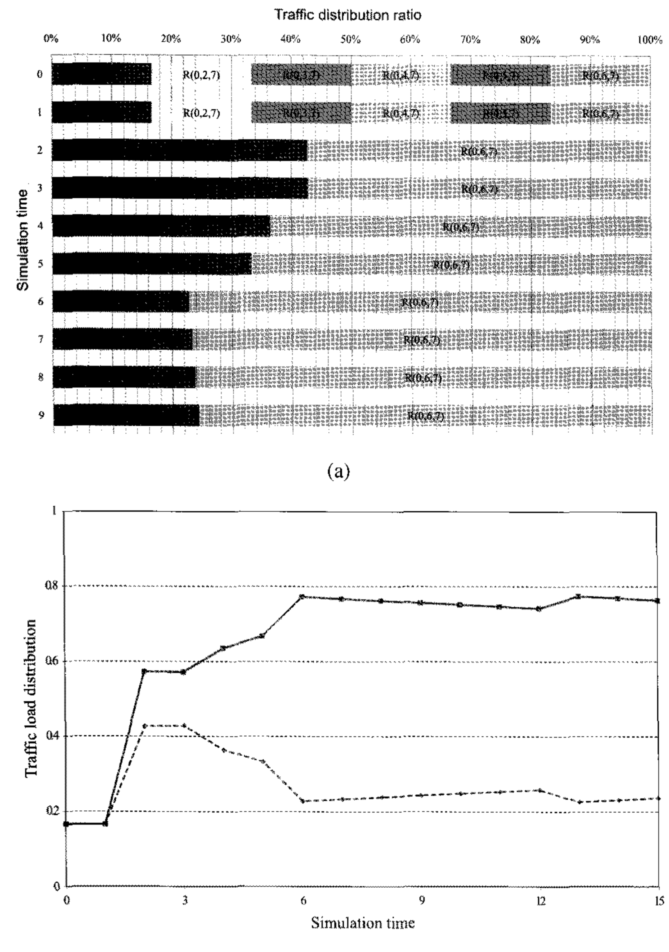
MSs are assumed to be connected to the BS either directly or via an RS, and the number of connected RSs is less than three. We also assume that MDVR is used only for the relay links, i.e., for the links between the BS and RSs or those between RSs.

We employ the parallel scheduler and channel allocation model mentioned in [12] for the SCA function. This scheduler was invented for wireless multichannel systems, and it attains the multiuser diversity gain in time and channel domains. After the completion of the SCA function, we calculate the marginal cost, which is the reciprocal of the bits transmitted during a single channel frame length. Details of the simulation parameters and models are provided in Tables 1 and 2, respectively. For more information on the models and parameters, refer to [13].

To observe the performance improvement of MDVR, a system with a conventional routing function is considered in this function, where the employed routing scheme is Dijkstra's algorithm, and the link state is used as the routing metric. Further, the link state of a wireless link is quantified by the average signal-to-interference/noise ratio (SINR). A similar SCA function is employed in the compared system; however, the routing and SCA functions operate independently, as described previously for a conventional system. A cell throughput gain is yielded to ensure that performance of MDVR is superior to that of the conventional single-route routing. The cell throughput gain G is given by

$$G = \frac{(U_m - U_s)}{U_s} \qquad (23)$$

where U_m and U_s refer to the cell throughput yielded by MDVR and the single-route routing scheme, respectively. The



(a)

(b)

Fig. 9. Rate of convergence of traffic load distribution values by the proposed traffic-shifting algorithm: (a) Traffic load distribution in symmetric RS topology and (b) traffic load distribution in two routes: $R(0,1,7)$, $R(0,6,7)$.

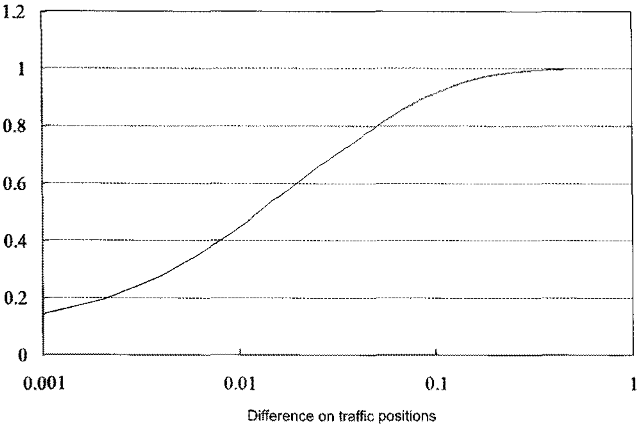


Fig. 10. CDF of difference between traffic portion with traffic in all nodes.

cell throughput is the amount of bits transmitted in unit time and is calculated by the sum of the bits received by the users in unit time.

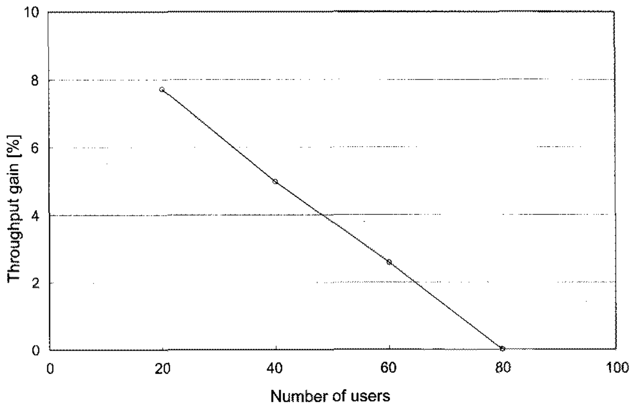


Fig. 11. Cell throughput gains with uniformly distributed users.

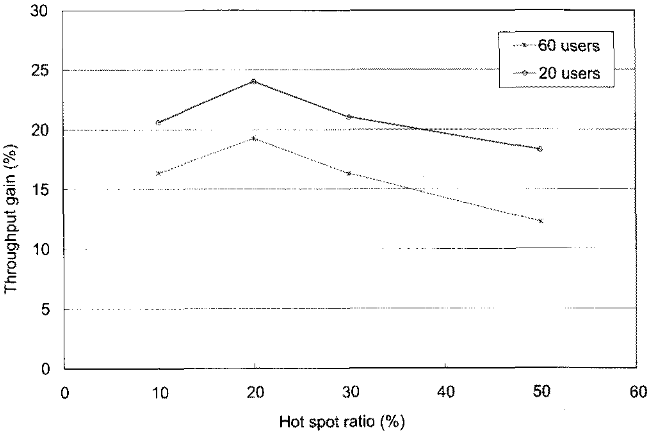


Fig. 12. Cell throughput gains with different numbers of users.

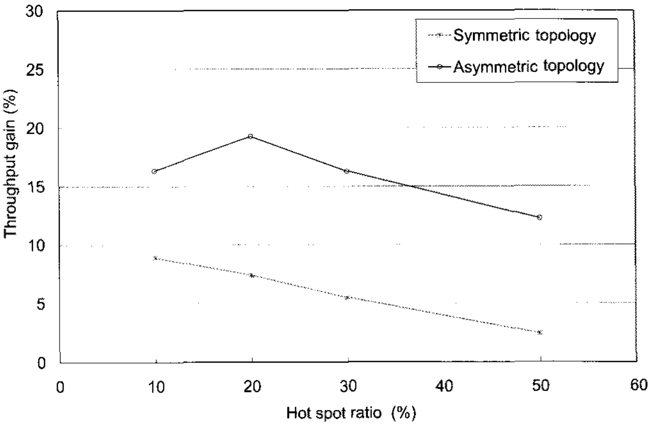


Fig. 13. Cell throughput gains in different RS topologies.

B. Convergence Rate

We discuss the change in the traffic load distribution with the simulation time length at a given node. A unit of the simulation time is assumed to be equal to the interval in the updating routing tables, as specified in Table 1.

In actual wireless packet transmission systems, the channel quality and traffic load on each link are time-varying. Therefore, it is difficult to expect the traffic load on the routing table to converge perfectly into an arbitrary constant level. To alter the time-varying nature, we assume that the channel quality of every relay link is stable and that the channel quality hardly changes in the simulation time length. Therefore, the traffic load variation is assumed to be caused only by load redistribution.

We show the convergence of the traffic load distribution with simulation time in a symmetric RS topology, as described in Fig. 8(a). Two detailed simulation scenarios are considered. In the first scenario, the source is node 0 (BS), and the destination is node 7. In the other scenario, the source is node 0, and all the nodes act as the destinations, i.e., nodes 7 to 12.

Fig. 9 shows the variation of the traffic load distribution with simulation time in the first scenario. The traffic load is concentrated on two routes R(0,1,7) and R(0,6,7) since simulation time 2. The traffic load distribution ratios of these two routes increase from 0.17 to 0.78/0.22, as shown in Fig. 9(b). The average of the traffic load distribution ratio variation per iteration is 0.046. In the second scenario, the average of the traffic load distribution ratio variation per iteration is 0.041, and the cumulative distribution function (CDF) of the traffic load distribution ratio variation of all routes over 10000 simulations is shown in Fig. 10. The CDF pattern in this case is similar to that in the first scenario. Therefore, a single multiroute set environment and multiple multiroute set environments show similar convergence patterns when the proposed traffic-shifting-algorithm is used.

C. Multiroute Channel Allocation Diversity Gain

Fig. 11 shows a comparison of the cell throughput gain by MDVR and that of a conventional single-route routing scheme when users are distributed uniformly in a cell. From the figure, it is clear that in MDVR, the cell throughput gain is up to 8% when 20 users are in the cell. An increase in the users causes a decrease in the number of traffic load distribution difference on a multiroute set; consequently, the marginal cost differences among the routes in a multiroute set decrease.

Fig. 12 shows the cell throughput gain by MDVR when the users are not distributed uniformly; the ratio of the number of users in the hot spot area to the total number of users in the cell varies from 10% to 50%. We perform simulations with 20 and 60 users in the cell. The cell throughput gain in MDVR is up to 25% when 20 users are in the cell. When the user ratio is greater than 20%, the difference in the traffic load distribution among routes related to the users in the hot spot is small. When the user ratio is less than 20%, the difference in the traffic load distribution between the routes in the hot spot area and those in the other region decreases. Therefore, the maximum gain is obtained when the user ratio is 20%.

Fig. 13 shows the cell throughput gains of MDVR for different RS topologies. The gain in an asymmetric RS topology is twice that in a symmetric RS topology. In the asymmetric topology, the number of routes for users in the hot-spot area is increased, and thus, the range of route selection is widened.

The asymmetric topology environment resembles more closely a real wireless communication environment than dose a symmetric one. In a real wireless communication environment, the BSs and RSs are not installed regularly. Moreover, the layout of RSs is more irregular than that of the BSs because the one of purposes of the RSs is coverage extension or/and capacity increase. Therefore, the throughput gain improvement in an asymmetric topology has significant meaning for the real situation

VI. CONCLUSION

In this paper, a new diversity concept, multiroute channel allocation diversity, is explored, and multiroute distance vector routing MDVR, a framework for cooperation between the routing function and the SCA function, is proposed. The routing table is logically placed in between the routing and the SCA functions in MDVR, so that both functions can simultaneously update and refer to the routing table.

Through simulations, the feasibility and performance of MDVR are investigated. It is shown that the MDVR reaches a steady state within a reasonable amount of time. In addition, the system throughput can be improved by up to 25% over that in a conventional approach.

MDVR is a generic extension of the classical distance vector routing; therefore, it can also be applied to wired networks. Most future networks are expected to incorporate both wireless and wired transmission technologies. In such cases, MDVR may help manage the traffic load over a mixed wireless/wired network and achieve high spectral efficiency in the wireless realm. Research is being purposed on the performance of multiroute diversity gain. Further, the performance of MDVR in various networks such as ad hoc networks and mesh networks will be evaluated.

REFERENCES

[1] E. Ko and D. Hong, "A robust STBC-based transmit diversity scheme for OFDM systems over spatially transmit correlated fading channels," *IEEE Trans. Veh. Technol.*, vol. 56, no. 2, pp. 984–991, Mar. 2007.

[2] R. Narasimhan, "Finite-SNR diversity-multiplexing tradeoff for correlated Rayleigh and Rician MIMO channel," *IEEE Trans. Inf. Theory*, vol. 52, pp. 3965–3979, 2006.

[3] C. Chen and L. Wang, "Enhancing coverage and capacity for multiuser MIMO systems by utilizing scheduling," *IEEE Trans. Wireless Commun.*, vol. 5, pp. 1148–1157, 2006.

[4] F. H. P. Fitzek and M. D. Katz, *Cooperation in Wireless Networks Principles and Applications*. Springer, 2006.

[5] K. Navaie, H. Yanikomeroglu, "Induced cooperative multi-user diversity Relaying for multi-hop cellular networks," in *Proc. IEEE VTC spring*, vol. 2, 2006, pp. 658–662.

[6] N. F. Maxemchuk, "Dispersity routing," in *Proc. IEEE ICC*, June 1975, pp. 41–44.

[7] N. F. Maxemchuk, "Dispersity routing: Past and present," in *Proc Military Commun. Conf.*, 2007, pp. 1–7.

[8] S. Merlin, N. Vaidya, and M. Zorzi, "Resource allocation in multi-radio multi-channel multi-hop wireless networks," in *Proc. INFOCOM*, Apr. 2008, pp. 610–618.

[9] Lin Xiaojun and S. Rasool, "A distributed joint channel-assignment, scheduling, and routing algorithm for multi-channel ad-hoc wireless networks," in *Proc. INFOCOM*, May 2007, pp. 1118–1126.

[10] S. Kompella, S. Mao, Y. T. Hou, and H. D. Sherali, "Cross-layer optimized multipath routing for video communications in wireless networks," *IEEE J. Sel. Areas Commun.*, vol. 25, no. 4, pp. 831–840, May 2007.

[11] B. Rong, Y. Qian, K. Lu, R. Q. Hu, and M. Kadoch, "Multipath routing over wireless mesh networks for multiple description video transmission," *IEEE J. Sel. Areas Commun.*, vol. 28, no. 3, pp. 321–331, Apr. 2010.

[12] D. Kim, S. Lee, J. Choe, D. Hong, and I. Hwang, "Resource management scheme reflecting relative utilities in multi-channel wireless systems," in *Proc. IEEE ICC*, vol. 10, 2006, pp. 4434–4439.

[13] D. Kim, B. Kang, J. Choi, D. Hong, and Y. Park, "Dynamic resource allocation scheme in cellular based distributed multi-hop/multi-channel systems," in *Proc. IEEE APCC*, 2007.

[14] W. Rhee and J. M. Cioffi, "Increase in capacity of multiuser OFDM system

using dynamic subchannel allocation," in *Proc. IEEE VTC*, vol. 2, 2000, pp. 1085–1089.

[15] H. Choi, J. Choe, and D. Hong, "Efficient combining scheme of scheduling and channel allocation in multi-channel systems," *IEICE Trans. Commun.*, vol. E90-B, no. 12, 2007.

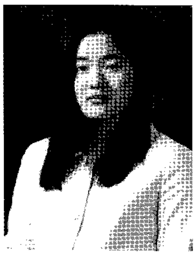
[16] C. E. Perkins and E. M. Belding-Royer, "Ad-hoc on-demand distance vector (AODV) routing," in *Proc. Workshop Mobile Comput. Syst. and Appl.*, Feb. 1999.

[17] D. B. Johnson and D. A. Maltz, "Dynamic source routing in ad hoc wireless networks," *Mobile Comput.*, 1996.

[18] C. E. Perkins, E. M. Royer, S. R. Das, and M. K. Marina, "Performance comparison of two on-demand routing protocols for ad hoc networks," *IEEE Trans. Wireless Commun.*, vol. 8, no. 1, pp. 16–28, Feb. 2001.

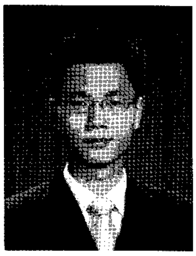
[19] S. Keshav, "A Control-theoretic approach to flow control," in *Proc. ACM SIGCOMM*, Sept. 1991.

[20] S. Vutukury and J. J. Garcia-Luna-Aceves, "MDVA: A distance-vector multipath routing protocol," *IEEE Conf. Computer Commun.*, pp. 557–564, Apr. 2001.

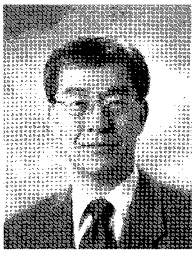


Bongjhin Shin received her B.S. and M.S. degrees from Department of Electronic Engineering, Sogang University, Seoul, Korea, in 2003 and 2005, respectively. She is currently working to obtain her Ph.D. degree in the same university. Her research interests include multihop networks, advanced network systems, and the 4th generation networks. She has been studying the development of effective multihop networks. Currently, she is researching on the architecture and development of performance of multihop systems and methods for effective multihop networks and the 4th generation networks.

Jinwoo Choe received his B.S. and M.S. degrees from Seoul National University in Seoul, Korea in 1990 and 1992, respectively. He received the Ph.D. degree from the School of Electrical and Computer Engineering at Purdue University in 1998. He joined as a faculty member with the Department of Electronic Engineering, Sogang University, Seoul, in 1998.



Byoungik Kang received his B.S. and M.S. degrees from Department of Electronic Engineering, Sogang University, Seoul, Korea, in 2002 and 2008, respectively. In 2008, he joined the Telecommunication Research and Development Center, Samsung Electronics Co., Ltd., Suwon, Gyeonggi, Korea. His research interests include wireless communications and next-generation systems.



Daehyoung Hong received his B.S. degree in Electronics Engineering from Seoul National University, Seoul, Korea, in 1977 and his M.S. and Ph.D. degrees in Electrical Engineering from the State University of New York, Stony Brook, in 1982 and 1986, respectively. In 1986, He joined Motorola Communication Systems Research Laboratory, Schaumburg, IL, where he was a Senior Staff Research Engineer, and he participated in the research and development of digital trunked radio systems as well as CDMA digital cellular systems. In 1992, He joined the Department of Electronic Engineering, Sogang University, Seoul, as a faculty member; currently, he is a professor here. He has been a consultant for a number of industrial firms. He has served as a Division Editor for wireless communications for the Journal of Communications and Networks. His research interests include design, performance analysis, control algorithms, and operations of wireless/mobile communication systems. He has published numerous technical papers and holds several patents in the areas of wireless communications. He has been an active member of a number of professional societies. He is the Executive Vice President of the Korea Institute of Communication Sciences. He also serves as the Director of the Asia Pacific Region for the IEEE ComSoc and Chair of the 2.3 GHz Portable Internet (WiBro) Project Group (PG302), Telecommunications Technology Association, Korea. He has served as Chair and Member of Technical Program Committees for several major conferences, including ICC2005.

Yongsuk Park received his Ph.D. and M.S degrees in Computer Science from Polytechnic Institute of New York University, New York, USA, and his B.S. degree in Computer Science from Sogang University, Seoul, Korea. He is a head researcher at SAMSUNG, Korea where he is focusing on wireless networks and mobile device security. Between 1999 and 2003, he was with AT&T Laboratories at Middletown, NJ, USA, as a senior technical staff member, and conducted various research and development studies on network optimization and management for data network and IP service. Since 1995, has been a visiting professor at the City University of New York, New York, USA as a research and teaching staff. He served as Editor for several journals and conferences such as Journal of SAMSUNG and published a number of papers and patents. His current research interests include broadband wireless cellular networks, and utility computing with emphasis on secure, seamless, cognitive aspects. He is also a Member of IEEE.