Extended Labeling Method for Achieving Maximum Data Message Flow in Wireless Multihop Networks

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***Abstract*—For multimedia data message transmissions in wireless multihop networks composed of wireless links with lower throughput, transmission capacity is reserved in wireless links included in one of wireless multihop transmission routes from a source node N^s to a destination node N^d. For reservation of transmission capacity required for applications, a method for achieving the maximum data message flow from N^s to N^d is required. For wired multihop networks, the labeling method has been proposed. However, in wireless multihop networks, since message transmission between neighbor nodes is realized by broadcast transmission of wireless signal, capacity of a wireless link is effected by data message transmissions by neighbor nodes due to the hidden-terminal and exposed-terminal problems. Thus, this paper proposes an extended labeling method based on a novel wireless network model for the maximum data message flow in wireless multihop networks and according to novel conditions for a wireless multihop transmission route to increase the amount of data message flow from N^s to N^d.**

***Keywords*- Ad Hoc Networks; Multimedia Communication; Throughput; Resource Reservation; Labeling Method.**

I. INTRODUCTION

In ad hoc networks, sensor networks and mesh networks, data messages are transmitted from a source wireless node to a destination one by wireless multihop transmission. In case that the destination node is not included in a wireless transmission range of the source one, intermediate wireless nodes in a wireless multihop transmission route forward the date messages. In order to realize multimedia communication which requires realtime transmission of vast number of data messages in such wireless multihop networks, reservation of transmission capacity in wireless links in the route in advance is required.

RSVP [1] is an internet-standard protocol for reservation of capacities in communication links along a transmission route from a source node to a destination one (Figure 1). In RSVP, it is assumed that available capacities in communication links are enough for requirements in network applications and capacity in each communication link can be reserved independently of the other communication links. That is, even when a certain amount of capacity in a communication link is reserved, available capacities in the other communication links are never reduced. However, in wireless multihop networks, available capacities in wireless links are not always enough for requirements in network applications. In addition, capacity reservation in a wireless link is not independent of available capacities of wireless links issued from the neighbor wireless nodes since wireless communication is intrinsically based on broadcast communication and there may be hidden- and/or exposed-terminals [4]. Therefore, it is difficult for multimedia network applications to be provided enough amount of data message flow by reservation of capacities in wireless links along a single wireless multihop transmission route.

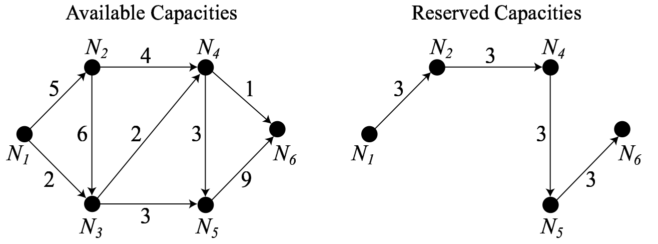

Fig. 1. Multihop Transmission along Single Route.

The authors have been proposed RSVMRD [7] link capacity reservation protocol in wired networks which satisfies required throughput of data messages for network applications by data message transmissions along multiple wireless multihop transmission routes from a source node to a destination one as shown in Figure 2. RSVMRD consists of the following 2-step algorithms. In the first step, the maximum amount of data message flows, i.e., the maximum available throughput of data messages, from the source node to the destination one along multiple transmission routes are calculated by using a well-known heuristic, the labeling method [2], modified for reduction of its computational complexity. Here, required capacities in communication links which are surely less than their available capacities to realize the maximum data message flows are also calculated. In the second step, based on the required capacities, capacities to be reserved to satisfy the requirements of network applications are finally induced and are reserved in nodes from which the communication links are issued by exchanging control messages. The authors propose the same approach to reservation of capacities in wireless links to satisfy requirements in multimedia network applications in wireless multihop networks. Since capacity reservation in a wireless link reduces available capacities in neighbor wireless links due to broadcast property in wireless networks, this paper discusses an extended labeling method to calculate the maximum data message flows in wireless multihop networks.

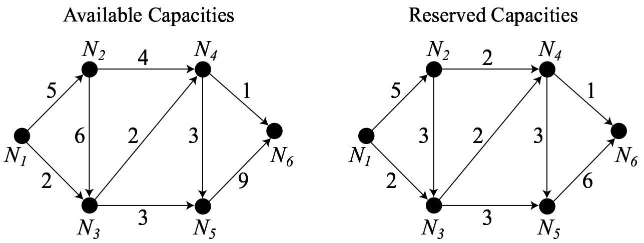

Fig. 2. Multihop Transmission along Multiple Routes.

II. RELATED WORKS

A. Wireless Multihop Communication

Let $\mathcal{NT} := \langle \mathcal{N}, \mathcal{L} \rangle$ be a wireless multihop network with a set $\mathcal{N} := \{N_i\}$ of wireless nodes N_i and a set $\mathcal{L} := \{\langle N_i N_j \rangle\}$ of wireless links $\langle N_i N_j \rangle$ between wireless nodes N_i and N_j. Wireless transmission ranges of all the wireless nodes are assumed to be equal and all wireless links are assumed to be bidirectional. Each data message is transmitted from its source wireless node N^s $(= N_0)$ to its destination one N^d $(= N_n)$ along a wireless multihop transmission route $R := ||N_0 \ldots N_n\rangle\rangle$ as in Figure 3. Each intermediate wireless node N_i $(i = 1, \ldots, n-1)$ in R forwards data messages. N_{i+1} is included in a wireless transmission range of N_i[1]. Thus, $N_{i+1} \in Nei(N_i)$ where $Nei(N)$ is a set of neighbor wireless nodes of $N \in \mathcal{N}$, i.e., a set of wireless nodes included in a wireless transmission range of N.

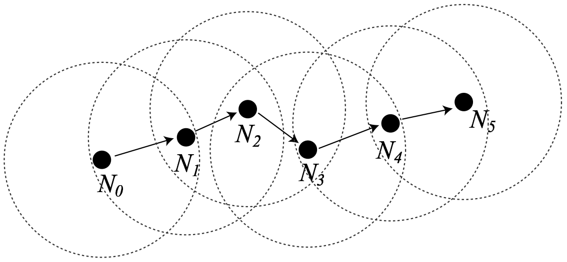

Fig. 3. Wireless Multihop Transmission of Data Messages.

Now consider forwarding of a data message from a transmitter wireless node N^t to a receiver one $N^r \in Nei(N^t)$ (Figure 4). Due to broadcast property of wireless communication, all data messages transmitted from N^t to N^r are also received by all its neighbor wireless nodes $N \in Nei(N^t)$. Thus, N is called an exposed-node of N^t. In most of wireless LAN protocols such as IEEE 802.11, a wireless node cannot transmit data messages simultaneously with its exposed-nodes for collision avoidance. The exposed-terminal problem is that neighbor wireless nodes which are exposed nodes each other but do not cause collisions are restricted to transmit data messages simultaneously. On the other hand, another type of collisions may occur when N^t and $N' \in Nei(N^r) - Nei(N^t)$ transmit data messages simultaneously. Since N^t and N' are not exposed nodes, they cannot detect their data message transmissions each other and collisions occur at N^r. Thus, N^t and N are hidden nodes each other and collisions between hidden nodes are called the hidden-terminal problem. As discussed, in wireless multihop communication, data message transmissions from an intermediate wireless node N_i to its next-hop wireless node N_{i+1} affects on data message transmissions from exposed and hidden nodes of N_i. That is, data message transmissions through wireless links are dependent one another, which is differrent from wired networks.

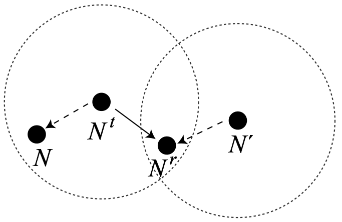

Fig. 4. Effects on Neighbor Nodes (Exposed and Hidden Nodes).

B. Labeling Method

Let $\mathcal{NT}' := \langle \mathcal{N}', \mathcal{L}' \rangle$ be a wired network where $\mathcal{N}' := \{N_i\}$ is a set of nodes and $\mathcal{L} := \{|N_i N_j\rangle\}$ is a set of wired links from a node N_i to its neighbor node N_j. In addition, for each wired link $|N_i N_j\rangle$, an available capacity $c(|N_i N_j\rangle) \geq 0$ is given and a potion of the available capacity is reserved for provision of required throughput to multimedia network applications independently of the other wired links. The labeling method [2] calculates the maximum amount of data message flows, i.e., the maximum data message throughput, from a source node N^s to a destination one N^d by using multiple multihop transmission routes. It also induces capacities to be reserved in wired links in one of the multihop transmission routes. The problem to achieve the maximum amount of data message flows is formalized as follows where a capacity to be reserved in a wired link $|N_i N_j\rangle$ is $r(|N_i N_j\rangle)$:

[Maximum Data Message Flows Problem]
Under the restrictions (1) $r(|N_i N_j\rangle) \leq c(|N_i N_j\rangle)$ in all wireless links $|N_i N_j\rangle \in \mathcal{L}'$ and (2) $\sum_{|N_k N_i\rangle \in \mathcal{L}'} r(|N_k N_i\rangle) = \sum_{|N_i N_j\rangle \in \mathcal{L}'} r(|N_i N_j\rangle)$ in all nodes $N_i \in \mathcal{N}' - \{N^s, N^d\}$, the maximum value of $\sum_{|N^s N_j\rangle \in \mathcal{L}'} r(|N^s N_j\rangle) = \sum_{|N_k N^d\rangle \in \mathcal{L}'} r(|N_k N^d\rangle)$ is calculated. □

In the labeling method, a multihop transmission route from a source node N^s to a destination one N^d which increases amount of data messages, i.e., data message throughput, one by one. Here, the maximum data message flow along a multihop transmission route is determined as the minimum available capacity of communication links along the route. If the maximum data message flow is greater than 0, the detected multihop transmission route increases total amount of data messages transmitted from N^s to N^d and it is called a flow increasing route. In the labeling method, flow increasing routes are detected one by one with a procedure to reduce the available capacities in communication links included in the

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[1] N_{i-1} is also included in a wireless transmission range of N_i since all wireless links are bidirectional in this paper.

route each time it is detected until no other flow increasing routes are detected. Many research results show that the labeling method is a better heuristic to achieve the pseudo maximum data message throughput and the required capacities to be reserved in the communication links in wired networks.

Figure 5 shows a naive example wired network $\mathcal{NT}' := \langle \mathcal{N}', \mathcal{L}' \rangle$ where $\mathcal{N}' := \{N^s, N_1, N_2, N^d\}$ and $\mathcal{L}' := \{|N^sN_1\rangle, |N^sN_2\rangle, |N_1N_2\rangle, |N_1N^d\rangle, |N_2N^d\rangle\}$. Suppose that available capacities are given as follows; $c(|N^sN_1\rangle) := 10$, $c(|N^sN_2\rangle) := 5$, $c(|N_1N_2\rangle) := 8$, $c(|N_1N^d\rangle) := 4$ and $c(|N_2N^d\rangle\}) := 8$.

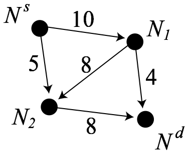


Fig. 5. Example Wired Network and Available Link Capacities.

As shown in Figure 6, at first, a flow increasing route $||N^sN_1N^d\rangle\rangle$ is detected and its maximum amount of data message flow is calculated as 4 since the available capacity of $c(|N_1N^d\rangle) = 4$ is the minimum in communication links along the route. Thus, capacity 4 is reserved in each link along the route and the available capacities are updated as follows; $c(|N^sN_1\rangle) := 6$ and $c(|N_1N^d\rangle) := 0$. Then, another flow increasing route $||N^sN_2N^d\rangle\rangle$ is detected. Since the maximum data message flow along the route is 5 ($= c(|N^sN_2\rangle)$), the total amount of reserved data message flows gets 9 and the available capacities are updated as follows; $c(|N^sN_2\rangle) := 0$ and $c(|N_2N^d\rangle) := 3$. Finally, a flow increasing route $||N^sN_1N_2N^d\rangle\rangle$ whose maximum data message flow is 3 ($= c(|N_2N^d\rangle)$) is detected and available capacities $c(|N^sN_1\rangle) := 3$, $c(|N_1N_2\rangle) := 5$ and $c(|N_2N^d\rangle) := 0$ are updated. As a result, there are no flow increasing routes and the total amount of data message flow 12 (=4+5+3) is achieved.

The order of multihop route detections from N^s to N^d depends on the route detection protocol. Hence, the multihop routes may be detected in different order. For example as shown in Figure 7, at first, a flow increasing route $||N^sN_1N_2N^d\rangle\rangle$ is detected. Its maximum amount of data message flow along the route is 8 ($= c(|N_1N_2\rangle) = c(|N_2N^d\rangle)$) and the available capacities in communication links along the route are updated differently from the previous example; $c(|N^sN_1\rangle) := 2$, $c(|N_1N_2\rangle) := 0$ and $c(|N_2N^d\rangle) := 0$. Then, another flow increasing route $||N^sN_1N^d\rangle\rangle$ whose maximum data message flow is 2 ($= c(|N^sN_1\rangle)$) is detected and the available capacities $c(|N^sN_1\rangle) := 0$ and $c(|N_1N^d\rangle) := 2$ are updated. Now, there are no multihop transmission route from N^s to N^d consisting of communication links whose available capacities are greater than 0. However, a multihop route $||N^sN_2N_1N^d\rangle\rangle$ is also a flow increasing route. This is because both $c(|N^sN_2\rangle) = 5$ and $c(|N_1N^d\rangle) = 2$ are greater than 0 and reduction of reserved capacity $r(|N_1N_2\rangle) = 8$ in a communication link $|N_1N_2\rangle$ is equivalent to reserve the same amount of flow in a reverse communication link $|N_2N_1\rangle$. Since the maximum amount of data message flow in the reverse communication link is $r(|N_1N_2\rangle) = 8$, the maximum amount of data message flow along $||N^sN_2N_1N^d\rangle\rangle$ is 2 ($= c(|N_1N^d\rangle)$) and the available capacities are updated as follows; $c(|N^sN_2\rangle) := 3$, $c(|N_1N_2\rangle) = 2$ and $c(|N_1N^d\rangle) := 0$. Now, there are no flow increasing route from N^s to N^d and the maximum amount of data message flow 12 (=8+2+2) is achieved.

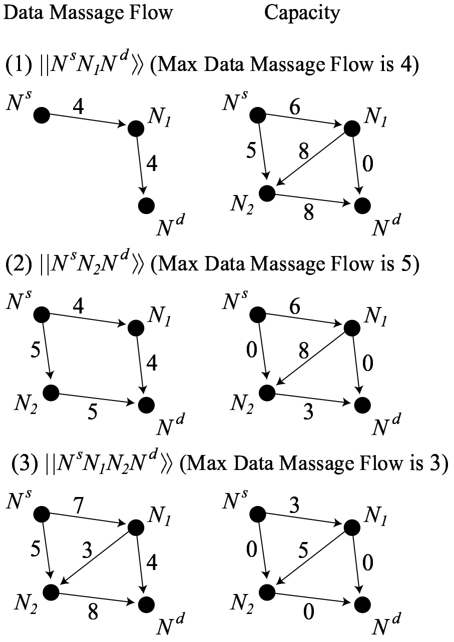


Fig. 6. The Original Labeling Method Example (1).

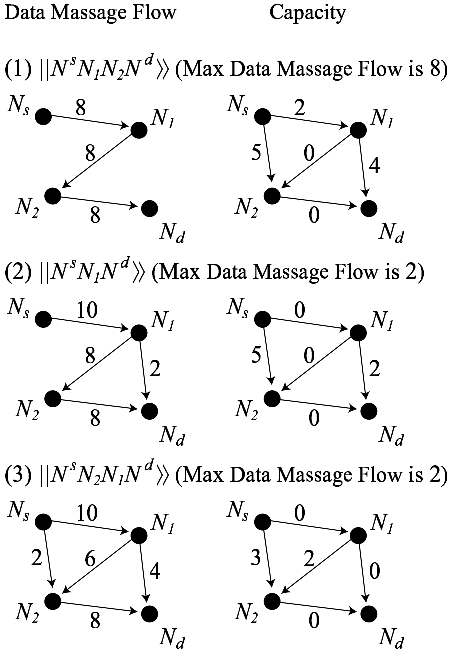


Fig. 7. The Original Labeling Method Example (2).

As a result of examination of the above 2 examples, there are 2 types of flow increasing routes and the finally achieved maximum amounts of data message flows are the same though reserved capacities in communication links are different.

[Flow Increasing Route in the Original Labeling Method]
A multihop transmission route $R = ||N_0 \dots N_n\rangle\rangle$ satisfying one of the following conditions is a flow increasing route;

- $c(|N_iN_{i+1}\rangle) > 0$ in all communication links $|N_iN_{i+1}\rangle \in R$ (trivial flow increasing route)
- $c(|N_iN_{i+1}\rangle) > 0$ or $r(|N_{i+1}N_i\rangle) > 0$ in all communication links $|N_iN_{i+1}\rangle \in R$ (flow increasing route with reduction of already reserved capacities) □

C. Multiple Route Wireless Multihop Transmissions

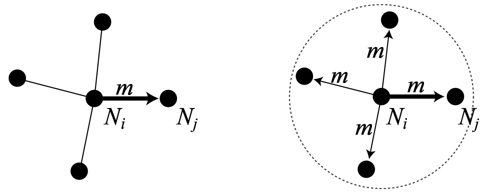
As a result of the labeling method, multiple multihop transmission routes are detected which provide the maximum throughput of data messages from a source node to a destination one. Until now, venous ad hoc routing protocols for detection of multiple wireless multihop transmission routes have been proposed [3,5,6]. However, most of them are designed for continuous data message transmissions even with wireless link breakages and node failures and detect link- or node-disjoint routes. [8] and some papers propose that data messages are transmitted along detected multiple routes simultaneously for higher data message throughput. However, these protocols do not intentionally detect multiple routes to achieve higher throughput for multimedia data transmission. Of course, they do not provide the maximum throughput of data messages with consideration of the exposed and hidden terminal problems.

III. PROPOSAL

A. Wireless Network Model

In the original labeling method, reservation of capacity in a wired link $|N_iN_j\rangle$ does not affect the available capacity of wireless links other than $|N_iN_j\rangle$ itself. That is, available capacity and reserved capacity in a wired link is independent of those of the other wired links. Thus, the maximum amount of data message flows are calculated based on the available capacities in wired links in a wired network. On the other hand in a wireless multihop network, since wireless communication is intrinsically based on broadcast transmission, even if a wireless node N_i transmits data messages to its neighbor wireless node N_j, the data messages are also transmitted to all its neighbor wireless nodes $N \in Nei(N_i)$ in its wireless transmission range. During transmission of the data messages, N can neither transmit nor receive data messages. Hence, data message transmission through $|N_iN_j\rangle$ reduces available capacities of not only $\langle N_iN_j\rangle$ but also all wireless links $\langle N_iN\rangle$ (Figure 8). Therefore, in wireless multihop networks, available capacity should be assigned not to wireless links but to wireless nodes[2].

Suppose wireless nodes N_i and N_j are neighbor, i.e., they are included in their wireless transmission range each other.



Wired Network Model

Wireless Network Model

Fig. 8. Wired and Wireless Network Model.

Reservation of capacity in a wireless link $|N_iN_j\rangle$ reduces the capacity of a wireless node N_i. In addition, since N_i cannot transmit and receive data messages simultaneously, reservation of capacity in a wireless link $|N_jN_k\rangle$ where N_k is a neighbor wireless node of N_j also reduces the capacity of N_i. In addition, as shown in Figure 9, since N_i is an exposed node for data message transmission from its neighbor wireless node N to N^t, reservation of capacity in a wireless link $|NN^t\rangle$ reduces the available capacity of N_i. Due to the same reason, since N_i is a hidden node for data message transmission from N^f to N as in Figure 9, reservation of capacity in a wireless link $|N^fN\rangle$ also reduces the available capacity of N_i. In accordance with the above examination, the problem to achieve the maximum data message flows in wireless multihop networks is formalized as follows where available capacity $c(N_i)$ is defined for a wireless node N_i, reserved capacity $|N_iN_j\rangle$ is determined for a wireless link $|N_iN_j\rangle$ and a source and a destination wireless nodes are N^s and N^d, respectively;

[Maximum Data Message Flow Problem in Wireless Multihop Networks]
Under the following restrictions, the maximum value of $\sum_{|N^sN_j\rangle \in \mathcal{L}'} r(|N^sN_j\rangle) = \sum_{|N_kN^d\rangle \in \mathcal{L}'} r(|N_kN^d\rangle)$ is calculated;
(1) For all $|NN'\rangle$ satisfying $N \in Nei(N_i) \cup \{N_i\}$ or $N' \in Nei(N_i) \cup \{N_i\}$, $\sum_{|NN'\rangle} r(|NN'\rangle) \leq c(N_i)$.
(2) For all $N_i \in \mathcal{N}' - \{N^s, N^d\}$, $\sum_{|N_kN_i\rangle \in \mathcal{L}'} r(|N_kN_i\rangle) = \sum_{|N_iN_j\rangle \in \mathcal{L}'} r(|N_iN_j\rangle)$. □

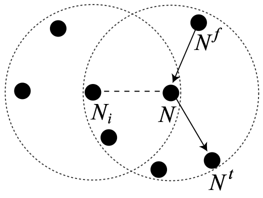


Fig. 9. Restrictions on Reservation of Capacity in Wireless Networks.

B. Capacity Increasing Flows

In the labeling method, multihop transmission routes from a source node to a destination one which increase amount of transmitted data messages, i.e., throughput, are detected one by one. Here, the conditions which the routes should satisfy are critical. In order to extend the original labeling method to be applied to wireless multihop networks, this

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[2] Capacities are reserved for wireless links to transmit data messages.

subsection discusses the conditions where a wireless multihop transmission route R provides a capacity increasing flow from a source wireless node N^s to a destination one N^d.

At first, we examine how capacities $c(N)$ of wireless nodes N are updated when an amount r of data message flow is reserved along a wireless multihop transmission route R. The initial values of capacities $c(N_i)$ of wireless nodes N_i is determined by the specification of wireless network interfaces. The current available capacities $c(N_i)$ that have not yet reserved for any data message transmission flow restricts the amount of data message flows including N_i and its 1-hop and 2-hop neighbor wireless nodes due to exposed and hidden nodes relation. Thus, we examine the following 3 cases where N is included in R and a case where N is not included in R.

$[N = N_0 \in R$ or $N = N_n \in R]$

As shown in Figure 10(a), if N is a source wireless node $N_0 = N^s$, since $N_1 \in Nei(N)$, the amount of reduction of $c(N)$ is totally reserved capacities in wireless links $|NN_1\rangle$ and $|N_1N_2\rangle$. In the same way, as shown in Figure 10(b), if N is a destination wireless node $N_n = n^d$, since $N_{n-1} \in Nei(N)$, the amount of reduction of $c(N)$ is totally reserved capacities in wireless links $|N_{n-2}N_{n-1}\rangle$ and $|N_{n-1}N_n\rangle$. Therefore, $c(N) := c(N) - 2r$.

$[N = N_1 \in R$ or $N_{n-1} \in R]$

As shown in Figure 10(a), if N is a next-hop wireless node N_1 of N^s, since $N_0 \in Nei(N)$ and $N_2 \in Nei(N)$, $c(N)$ is reduced the total of reserved capacities in wireless links $|N_0N\rangle$, $|NN_2\rangle$ and $|N_2N_3\rangle$ along R. In the same way, as shown in Figure 10(b), if N is a previous-hop wireless node N_{n-1} of N^d, since $N_{n-2} \in Nei(N)$ and $N_n \in Nei(N)$, $c(N)$ is reduced the total of reserved capacities in wireless links $|N_{n-3}N_{n-2}\rangle$, $|N_{n-2}N\rangle$ and $|NN_n\rangle$ along R. Therefore, $c(N) := c(N) - 3r$.

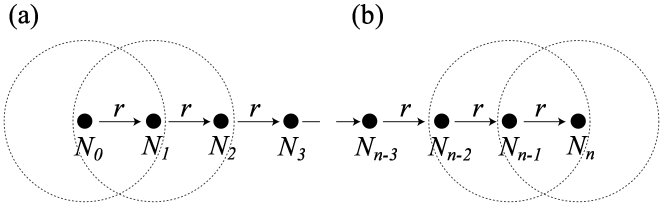

Fig. 10. Update of Capacities of Wireless Nodes (1).

$[N = N_i \in R]$

As shown in Figure 11, if N is an intermediate wireless node N_i in R where $i \neq 0, 1, n-1, n$, since $N_{i-1} \in Nei(N)$ and $N_{n+1} \in Nei(N)$, $c(N)$ is updated as reduction of the total amount of reserved capacities in wireless links $|N_{i-2}N_{i-1}\rangle$, $|N_{i-1}N\rangle$, $|NN_{i+1}\rangle$ and $|N_{i+1}N_{i+2}\rangle$ along R. Therefore, $c(N) := c(N) - 4r$.

$[N \notin R$ and $Nei(N) \cap R \neq \emptyset]$

For avoidance of collisions with exposed and hidden nodes in R, though N is not included in R, $c(N)$ is reduced. The amount of reductions is total reservation capacities in wireless links whose transmitter or receiver nodes are included in a wireless range of N as shown in Figure 12. That is, $c(N) := c(N) - lr$ where l represents a number of such wireless links.

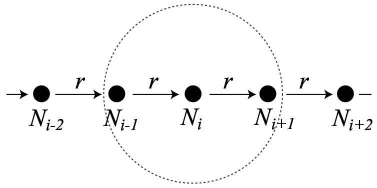

Fig. 11. Update of Capacities of Wireless Nodes (2).

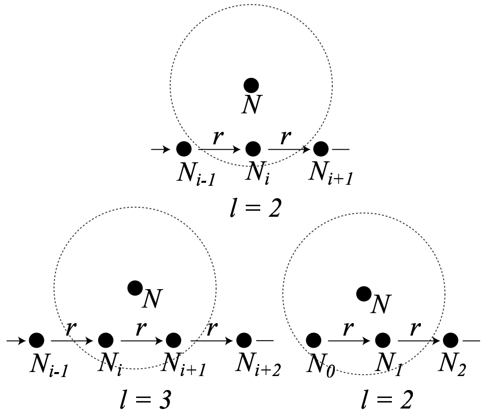

Fig. 12. Update of Capacities of Wireless Nodes (3).

According to the examination of update of $c(N)$, the following trivial condition for a wireless multihop transmission route R to be a flow increasing one is induced.

[Condition for Flow Increasing Route]

A wireless multihop transmission route $R = ||N_0 \dots N_n\rangle\rangle$ increments data message flow if $c(N_i) > 0$ for all the wireless nodes in R and $c(N) > 0$ for all 1-hop neighbor wireless nodes $N \in Nei(N_i)$ of $N_i \in R$. □

Next, same as in the original labeling method, we examine cases when a flow increasing route is configured by reduction of already reserved amount of data messages in wireless links. Due to effect on exposed and hidden nodes, the conditions induced for additional reservation of capacities along a wireless multihop transmission route $R = ||N_0 \dots N_n\rangle\rangle$ by reduction of reserved capacity in a wireless link $|N_{i+1}N_i\rangle$ is different from the original labeling method.

Figure 13 shows an example where there has already been a wireless multihop transmission route R' from a source wireless node N^s to a destination one N^d along which capacity r' has been reserved in all the wireless links and an additional wireless multihop transmission route R provides an additional flow r of data messages from $N^s = N_0$ to $N^d = N_n$. Here, $|N_iN_{i+1}\rangle \in R$, $|N_{i+1}N_i\rangle \in R'$ and $r' > r$. By addition of R as a wireless multihop transmission route from N^s to N^d, reserved capacities $r(|N_jN_{j+1}\rangle)$ $(j \neq i)$ increase r, i.e., available capacities $c(|N_jN_{j+1}\rangle)$ decrease r; however, $r(|N_{i+1}N_i\rangle)$ decreases r by update from r' to $r' - r$, i.e.,$c(|N_{i+1}N_i\rangle)$ increases r. Thus, though capacities $c(N_j)$ of intermediate wireless nodes N_j $(j \leq i-2$ or $j \geq i+3)$ and those of its 1-hop neighbor wireless nodes are updated as usual by reduction of $4r$, i.e., $c(N_j) := c(N_j) - 4r$. On the other hand, capacities $c(N_j)$ of N_j $(j = n-1, n, n+1, n+2)$ and those of 1-hop neighbor wireless nodes of N_i and N_{i+1} reduces only $2r$, i.e, $c(N_j) := c(N_j) - 2r$. Hence, in order for R to be a flow increasing route, $c(N_j) > 0$ is required in all wireless nodes in R.

However, consider a wireless node N which is in a wireless range of N_i and is out of wireless ranges of N_j $(j \neq i)$. In this case, since reserved capacities $r(|N_{i-1}N_i\rangle)$ and $r(|N_iN_{i+1}\rangle)$ increases and decreases r, respectively, capacity of N is unchanged. Thus, even if $c(N) = 0$, R is a flow increasing route and r can be reserved along R. Same as this way, for a wireless node N' in a wireless range of N_{i+1} and out of wireless ranges of N_j $(j \neq i{+}1)$, even if $c(N') = 0$, it does not prohibit R to be a flow increasing route. This is also because $r(|N_iN_{i+1}\rangle)$ decreases r and $r(|N_{i+1}N_{i+2}\rangle)$ increases r.

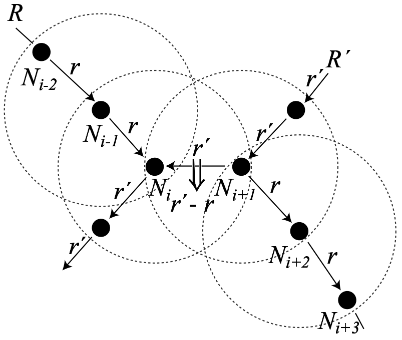

Fig. 13. Flow Increasing Route with Wireless Link in Another Route in Opposite Direction.

Figure 14 shows cases where a newly detected wireless multihop transmission route R contains some wireless links in which capacities have already reserved for another route in opposite direction. Here, reserved capacities in wireless links along R is r which is less than r' reserved in opposite direction in shared wireless links. As discussed above, if $r(|N_{i+1}N_i\rangle) \geq r$ has already reserved in $|N_{i+1}N_i\rangle$, $r(|N_{i+1}N_i\rangle)$ decreases r. Hence, distribution of reduction of capacities in wireless nodes are as Figure 14(a). In order for R to be a flow increasing route, all wireless nodes N in areas where the reduction of capacities are greater than 0 have positive capacities, i.e., $c(N) > 0$.

In cases that capacities have already been reserved in multiple successive wireless links in opposite direction along a newly detected route where these wireless links may be included in different routes, the restriction on the newly detected route to provide additional flow of data messages are relaxed. Figure 14 shows a case where $r(|N_iN_{i-1}\rangle) \geq r$ and $r(|N_{i+1}N_i\rangle) \geq r$ have been reserved and by reservation of r along R both $r(|N_iN_{i-1}\rangle)$ and $r(|N_{i+1}N_i\rangle)$ decreases r. Capacities in areas where amount of reduction of capacities is greater than 0 should be greater than 0 as N_j $(j \leq i-2$ or $j \geq i+2)$. However, in N_{i-1}, N_i and N_{i+1}, changes of capacities are 0. That is, even if $c(N_j) = 0$ $(j = i{-}1, i, i{+}1)$, R is a flow increasing route. In addition, capacities in wireless nodes in areas where the amount of reduced capacities by additional reservation is negative, their available capacities increases. Hence, in such wireless nodes N, $c(N) = 0$ is allowed for the reservation of r along R. Figure 14(c) shows a case that wireless links with reservation in opposite direction distributes separately along R.

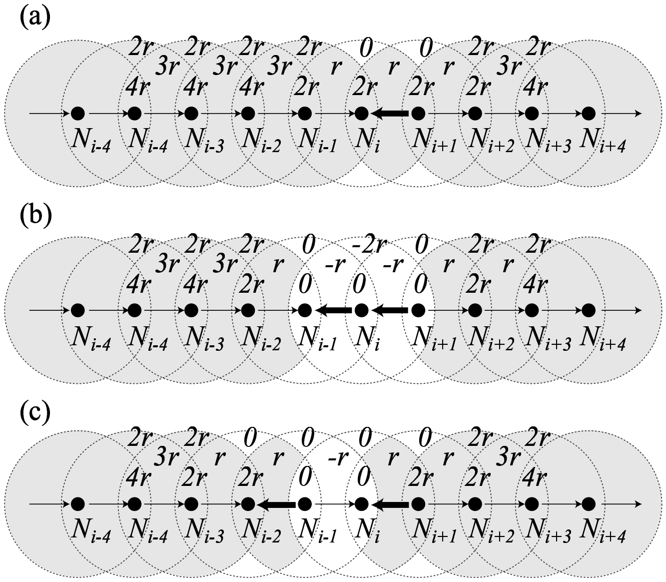

Fig. 14. Amount of Reduction of Available Capacities in Wireless Nodes with Capacity Reservation in Opposite Direction in Multiple Wireless Links.

Therefore, conditions for a flow increasing route containing wireless links with capacity reservation in opposite direction are as follows:

[Condition for Flow Increasing Route]
Suppose a pseudo capacity $r > 0$ is reserved in wireless links along a wireless multihop transmission route R from a sources wireless node N^s to a destination one N^d. For wireless links in R, reserved capacity $r(|N_iN_{i+1}\rangle)$ increases r if $r(|N_{i+1}N_i\rangle) = 0$ and $r(|N_{i+1}N_i\rangle)$ decreases r if $r(|N_{i+1}N_i\rangle) > 0$ by this reservation. According to this calculation, the amount of reduction of available capacities $c(N)$ of wireless nodes N are evaluated. If available capacities $c(N')$ of wireless nodes N' whose evaluated reduction of capacities are greater than 0 satisfy $c(N') > 0$, R is a flow increasing route from N^s to N^d. □

Figure 15 shows amount of reduction of available capacities of wireless nodes for a newly detected wireless transmission route R without reservation of capacities in wireless links $|N_{i+1}N_i\rangle$ in opposite direction. Since $r(|N_{i+1}N_i\rangle) = 0$ is satisfied in all wireless links in R, available capacities of all wireless nodes included in R and its 1-hop neighbor decrease for capacity reservation along R. Thus, $c(N) > 0$ is required in all wireless nodes N in R and its 1-hop neighbor ones. This is equivalent to the trivial condition mentions in this subsection and the latter condition contains the former one. In addition, since the pseudo reservation capacity may be any positive value for evaluation of changes of available capacities, only numbers of links which increase and decrease capacities of neighbor wireless nodes are required. Therefore, the condition for a flow increasing route is summarized as follows:

[Condition for Flow Increasing Route]

A wireless multihop transmission route R from a source wireless node N^s to a destination one N^d increases an amount of data message flow by capacity reservation if available capacities $c(N') > 0$ where a wireless node N' is included in R or 1-hop neighbor wireless nodes of them and the number of wireless links which connect to N' or its 1-hop neighbor wireless nodes and whose reserved capacity increases is larger than the number of wireless links which also connect to N' or its 1-hop neighbor wireless nodes and whose reserved capacity decreases. □

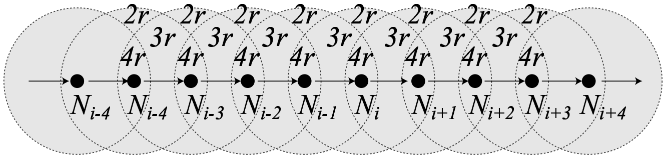

Fig. 15. Amount of Reduction of Available Capacities in Wireless Nodes without Capacity Reservation in Opposite Direction.

IV. CONCLUDING REMARKS

This paper proposes an extended labeling method for reservation of wireless link capacities in wireless multihop networks. For multimedia data transmission which requires high and stable throughput of data messages, capacity reservation is applied to multiple multihop routes. The original labeling method only applied to point-to-point based wired networks in which capacity in each wired link is reserved independently of the others. In wireless networks, due to broadcast based communication and existence of exposed and hidden nodes, reservation in neighbor wireless links is dependent each other. This paper proposes a modified condition of flow increasing wireless multihop transmission route which is critical to design a capacity reservation protocol based on the extended labeling method.

Based on the proposed condition, we are now designing a capacity reservation protocol. The extended labeling method with a depth-first search algorithm detects a set of wireless multihop transmission routes which realize the (pseudo) maximum throughput from a source wireless node to a destination one. Based on this examination, we are now considering a protocol to realize a set of wireless multihop transmission routes satisfying the application requirements with less communication overhead to exchange required control messages. In paper [9], we have already proposed a search cut-off algorithm to reduce the search area for lower overhead route search.

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