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A New Routing Protocol in Wireless Ad-hoc Networks with Multiple Radios and Channels

Sung-Won Ko* · Jeong-Hwan Cho · Kwon-Eui Hong

Abstract

We propose a new routing protocol, MCQosR, that is based on bandwidth estimation, admission control, and a routing metric, MCCR - suitable for wireless ad-hoc networks with multiple radios and channels.

To use the full capacity of a wireless link, we assume a node with multiple radios for full duplex operation, and a radio using multiple channels to exclude route-intra interference. This makes it possible to use the capacity of a wireless link. Then, to provide bandwidth and delay guarantee, we have a radio with a fixed channel for layer-3 data reception at each node, used to estimate the available bandwidth and expected delay of a wireless link.

Based on the estimate of available bandwidth and delay, we apply the call admission control to a new call requiring bandwidth and delay guarantee. New calls with traffic that will overflow link or network capacity are rejected so the accepted calls can use the required bandwidth and delay.

Finally, we propose a routing metric, MCCR, which considers the channel contentions and collisions of a wireless link operating in CSMA/CA.. MCCR is useful for finding a route with less traffic and distributing traffic over the network to prevent network congestion as much as possible. The simulation of the MCQosR protocol and the MCCR metric shows traffic is distributed and guaranteed service is provided for accepted calls.

Key Words : Wireless Multi-hop Ad-hoc Network, Multiple Radios and Channels,
Available Bandwidth Measurement, Call Admission Control, Quality of Service

1. Introduction

In wireless ad-hoc communication networks based on CSMA/CA control packets such as RTS, CTS, and ACK and data packets are carried on a single channel, which results in a reduction [1] of available bandwidth of a wireless link because of half-duplex transmission and route-intra interference. For

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* Main author : Associate Professor at Kimpo College
Tel : +82-31-999-4154, Fax : +82-31-999-4775
E-mail : swko@kimpo.ac.kr
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multimedia service that requires bandwidth or delay guarantee (QoS), the uncontrollability of available bandwidth becomes a more difficult problem than in wired networks.

In this paper, we present the use of multiple radios and multiple channels to solve the bandwidth reduction and QoS provision problems of conventional single channel wireless ad-hoc communication networks.

A wireless LAN based on CSMA/CA, such as 802.11, defines multiple channels for adjacent access points. The use of a different channel at each node in multi-hop ad-hoc networks can increase available bandwidth by decreasing the route-intra interference. However, the use of a different channel at each node results in deafness or a multi-channel hidden terminal problem [2]. This makes the connectivity of a flooding-based ad-hoc network difficult to maintain..

To overcome this difficulty, a common channel can be periodically used, but the implementation becomes complex. Also, the use of multiple channels with a single radio as a network interface does not use full link capacity because of half-duplex transmission.

Recent technologies provide cheap radios, making the use of multiple radios at each ad-hoc node possible. The approach proposed by Bahl et al. [3], where a node is equipped with multiple radios and different channels are assigned to each radio, is able to enhance network performance, but it is not effective in terms of cost. To minimize the cost of multiple radio use and maximize the merit of multiple channel use, an approach of using fewer multiple radios than the number of channels has been researched, and static or dynamic channel assignment at each radio was proposed.

Using 2 radios and 12 channels, Raniwala et al. [4] brought results to a static mesh network based on channel assignment and routing. They assumed that traffic was from or to a specific gateway, and 2 radios at each node were used to send traffic, one for to-gateway and the other for from-gateway. This approach increased throughput 7 times more than a single-radio single-channel method.

For the purpose of the QoS provision, the traffic in a network has to be managed. In an 802.11 wireless LAN with a contention-based MAC layer, management can be difficult. It is difficult to assign bandwidth to a specific flow. As opposed to a wired network where the bandwidth required can be assigned to a specific flow, CAC is used to provide QoS, and the bandwidth assigned to an already accepted flow is guaranteed by restricting new flow into a network [5]. When a new flow needs guaranteed service, the flow must provide the bandwidth required. A network accepts the flow if it can assign the required bandwidth, or rejects it if not.

We propose a new routing protocol, called MCQosR, where multiple radios are used at each node and each radio uses multiple channels to solve the bandwidth problem. Using a channel fixed for receive-only at a fixed radio of each ad-hoc node, MCQosR can do two things to satisfy the QoS provision:

1. measure available bandwidth of a wireless link, and use the measurement to estimate delay of the wireless link, and
2. offer a call admission control based on measured bandwidth and estimated delay. This will eventually provide a bandwidth and delay guaranteed QoS in wireless ad-hoc communication networks.

We also propose a new routing metric, MCCR, which is suitable for MCQosR.

The conventional ETT-based routing metric is not suitable for MCQosR because it makes available bandwidth measurement inaccurate by its use of a probe packet over the data link. Also, it does not reflect wireless link characteristics such as channel contention and collision. The MCCR depicts our use of multiple radios and channels and contention-based wireless links, and causes MCQosR to choose a path with less contention and delay for best-effort service.

The node model for use of multiple radios and channels as well as the definition "CAR1", the required channel arrangement to exclude route-intra interference is presented below in section 2. The destination node chose the best path with minimum MCCR metric in section 3. The transmittable bandwidth requirement definition "CAR2" for bandwidth guarantee and the endurable delay requirement definition "CAR3" for delay guarantee are proposed in section 4. They are used in CAC during the routing process of MCQosR in section 5. The performance of the proposed MCQosR with MCCR is simulated in section 6.

2. Use of Multiple Radios/Channels and route-intra Interference Exclusion

There are two ways to use multiple radios and channels, on the basis of previous research:

1. In one way, such as DCA (Dynamic Channel Assignment) [6], the radios(/channels) are used for common control or for data transmit/receive. In this approach, a radio(/channel) can transmit or receive data according to a dynamically assigned role.
2. In another way, such as MCR [7,8], the radios(/channels) are used for data receive-only and data transmit-only without common control.

For the former, channels can be used without a deafness problem, and for the latter, the complex channel assignment problem can be eliminated.

Since we use CAC for the QoS provision, based on available bandwidth measurement, we need at least one fixed radio with a fixed channel (static approach) at each ad-hoc node. This is because it is difficult to measure an available bandwidth of a wireless link in a dynamic channel assignment approach. To address this need, we use a static radio (only for data reception), an RoR with a fixed channel, and an RoC at each node, which also eliminates the complexity of dynamic channel assignment.

In addition, we use a common control radio with a fixed channel in common for all ad-hoc nodes in a network. The reason for common control is to measure available bandwidth more accurately without the overhead of control packets, such as Hello and routing messages, and also to provide connectivity between nodes in ad-hoc wireless networks.

2.1 An ad-hoc node with M radios using N channels

Assumptions:

- CSMA/CA, as a MAC layer protocol,
- RTS/CTS packets are used for reservation of a wireless link,
- An ACK packet is used to confirm a successful data transmission.
- Each ad-hoc node, shown as a red circle in Fig. 1, has M (=3) Radios and uses N (=4) channels including a common control radio(/channel).
- A radio is a transceiver, and
- A network interface card has a transceiver.

In this paper, radios/channels at each node are used differently according to their function. Radios are abbreviated as CoR, RoRs, and ToRs. Channels are CoC, RoCs, and ToCs. A node can receive data only through an RoC,. Thus, when a node wants to send data, it changes its ToC to the RoC of a receiving node.

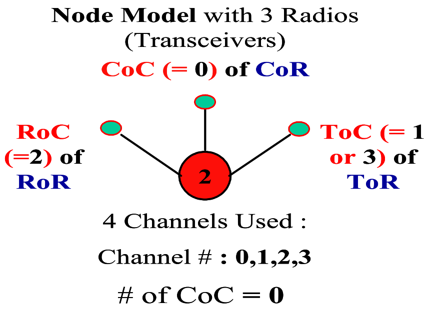


Fig. 1. Ad-hoc node model

The number inside the circle in Fig.1 identifies the RoC. The function of each radio/channel is shown in Table 1.

Table 1. Function of radios/channels

Radio	Channel used	Function
A CoR : Fixed at each ad-hoc node	A CoC : · Fixed for all ad-hoc nodes in a network.	· Used to broadcast messages such as periodic Hello messages for network connectivity and control messages for routing.
RoRs : Fixed at each ad-hoc node	RoCs : · Almost fixed for each ad-hoc node. · Can be changed, but should not be changed if possible. · Should be as different as possible from the RoCs of surrounding nodes.	· Used for Layer-3 data reception only.
ToRs : Fixed at each ad-hoc node	ToCs : · Change dynamically depending on RoC of a receiving node. · Can be any available channel except CoC and RoCs of itself.	· Used for Layer-3 data transmission only.

If there are more than 3 radios, the number of RoRs and ToRs can be determined by the amount of sending or receiving traffic. If there is an equal amount of sending and receiving traffic at a node, the number of RoRs and ToRs can be $\lfloor (M-1)/2 \rfloor$ and $\lceil (M-1)/2 \rceil$ respectively. In the rest of this paper, a node is assumed to have the following:

- 3 radios, each of which is used as CoR, RoR and ToR, and
- 4 interference-free channels, one for CoC, one for RoC, and the other two for ToC.

2.2 Route-intra interference exclusion requirement

To exclude route-intra interference [9], we apply the route-intra interference exclusion requirement during the routing process.

For CSMA/CA using RTS/CTS, the route from node A to node E, as shown in Fig. 2, experiences three different transmission cases from the viewpoint of node C depending on the way radios and channels are used. We assume no interference from neighbor nodes not on the route, and RoC(node) represents RoC of a node.

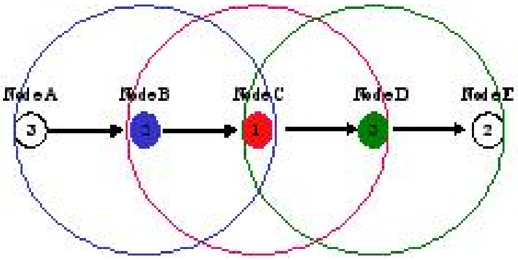


Fig. 2. Effects of route-intra interference

- Case 1. Assume a radio, and RoC(B) = RoC(C) = RoC(D) (single radio and single channel). For node C receiving data from node B and sending data to node D, there are 4 separated node operations (channel reservation and half-duplex transmission):

1. when node B receives data from node A,
2. when node C receives data from node B,
3. when node C sends data to node D. and
4. when node D sends data to node E.

Therefore, the bandwidth that can be used by node

C is 1/4 of the link capacity.

- Case 2. Assume a radio, and RoC(B) ≠ RoC(C), RoC(C) ≠ RoC(D), RoC(B) ≠ RoC(D) (single radio and multiple channel). When node C receives data from node B and sends data to node D (half-duplex transmission), node C can send data to node D using a channel different from the channel used by node B for receiving data from node A. Node C can then receive data from node B using a different channel from the channel used by node D for sending data to node E. Thus, the bandwidth used by node C is 1/2 of the link capacity.

- Case 3. Assume multiple radios, single receive-only radio, and RoC(B) ≠ RoC(C), RoC(C) ≠ RoC(D), RoC(B) ≠ RoC(D) (multiple radios and multiple channels). Node C can receive and send data independently of node B's data reception and node D's data transmission (full duplex transmission). Node C uses the full capacity of a wireless link.

For case 3, we find that in order for a node on a route to exclude route-intra interference, it needs to use a different channel (RoC) from the channels (RoCs) of the previous and next nodes on a route, and the channels of the previous, and next nodes should be different from each other. Thus, during the routing process, the three consecutive nodes on a route, for example, B, C, and D in Fig. 2, are examined to satisfy the CAR1 definition, as follows:.

- Definition CAR1 (route-intra interference exclusion requirement) :
  RoC(B) ≠ RoC(C), RoC(C) ≠ RoC(D), RoC(B) ≠ RoC(D)

In MCQosR, a node receiving RREQ compares its RoC with the RoC of a node sending RREQ, and drops the RREQ if the same RoC is used. Further, to check CAR1, a node needs to know the RoC of a preceding node of a node sending RREQ. We therefore define a preceding node's RoC, and add it to RREQ as a new field. A node sending RREQ includes the RoC of the preceding node as pre-RoC, and a node receiving RREQ compares its RoC with pre-RoC in RREQ.. If they are the same, the node drops RREQ.

3. Routing Metric : ccf and MCCR

With a new call request, a source node begins to search a route to destination node by sending an RREQ message and a destination node sends an RREP message confirming that a route has been set up. During this routing process, a routing protocol uses a link metric, and a path metric (the sum of link metrics on the route) to find the best route. For link metrics, there are hop-count, ETX [10], and ETT [8]. For path metrics, there are WCETT [8], which reflects route-intra interference, and MCR [7], which reflects channel switching delay (CSD, = 1[ms]) for multi-channel use. But none of these considers channel contention and collision. Moreover, the use of probe packets makes the bandwidth measurement in MCQosR inaccurate.

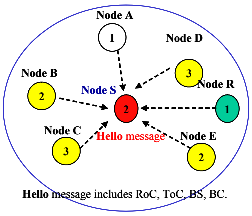
A node using CSMA/CD with RTS/CTS uses a contention window to avoid collision. A node waits to transmit data for BC, which is a contention window size in the scale of slot time (= 50[μs]) and depends on BS. If there is a collision, a node enters a new backoff stage, and gets a new backoff counter. Whenever the channel senses idle for a slot time, the BC decreases by 1. A node transmits data when its BC goes to zero [11]. If there are more neighbors around a node, there are more contention, less chances for channel acquisition, and more collisions, and then more delay and fewer throughput results in. So, it is necessary to find a route with less contention and fewer collisions.

We propose a routing metric which considers channel contention and collisions: for link metric, ccf, and for path metric, MCCR.

3.1 Link metric: ccf

As well as the number of contending nodes, collision probability will affect network performance. More collision brings longer delay and fewer throughputs, so our link metric considers collision probability and contending nodes.

An ad-hoc node periodically broadcasts a Hello message informing 1-hop neighbors of channel usage state (RoC and ToC) and channel contention state (BS and BC), as shown in Fig. 3(a), and stores information, as shown in Fig. 3(b) for node S.



(a) Broadcast of Hello message

Node	RoC	ToC	BS	BC
A	1	2	1	8
B	2	1	2	7
C	3	2	3	10
D	3	2	2	9
E	2	1	3	5
R	1	2	2	7

RoC : Receive only Channel,
ToC : Transmit only Channel,
BS : Backoff Stage, BC : Backoff Counter

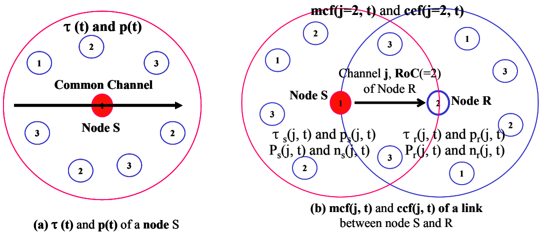
(b) Data structure of node S

Fig. 3. Broadcast of Hello Message

In a 1-hop network as shown in Fig. 4(a) with n neighbors within a transmission range, the packet transmission attempt probability, τ(t), of an ad-hoc node at any time, t, is given by BC(t) of n neighbors [12], and the collision probability, p(t), of a node at any time, is given as a function of n and τ(t) [13], as shown in equation (1).

$$\tau(t) = \left(1/n\right) * \sum_{i=1}^{n} \left(\frac{1}{BC_i(t)} \right), \ p(t) = 1 - \left(1 - \tau(t)\right)^{n-1} \qquad (1)$$

We apply the τ(t) and p(t) of a node in a 1-hop network, to a link in a multi-hop ad-hoc network, shown in Fig. 4(b), with channel j, RoC (here, =2) of a receiving node R. A link can be seen as an overlapping of two 1-hop networks, one for node S, and the other for node R. The subscript s stands for sending node, and subscript r stands for receiving node.



(a) τ (t) and p(t) of a node S

(b) mcf(j, t) and ccf(j, t) of a link between node S and R

Fig. 4. Transmission attempt probability and collision probability

We define P(j,t) as a collision probability on channel j, at any time t. Then, P(j,t) can be expressed as in eq. (2). Here, n(j,t) is the number of nodes whose ToC is equal to j.

$$P(j,t) = 1 - (1 - \tau(j,t))^{n-1},$$
$$\tau(j,t) = \left(1/n(j,t) \right) * \sum_{i=1}^{n} \left(\frac{1}{BC_i(t)} \right), ToC(i) = j \qquad (2)$$

For the calculation of Ps(j,t) and Pr(j,t), a sending node is included with BC (=$\left\lceil \frac{W-1}{2} \right\rceil$), and a receiving node is not included because it does not contend for a channel. Here, W is a minimum contention window size (ex, 16). Also, nodes with RoC = j and BC = 0 that surround the sending and receiving node are excluded in the calculation.

Using Ps(j,t) and Pr(j,t), we can define a minimum collision factor (mcf) in eq. (3) of a link with channel j, which reflects collision probability. We also define a contention and collision factor (ccf), which includes the number of contending nodes in eq. (3) as well as mcf.

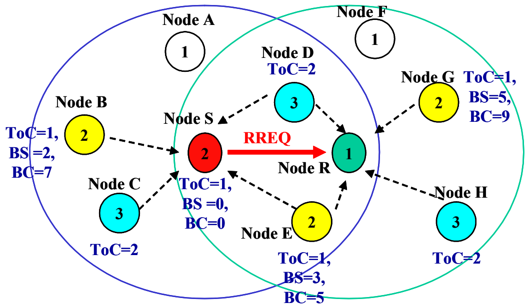
$$mcf(j,t) = \left(\frac{1}{2}\right) * \left(P_s(j,t) + \mathrm{P_r}(j,t)\right),$$
$$ccf(j,t) = \alpha * (n_s(j,t) + n_r(j,t)) * mcf(j) \qquad (3)$$

The ns(j,t) and nr(j,t) are defined as the number of contending nodes of the sending and receiving nodes, respectively. A weight-factor (α) of 3/4 (= 0.75) is included to exclude duplicated nodes in the calculation. Surrounding nodes with ToC = j and BC = 0 are included in the calculation of ns(j,t) and nr(j,t).

A node sending RREQ calculates Ps(j,t) and ns(j,t) for all available channels except its RoC, and includes them in RREQ and sends RREQ. A node receiving RREQ calculates ccf(j,t) on channel j (= RoC of a receiving node) using Ps(j,t) and ns(j,t) in RREQ.

The calculation of ccf(j) is demonstrated in Fig. 5. We assume that node R receives RREQ from node S, and we calculate ccf(1) of a link between node S and R on channel 1, which is RoC of a receiving node R.

At any time, neighbor nodes B and E of node S can attempt to transmit using channel 1. Thus, ns(1) of node S is 3 including node S itself, and τ(t) = (1/3) ∗ (1/7 + 1/5 + 1/8) = 0.16. Then, Ps(1) = 1 – (1 – 0.16)2 = 0.29. Using the same calculation for node R, we get nr(1) = 3 (node E, G, and S), τ(t) = (1/3) ∗ (1/5 + 1/9 + 1/8) = 0.14, Pr(1) = 1 – (1 – 0.14)2= 0.26. Now, node R can calculate mcf(1) [= 0.5 ∗ (0.29 + 0.26) = 0.27] and ccf(1) [= 0.75 ∗ (3 + 3) ∗ 0.27 = 1.13] for a link between nodes S and R with channel 1.



RREQ includes P_s(channels), n_s(channels), and pre-RoC. Here, channels are the available ToCs of a sending node.

Fig. 5. Calculation of ccf

3.2 Path metric: MCCR

In our MCQosR, ToC of a sending node must be equal to RoC of a receiving node. If not, a sending node must change its ToC to RoC of a receiving node, which needs a time delay to switch channels. To represent the channel switching delay, we add a Channel switching factor (Chsf), defined in eq. (4). Chsf is 0 if ToC of a sending node is equal to RoC of a receiving node, otherwise 1.

$$Chsf = \begin{cases} 0, equal \\ 1, other \end{cases} \qquad (4)$$

Also, for m-hop route, links using the same channel can cause route-intra interference. To include a route-intra interference effect, we define a route-intra Interference factor (RintraI), in eq. (5), and add it in path metric. RintraI is 0 if pre-Roc in RREQ is not its RoC., otherwise it is 1.

$$R\,\mathrm{int}\,raI = \begin{cases} 1, equal \\ 0, other \end{cases} \tag{5}$$

For m-hop route, the path metric that reflects the number of channel contending nodes, collision probability, channel switching delay, and route-intra interference are defined in eq. (6). The destination node selects a route with a minimum metric.

$$MCCR = \sum_{x=1}^{m}\left[ccf^{x} + Chsf^{x} + R\,\mathrm{int}\,raI^{x}\right] \tag{6}$$

4. Estimating Available Bandwidth of a Wireless Link by Measuring Idle Time

The available bandwidth of a link is estimated by measuring the idle time, the time during which the link is not activated by itself and other nodes [14]. In an ad-hoc node model with multiple radios/channels, the available bandwidth (aBw) of a wireless link between 1-hop neighbors is determined by the available bandwidth for transmission (TaBw, Transmittable Bandwidth) of a sending node and the available bandwidth for reception (RaBw, Receivable Bandwidth) of a receiving node, as shown in Fig. 6.

At a receiving node, the RaBw of RoR, RaBw(RoR), is estimated by measuring the idle time of RoR. And the RaBw of RoC, RaBw(RoC), is equal to RaBw(RoR) because RoR uses RoC statically. For a receiving node, the TaBw of ToC, TaBw(ToC), cannot be estimated because ToR changes its ToC according to the RoC of a receiving node.

It is not necessary to know TaBw(ToC) because we are not concerned with which channel is used for transmission, but only with transmittable bandwidth of ToR. The TaBw of ToR, TaBw(ToR), is estimated by measuring the idle time of ToR.

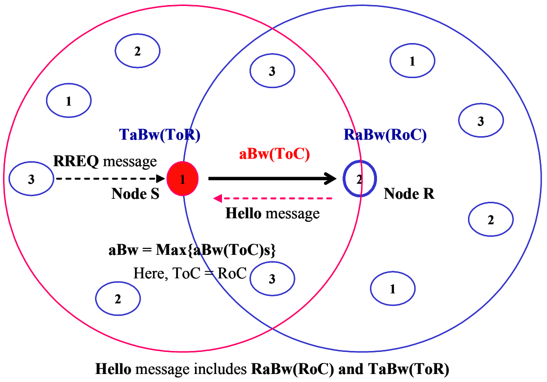


Fig. 6. aBw calculation of a wireless link between Node S and Node R

The abbreviation of available bandwidth of a node, a radio and a channel, and the relationships between them is shown in Table 2.

Table 2. Abbreviation and relationship of available bandwidth

	Node	Radio	Channel
Available bandwidth	RaBw = RaBw(node)	= RaBw(RoR)	= RaBw(RoC)
	TaBw = TaBw(node)	= TaBw(ToR)	TaBw(ToC) : meaningless
	aBw = aBw(node)	= aBw(ToR)	aBw(ToC)s: :here, ToC=RoC of a receiving node except its RoC

A node informs 1-hop neighbors of its RaBw(RoC) and TaBw(ToR) by broadcasting a Hello message, as shown in Fig. 6, and a node stores the RaBw(RoC)s and TaBw(ToR)s. it receives. When a node receives RREQ, it uses the RaBw(RoC)s to find the minimum RaBw according to RoC and to estimate an available transmittable bandwidth with the RoC for the next hop. Also, it uses the TaBw(ToR)s to find the used bandwidth, UsBw(RoC), over a link with the previous hop on a routing path. The aBw and UsBw(RoC) are used for Call Admission Control.

To find aBw for the next hop, a node with MCQosR performs a 3-step operation, as follows :

- Step 1. Estimation and broadcast of available bandwidth at each node .

A node measures the idle time of an RoR and ToR with period (T), and estimates the RaBw(RoC) and TaBw(ToR) using equation (7) from the raw link capacity (Bw, Bandwidth of a link). Then, a node informs its neighbors of the estimated RaBw(RoC) and TaBw(ToR).

$$TaBw(ToR)andRaBw(RoC) = Bw * \left(\frac{idleTime}{measuredTime, T}\right) * \left(\frac{1}{\beta}\right) \tag{7}$$

Here, weight-factor (ß) is greater than or equal to one, and includes the extra time due to the 802.11 overhead, such as DIFS (DCF InterFrame Space), SIFS (Short InterFrame Space), and control packets.

- Step 2. Receivable bandwidth of a receiving node .

A sending node determines the minimum RaBw(RoC) from RaBw(RoC)s of 1-hop neighbors by using eq.(8) for each RoC which can be used for ToC. Here, the RoC of itself is excluded.

$$RaBw(RoC) = Min\{RaBw(RoC)s\} \tag{8}$$

- Step 3. Available bandwidth of a wireless link.

A sending node determines aBw(ToC) from RaBw(RoC)s of 1-hop neighbors and its own TaBw(ToR) by using eq. (9), as shown below. Here, the RoC of a receiving node is used as ToC of a sending node. Then a sending node determines maximum available bandwidth, aBw, of a link.

$$aBw(ToC) = Min\{RaBw(RoC), TaBw(ToR)\},$$
$$aBw = Max\{aBw(ToC)s\} \tag{9}$$

To find UsBw(RoC) for the previous hop, a node with MCQosR performs a 4th step :

- Step 4. Bandwidth assumed to be used by a node sending RREQ.

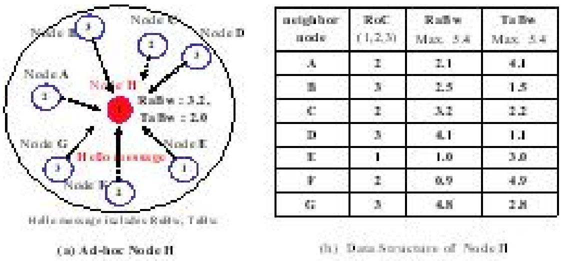
A node receiving RREQ calculates UsBw(RoC) which is a bandwidth used over a preceding link with a node sending RREQ by choosing the minimum between its own RaBw(RoC) and TaBw(ToR) of a node sending RREQ, as shown in eq. (10).

$$UsBw(RoC) = Min\left\{\begin{matrix} RaBw(RoC), itsOwn \\ TaBw(ToR), ofNodeSendingRREQ \end{matrix}\right\} \tag{10}$$

In Fig. 7(a), there are seven 1-hop neighbors (A,B,C,D,E,F,G) within transmission range of node H. Node H determines the transmittable bandwidth according to channels as follows.:

Each node measures and estimates its own RaBw(RoC) and TaBw(ToR), and broadcasts a Hello message with RaBw(RoC). Node H stores the information from neighbors as shown in Fig. 7(b), and determines the receivable bandwidth of neighbor nodes according to channels 2 and 3, and not its own receiving channel, 1. For channel 2, any neighbor node can receive data at Min{2.1, 3.2, 0.9} = 0.9[Mbps]. For channel 3, any neighbor node can receive data at Min{2.5, 4.1, 4.8} = 2.5[Mbps].

To determine the transmittable bandwidth according to a channel, the sending node H compares RaBw(RoC) with TaBw(ToR). Node H can determine that it can transmit on channel 2 with Min{0.9, 2.0} = 0.9[Mbps], and on channel 3 with Min{2.5, 2.0} = 2.0[Mbps]. The aBw(node H), the maximum transmittable bandwidth of node H, is Max{0.9, 2.0} = 2.0[Mbps]. When node H receives a RREQ from node A, it knows UsBw(RoC=1) = Min{3.2, 4.1} = 3.2[Mbps].



(a) Ad-hoc Node H

neighbor node	RoC (1,2,3)	RaBw Max. 5.4	TaBw Max. 5.4
A	2	2.1	4.1
B	3	2.5	1.5
C	2	3.2	2.2
D	3	4.1	1.1
E	1	1.0	3.0
F	2	0.9	4.9
G	3	4.8	2.8

(b) Data Structure of Node H

Fig. 7. Data structure of an ad-hoc node H

5. Call Admission Control during Ad-hoc Routing

During the routing process, a source node broadcasts an RREQ message with information of a new call, and intermediate nodes relay the message until a destination node receives it. The destination node receiving RREQ message replies to the source node with an RREP message. A node with MCQosR restricts new calls by applying call admission requirements for its bandwidth and delay guarantee service.

5.1 Call admission requirements

In addition to CAR1 for route-intra interference exclusion, we define CAR2 for bandwidth guarantee, and CAR3 for delay guarantee.

For bandwidth guarantee, a new call provides the required bandwidth (rBw). A node receiving RREQ compares UsBw(RoC) for the previous hop, and aBw for next hop, with rBw. It drops the RREQ if rBw is greater than UsBw(RoC) or aBw. Thus, we define a transmittable bandwidth requirement (CAR2) as follows:.

- Definition CAR2 (Transmittable bandwidth requirement):
  UsBw(RoC) > rBw and aBw > rBw

For the case of delay guarantee, a new call provides endurable maximum delay (maxD) as well as rBw. A node receiving RREQ calculates the expected delay (eD) for a previous hop, and cumulative eD (CeD) for the path from a source node using eq. (11). Then, the node compares CeD with maxD, and drops the RREQ if CeD is greater than maxD.

$$eD[ms]=\left(\frac{rBw}{UsBw(RoC)}\right)*1000+(chsf*CSD), CeD=CeD+eD \tag{11}$$

The node calculates the dashed- expected delay (eD′) for a next hop, and cumulative eD′ (CeD′) for the path from a source node using eq. (12). Then the node compares CeD′ with maxD, and drops the RREQ if CeD′ is greater than maxD.

$$eD'[ms]=\left(\frac{rBw}{aBw}\right)*1000, CeD'[ms]=CeD+eD' \tag{12}$$

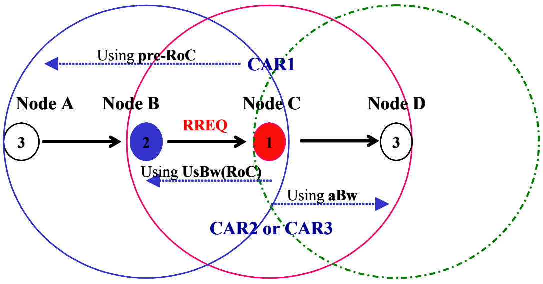
Thus, we define an endurable delay requirement (CAR3) as follows:

- Definition CAR3 (Endurable delay requirement):
  CeD < maxD and CeD′ < maxD

In this study, we add 3 fields to the RREQ packet: for CAR2 and CAR3:

1. the bandwidth requested by a new call, rBw, for CAR2,
2. maximum delay required by a new call, maxD, and
3. Cumulative eD, CeD for CAR3.

In Fig. 8, the call admission control operation of node C receiving RREQ is shown. Node C decides whether the CAR1 is satisfied by using RoCs of nodes A and B. It decides whether the CAR2 is satisfied by comparing rBw and aBw, and it decides whether the CAR3 is satisfied by comparing maxD and CeD.



RREQ message includes **pre-RoC**, rBw, maxD, **CeD**, and MCCR

Fig. 8. Requirements for call admission

5.2 Routing with call admission control

MCQosR operates differently according to the role of a node on a route, for example, as a source node, an intermediate node, or as a destination node. The algorithm in Fig. 9 shows the operations of MCQosR.

```
Stores own information : RoC, ToC, BS, BC, TaBw, RaBw
Sorts and stores neighbor's information according to channel: RoC, ToC, BS, BC, TaBw, RaBw
Calculates and stores : $P_s$(RoC), $n_s$(RoC), aBw (channels except RoC)

if a source node                        // for source node //
  if (bandwidth guarantee) and (!SAR2 for next hop) then return; else puts rBw in RREQ;
  else if (delay guarantee) and (!SAR3 for next hop) then return; else puts maxD and CeD(=0) in RREQ;
  puts pre-RoC, $P_s$(RoC), $n_s$(RoC), MCCR(=0) in RREQ; broadcasts RREQ; return;

else if an intermediate node            // for intermediate node //
   if (!SAR1) then drops RREQ; return;
   if (bandwidth guarantee)
      if (!SAR2 for previous hop) or (!SAR2 for next hop) then drops RREQ; return;
   else if (delay guarantee)
      if (!SAR3 for previous hop) then drops RREQ; return; else updates CeD in RREQ;
      if (!SAR3 for next hop) then drop RREQ; return;
   calculates ccf(RoC); updates MCCR, pre-RoC, $P_s$(RoC), $n_s$(RoC), MCCR in RREQ;
   broadcasts RREQ; return;

else if a destination node              // for destination node  //
  if (!SAR1) then drops RREQ; return;
  if (bandwidth guarantee) and (!SAR2 for previous hop) then drops RREQ; return;
  else if (delay guarantee) and (!SAR3 for previous hop) then drops RREQ; return;
  updates CeD in RREQ; calculates ccf(RoC); updates MCCR;
  if (better MCCR) then store MCCR as previous-MCCR; unicasts RREP to a source node;
return;
```

Fig. 9. Pseudo algorithm of MCQosR operation

6. Simulation

MCQosR with MCCR has different effects before and after network congestion happens due to the call admission control. Before network congestion happens, there is a load balancing effect of distributing traffic over a network. After network congestion happens, a bandwidth and delay guarantee a QoS effect occurs for accepted calls. In a simulation with Qualnet [15], the performance of MCQosR is compared with that of MCR to verify improvement.

During simulation, we assume a node with 2 IEEE 802.11a network interfaces and 5 interference-free channels (36, 48, 64, 149, 161) [7] for comparison with MCR, and we assume that the channel switching delay is 1[ms]. We also assume the data transmission rate of a wireless link is 12[Mbps], and the transmission range is 150[m], and the interference range is 300[m].

6.1 Transmission bandwidth of a wireless link

To confirm the effect of full duplex transmission and route-intra interference on transmission bandwidth of a wireless link, we use a chain topology where nodes are linearly lined up and fixed. We then generate a single 12[Mbps] call, increase path length, hop by hop, and measure throughput. As shown in Fig. 10, there is a static 7.6[Mbps] throughput, about 65[%] of link capacity, even though hop count increases. The static throughput means that no route-intra interference exists, and the throughput, 65[%] of link capacity, occurs because there are Hello messages and routing messages on RoC.

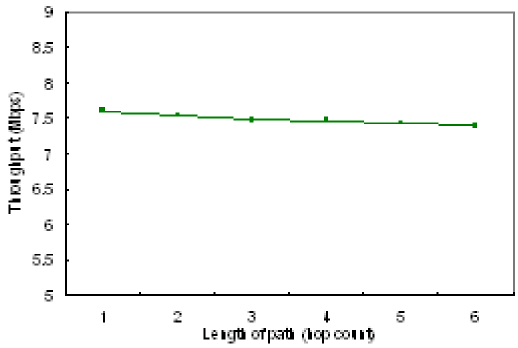


Fig. 10. Available Bandwidth of a wireless link

6.2 Throughput and delay guarantee after congestion happens

To see the throughput and end-to-end delay maintained for the duration of a call, we simulate with 100 nodes placed in a lattice (900[m]×900[m]). We generate 1[Mbps] CBR (Constant Bit Rate) calls with rBw (= 1[Mbps]) for throughput guarantee, or maxD (= 120[ms]) for delay guarantee, until network congestion occurs. We then measure the throughput and the end-to-end delay for each MCQosR and MCR routing protocol, and compare the results of MCQosR with those of MCR. The total simulation time is 60 seconds, and the duration of the CBR call is 60 seconds.

6.2.1 Throughput guarantee

Fig. 11 shows network throughput, which is a cumulative of each call's throughput. It shows that network congestion occurs with the 17th CBR call for both MCQosR and MCR, and that the throughput for MCR drops with increasing calls,. The throughput for MCQosR is maintained steadily even after congestion occurs. That is because MCR accepts new calls, but MCQosR does not accept them due to the CAR2 requirement after network congestion.

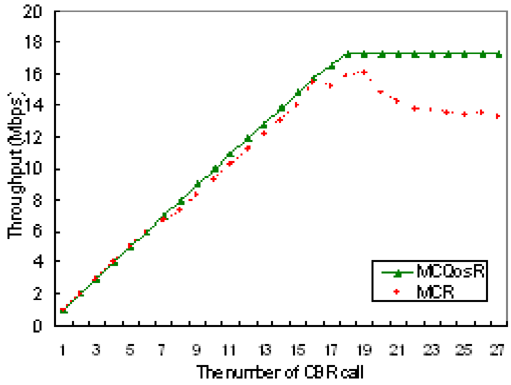


Fig. 11. Congestion and throughput

Fig. 12 illustrates the acquired throughput of each CBR call for MCQosR at the 27th call in Fig. 11. The requested bandwidth (= 1[Mbps]) is provided by the network except for the 1st and 2nd calls because the paths of the 2 calls are centered in the lattice structure and are affected by the following calls.

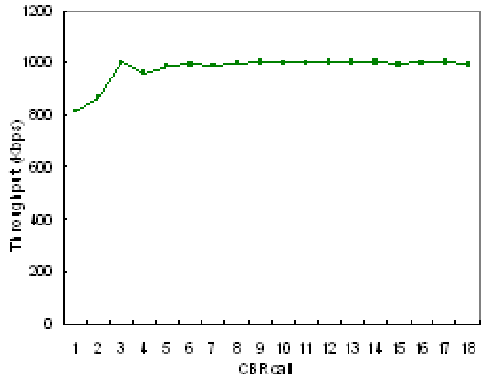


Fig. 12. Bandwidth guarantee for each call

6.2.2 Delay guarantee

Fig. 13 shows an average end-to-end delay for each call, and the simulation result that occurs with a delay guarantee. For MCR, there is a rapid change of the end-to-end delay, seven calls after congestion occurs. This result confirms the drop of throughput with congestion in Fig.11. A little more delay occurs with MCQosR, but no rapid change, just as for MCR.

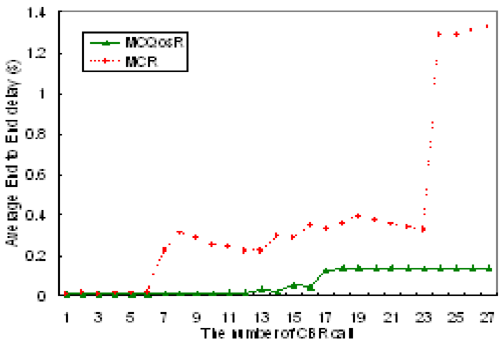


Fig. 13. Congestion and end-to-end delay

The MCR shown in Fig. 13, illustrates a rapid increase of end-to-end delay at the 24th CBR call. This indicates a degradation of network resource usage and a decrease of throughput. MCQosR, with the use of CAC mechanism, can use network resources more efficiently without wasting network resource on collisions or packet drops during data transmission., MCQosR can maintain steady throughput and end-to-end delay after congestion.

Fig. 14 shows the experienced end-to-end delay of each CBR call at the 27th call in Fig.13. Calls gain the required maximum delay (= 120[ms]), except for the 1st and 2nd calls. The reason for this unexpected result is the same as that of the throughput guarantee in Fig.12.

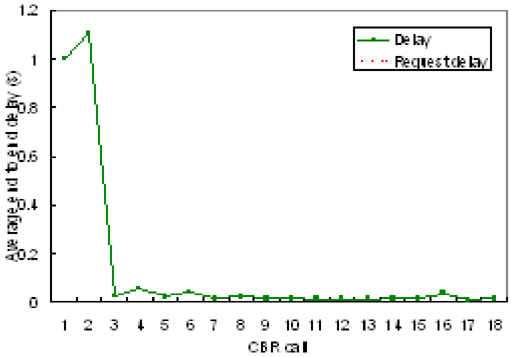


Fig. 14. Delay guarantee for each call

As demonstrated in Figure 14 above, MCQosR provides not only guaranteed QoS but also better performance than MCR in terms of throughput and end-to-end delay.

6.3 Load balancing before congestion

When establishing routes, MCQosR with MCCR chooses, differently from MCR, a node with a different RoC, less contention, fewer collisions, and more available bandwidth. Thus, MCQosR avoids duplicated use of parts of a route or nodes already used, and it distributes traffic throughout a network, leading to a load balancing effect. As a result, the throughput for MCQosR in Fig. 11 shows better performance than for MCR. In addition, end-to-end delay in Fig. 13 shows a 50[%] decrease with MCQosR compared to MCR before congestion. Fig. 13 shows that duplicated usage happens at the 7th call and at the 23th call for MCR, and at 17th call for MCQosR.

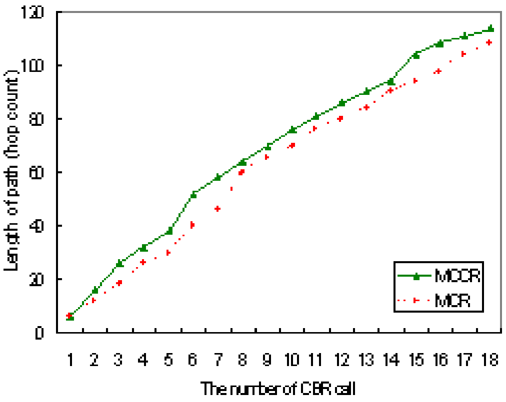


Fig. 15. Cumulative path length

To verify the load balancing effect, we measured the length of a call and the number of active nodes in a network for best-effort service calls that do not require guaranteed service. Fig. 15 shows the cumulative path length. For MCQosR, a call tends to have slightly longer hops, 2 to 10, but almost 10[%] longer length than for MCR.

Fig. 16 shows the cumulative number of active nodes. As shown, 7 more nodes are active in MCQosR than in MCR from the 5th CBR call.

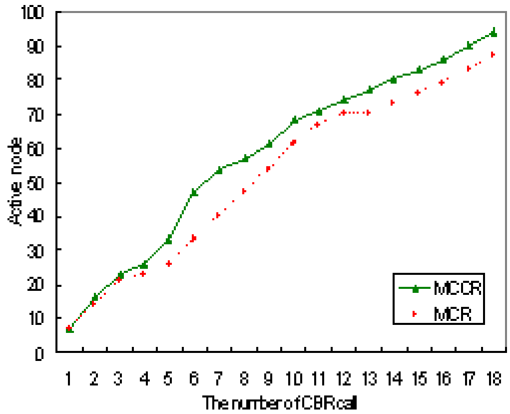


Fig. 16. Cumulative active nodes

These simulations, point out that we cannot use the full capacity of a wireless link using MCR because the extra interference and the overhead of Hello messages still exist, even if we exclude the route-intra-interference.. We cannot guarantee the bandwidth assigned because of contention-based MAC protocol.

In order to improve the performance of MCQosR with MCCR, it is necessary to use a separate radio and channel for common control to separate control packets such as Hello message and routing packets from data packets. It is also necessary to use the service level of IEEE 802.11e for higher quality service.

7. Conclusion

In wireless ad-hoc networks based on CSMA/CA, the use of a single radio and a single channel reduces the available bandwidth of a wireless link because of route-intra interference. Also, the use of contention-based MAC protocol makes it difficult to estimate and guarantee the available bandwidth, and therefore the QoS provision becomes more difficult.

In this paper, we proposed a node model that uses multiple radios and channels to increase the available bandwidth of a wireless link. We also proposed a routing protocol to provide bandwidth and delay guarantee QoS by admission control, based on available bandwidth measurement and an estimation of a wireless link.

With the proposed node model, the RoC at each node is used to exclude route-intra interference and to measure the available bandwidth of a wireless link. When establishing routes with the MCCR routing metric, nodes with less contention and fewer collisions are selected as often as possible, to prevent congestion, by distributing traffic as widely possible.

A call admission control based on bandwidth measurement and the requested bandwidth rejects new calls requiring more bandwidth than can be supported by a network. This guarantees the bandwidth and the delay of accepted calls.

The MCQosR protocol has the effect of balancing the load before network congestion occurs because of the MCCR metric and the CAC operation. It also has the effect of the QoS provision after network congestion occurs.

Before network congestion, the length of a route and the number of active nodes increase, but traffic is distributed over a single network,. This prevents traffic concentration at a single location.. After network congestion occurs, new calls are rejected and the requested bandwidth and delay is provided. These effects have been verified by simulation.

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Biography

Sung-Won Ko

B.A. in Electronics From Hanyang University, M.A. in Electronics from Hangyang University, and Ph.D. in Electronics from Soongsil University. Currently professor at kimpo college.

Jeong-Hwan Cho

B.A. in Electronics From Hanyang University, M.A. in Electronics from Hangyang University, and Ph.D. in Electronics from Hanyang University. Currently professor at kimpo college.

Kwon-Eui Hong

B.A. in Electronics From Konkuk University, M.A. in Electronics from Konkuk University, and Ph.D. in Electronics from Konkuk University. Currently professor at kimpo college.