The Fourth International Conference on Wireless and Mobile Communications

Proposal, Implementation, and Evaluation of a QoS-aware Routing Mechanism for Multi-Channel Multi-Interface Ad-Hoc Networks

Shinsuke Kajioka*, Naoki Wakamiya*, Masayuki Murata*,
Hiroki Satoh†, Kazuya Monden†, Masato Hayashi†, and Susumu Matsui†
*Graduate School of Information Science and Technology, Osaka University
1-5 Yamadaoka, Suita, Osaka 565-0871, Japan
Email: {s-kajioka, wakamiya, murata}@ist.osaka-u.ac.jp
†Hitachi, Ltd., System Development Laboratory
292, Yoshida-cho, Totsuka-ku, Yokohama, Kanagawa 244-0817, Japan
Email: {hiroki.satoh.yj, kazuya.monden.vw, masato.hayashi.eg, susumu.matsui.cb}@hitachi.com

***Abstract*—Without any control mechanism, a wireless ad-hoc network is easily congested and the perceived quality of applications considerably deteriorates. Therefore, we need QoS control mechanisms to accommodate real-time multimedia application such as video conferencing, VoIP (Voice over IP), and remote monitoring while satisfying application QoS requirements. In this paper, we propose a new routing mechanism to support real-time multimedia communication by efficiently utilize the limited wireless network capacity. Our mechanism considers a wireless ad-hoc network composed of nodes equipped with multiple network interfaces to each of which a different wireless channel can be assigned. By embedding information about channel usage in control messages of OLSRv2, each node obtains a view of topology and bandwidth information of the whole network. Then, a source node determines a logical path on which application QoS requirements are satisfied. Through experiments on a simulator, our mechanism could achieve the packet delivery ratio of about 95% at the end-to-end delay of about 10 ms. In addition, real-time traffic was more evenly distributed over the whole network.**

***Index Terms*—ad-hoc network, QoS routing, multi-channel, multi-interface.**

I. INTRODUCTION

Wireless ad-hoc network needs no fixed communication infrastructures such as routers, switches, access points, and cables. Nodes communicate with each other to organize a network and transmit data from one node to another. Packets transmitted over a wireless ad-hoc network include both of best-effort traffic (file transfer, e-mail, and Web) and real-time traffic (video conferencing, VoIP (Voice over IP), and remote monitoring). Since the capacity of wireless link is limited and the effective bandwidth is much smaller for contention among nodes [1], [2], it is not trivial to accommodate real-time multimedia traffic in a wireless ad-hoc network. Especially, they require certain level of QoS guarantee or control in terms of delay, delay jitter, and packet loss.

Over the past several years, many studies have been devoted to QoS control in wireless ad-hoc networks [3], [4], [5], [6]. There are several techniques or methods for controlling QoS in wireless ad-hoc networks, such as bandwidth reservation, channel switching, channel separation, and QoS-aware routing. For example, QOLSR (QoS-enhanced Optimized Link State Routing) decreases the packet loss rate about a half of the conventional OLSR by considering more appropriate metrics, i.e. delay and bandwidth, than the hop distance used in OLSR in route calculation [5]. The modification of IEEE 802.11 standard MAC protocol supports frame transmission over a multi-channel and multi-interface wireless ad-hoc network. A node switches wireless channels [7] or both of channels and interfaces [8], [9] in a hop-by-hop manner or a time-based manner, to reduce the packet loss and improve the network throughput. Although having multiple channels and interfaces contributes to avoidance of competition and collision for a wireless channel, in [10], they noticed that channel switching at an interface introduced the switching delay and proposed a new method which classified interfaces to “fixed” interfaces and “switchable” interfaces to avoid the delay. Fixed interfaces stay on certain channels for a longer period than switchable interfaces and they are used when a switchable interface is switching a channel.

In this paper, we propose a QoS-aware routing mechanism for wireless ad-hoc networks, especially used for temporal communication vehicle at a festival or disaster-affected area. Our mechanism assumes a node equipped with multiple network interfaces, each of which a different wireless channel can be assigned to. A node estimates the usage of its wireless channels and disseminates the information about the available bandwidth on the node, called the bandwidth information, to the other nodes in the whole network. For this purpose, the bandwidth information is embedded in control messages of OLSRv2 (OLSR version 2) [11] and propagated in the whole network in an efficient and effective way. To transmit packets, a node estimates the optimal path to a destination node to satisfy application QoS requirements. However, the derived path, called a logical path, is different from the physical path to the destination established by the underlying OLSRv2. Therefore, packets are encapsulated so that it traverses the logical path. In addition, each intermediate node chooses or switches a wireless channel for packet transmission in a hop-by-hop manner for efficient use of wireless channels and collision avoidance.

In the rest of this paper, we first describe our proposal in Section II and introduce system architecture of our proposal in Section III. Then, we perform simulation experiments to

978-0-7695-3274-5/08 $25.00 © 2008 IEEE
DOI 10.1109/ICWMC.2008.37

TABLE I
AN EXAMPLE OF WIRELESS CHANNEL AND IP ADDRESS ASSIGNMENT.

interface	IP addr–node 1	IP addr–node 2	IP addr–node 3
0 (wlan0)	192.168.0.1/24	192.168.0.2/24	192.168.0.3/24
1 (wlan1)	192.168.1.1/24	192.168.1.2/24	192.168.1.3/24
2 (wlan2)	192.168.2.1/24	192.168.2.2/24	192.168.2.3/24

evaluate the effectiveness of our proposal from viewpoints of packet delivery ratio, end-to-end delay, channel utilization, and node utilization in Section IV and we build a prototype and conduct practical experiments to verify the practicality in Section V. Through simulation experiments, we confirmed that our mechanism could achieve the packet delivery ratio of about 95% at the end-to-end delay of about 10 ms in a grid network of 100 nodes by assigning three dedicated channels to real-time traffic and conducting logical routing. In addition, we confirmed that real-time traffic was more evenly distributed over the whole network. Finally, we summarize and describe some future work in Section VI.

II. QOS-AWARE ROUTING MECHANISM ON WIRELESS AD-HOC NETWORKS

In this section, we give an overview of our proposed mechanism and its target system for QoS-aware routing on wireless ad-hoc networks. There are three key points in our proposed mechanism, estimation of the available bandwidth, exchange of the bandwidth information by using OLSRv2, and logical routing based on the information about the network topology and the available bandwidth.

A. Overview of our proposed mechanism and its target system and application

We consider a wireless ad-hoc network consisting of nodes equipped with K ($2 \leq K$) wireless network interfaces. The same number K of wireless channels are available for wireless communication. Wireless channels are assigned to interfaces without overlap. Because of its application scenario, we assume that nodes are immobile. Nevertheless, condition of wireless communication dynamically changes. In our proposed mechanism, one channel numbered 0 from K channels is reserved for best-effort traffic and called best-effort channel, and the other $K - 1$ channels, called real-time channels, are used for real-time traffic such as voice or video data. On the best-effort channel, the OLSRv2 with extension for our mechanism operates for proactive physical routing and bandwidth information dissemination.

Table I shows an example of wireless channel and IP address assignment on our proposed mechanism. The wireless network interfaces are numbered as 0, 1, and 2, respectively. The interface wlan0 is assigned to channel 1, wlan1 to channel 6, and wlan2 to channel 11. Each interface belongs to a different network, i.e. 192.168.0.0/24 for wlan0, 192.168.1.0/24 for wlan1, and 192.168.2.0/24 for wlan2. Each node has a unique host address, 1, 2, and 3. Therefore, node 1 for example has three IP addresses, 192.168.0.1, 192.168.1.1, and 192.168.2.1, on three network interfaces. Since wireless channels are assigned to different networks, channel switching can be easily done by changing a network address of a packet at a source node and intermediate nodes.

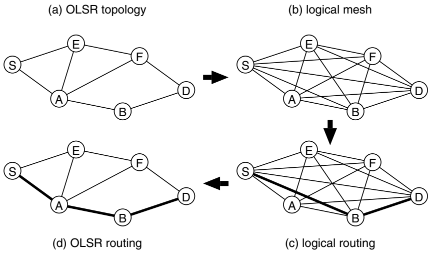


Fig. 1. QoS-aware routing by our proposed mechanism.

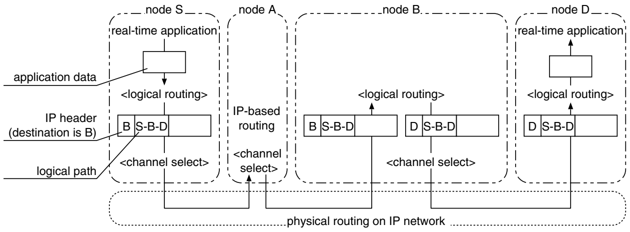


Fig. 2. Packet processing in our proposed mechanism.

Each node always probes the usage of real-time channels and estimates the available bandwidth. The estimated available bandwidth is disseminated over the whole network by embedded on control messages, i.e. HELLO messages and TC (Topology Control) messages of OLSRv2 operating on the best-effort channel. In our mechanism, all nodes obtain and maintain the complete information about the available bandwidth on all nodes in the network.

Packets belonging to best-effort traffic are transmitted to a destination node on the best-effort channel. Intermediate nodes choose a next hop node for the destination node of a received packet in accordance with the routing table maintained by OLSRv2. On the other hand, packets belonging to real-time traffic are transmitted to a destination traversing a so-called logical path. A logical link consists of one or more physical links from one end to the other. A logical path is determined taking into account the topology of a wireless ad-hoc network, the available bandwidth on all physical links, and application QoS requirements.

Figure 1 illustrates an example of logical path construction and packet forwarding. Figure 2 shows the way that a packet is processed in our system. When a packet to a new destination is generated by a real-time application, a node determines a logical path to its destination for the session. For example in Figure 1, the source node S first considers the logical mesh topology on the physical network (Figure 1(b)). Each of logical links in the logical mesh topology is related to the available bandwidth on the physical path connecting the two ends of the logical link. Then, the source node S tries to find the optimal path, which satisfies application QoS requirements and some other metric if needed, to the destination node D. In this example, the logical path S-B-D is chosen (Figure 1(c)).

Since the physical path from the node S to the node D can be different from the optimal logical path as for example S-E-F-D, all packets belonging to the session for this destination are encapsulated indicating the first destination node B and the last destination node D, as shown in Figure 2 (in the node S). Encapsulated packets are sent to the first destination node B through the physical path from the source node S to the node B, and then sent to the final destination node D from the node B (Figure 1(d)). In this case, the logical next hop node at the node S is the node B while the physical next hop node at the node S is the node A, i.e. the node S sent a packet to the node A, then the node A forwarded the packet to the node B. The intermediate node A of the logical path S-B only relays a received packet to the node B, which is regarded as the destination of the packet from the physical routing view point (Figure 2, node A). For efficient use of wireless bandwidth, each node chooses the real-time channel with the largest available bandwidth in forwarding a packet to a physical next hop node, which is determined in accordance with the OLSRv2 routing table.

B. Estimation of available bandwidth

There have been some studies on estimation of the available bandwidth on a wireless network [2], [12]. In our proposal, for the sake of simplicity, the available bandwidth $B_k(c)$ of the channel c ($1 \leq c \leq K-1$) on the node k is estimated by Equation 1, where $W_k(c)$ corresponds to the ideal capacity of the channel c on the node k, e.g. 54 Mb/s for IEEE 802.11g, T is the estimation interval, and $D_k(c)$ is the total amount of data transmitted and received on the channel c at the node k in the estimation interval.

$$B_k(c) = W_k(c) - D_k(c)/T. \tag{1}$$

Then, the available bandwidth B_k for real-time traffic on the node k is derived by the following equation.

$$B_k = \sum_{c=1}^{K-1} B_k(c). \tag{2}$$

We should note here that we do not limit to the above estimation and a node can use any of estimations in literatures.

C. Exchange of bandwidth information on OLSRv2

OLSRv2 reduces the overhead in flooding control messages for information dissemination by limiting nodes participating in flooding. They are called MPR (MultiPoint Relay). A set of MPRs are chosen in a distributed manner aiming to have the smallest number of MPRs while keeping the connectivity. Nodes exchange HELLO messages with neighboring nodes in the range of radio signals at regular HELLO intervals. In addition, an MPR generates and disseminates TC messages at regular intervals.

In our proposal, the bandwidth information is also entrained in HELLO and TC messages by adding the extended field in the form of TLV (Type Length Value) block. On receiving control messages, a node builds or updates a new table, called the Extended Topology Set, to maintain the bandwidth information in addition to the above-mentioned tables.

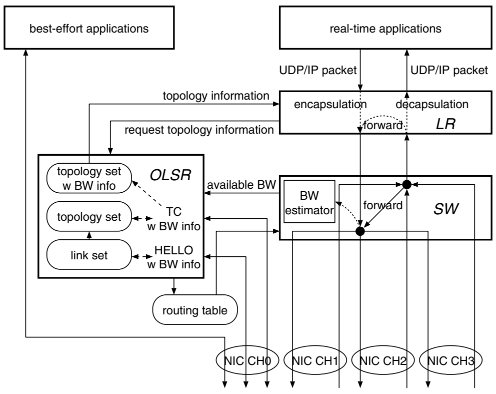


Fig. 3. Module components of proposed mechanism.

D. Logical routing based on bandwidth information

On receiving the first packet to a new destination, the node generates a logical mesh network. The logical link between the node i and the node j in the logical mesh network is associated with the available bandwidth $B(i,j)$. The available bandwidth $B(i,j)$ is given as the minium of the available bandwidth among all physical links on the shortest path between the node i and the node j. The available bandwidth of the physical link is defined as the minimum of the available bandwidth on nodes at the both edges. For example, the available bandwidth $B(S,B)$ in Figure 1 is given as $B(S,B) = \min(\min(B_S, B_A), \min(B_A, B_B))$. When there are two or more shortest paths for a logical link, one with the minimum available bandwidth is chosen.

Once a logical mesh network is constructed, a source node begins to find the optimal path which satisfies application QoS requirements. First, a set of logical paths with a logical hop count of less than H are obtained from the logical mesh network. The upper bound H is introduced to avoid to generate an unnecessarily long path and shorten the calculation time. Then, for each of logical paths in the set, a node derives the available bandwidth as the minimum available bandwidth of logical links constituting the logical path. Finally, the logical path with the largest available bandwidth in the set is chosen for the session. When there are two or more logical paths with the same largest available bandwidth, the logical path that has the smallest physical hop count is chosen for the session to minimize end-to-end delay. When there are two or more logical paths with the same largest available bandwidth and the smallest physical hop count, the logical path found the earliest is chosen for avoidance of overhead in memory copy.

III. SYSTEM ARCHITECTURE

Figure 3 shows module components of our proposed mechanism. In this figure, a node has four network interfaces and we assign channel 0 for best-effort traffic and channels 1, 2, and 3 for real-time traffic.

UDP/IP packets generated by a real-time application are first processed by the logical QoS-aware routing module (LR). The LR builds a logical path for the first packet of a new session.

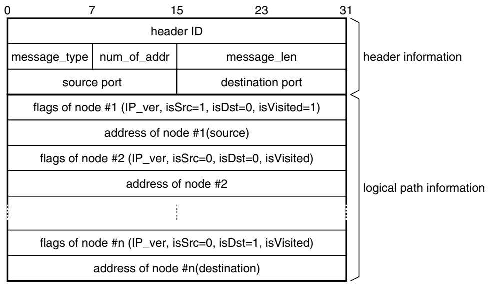


Fig. 4. LR header format.

Packets are encapsulated by an LR header indicating addresses of intermediate nodes of the logical path as shown in Figure 4, so that it traverses the logical path on the physical network operated by OLSRv2. Finally, the LR passes the encapsulated packet to the switching module (SW). On receiving a packet from the LR, the SW determines the physical next hop node in the physical network for the logical next hop node. Then, the SW emits the packet destined to the logical next hop node though a network interface for a channel with the maximum available bandwidth.

When the SW receives a packet from the network, the SW investigates an LR header to identify the logical next hop node of the packet. If the logical next hop node is the node itself, the SW forwards the packet to the LR. Otherwise, the SW sends the packet to the physical next hop node on the physical path toward the logical next hop node. On receiving a packet from the SW, the LR investigates the LR header to check whether it is the final destination or not. If the node is the destination, the LR removes the LR header from the packet and passes it to the corresponding real-time application.

The SW is also responsible for estimation of the available bandwidth. The BW estimator module in the SW observes packet transmission and reception, estimates the available bandwidth of each channel by using Equation 1, determines the available bandwidth of the node by using Equation 2, and reports the result to the OLSR module (OLSR).

The OLSR manages the physical network by exchanging HELLO and TC messages on the best-effort channel. The OLSR obtains the information about the available bandwidth of the node from the SW. The OLSR generates and exchanges HELLO messages embedded the information about its available bandwidth with neighboring nodes. The OLSR of an MPR generates and disseminates TC messages embedded with the information about its available bandwidth and the available bandwidth of its MPR selectors. On receiving HELLO or TC message, a node builds and updates the Extended Topology Set. On receiving a request from the LR, the OLSR provides the LR with the Extended Topology Set.

IV. SIMULATION EXPERIMENTS AND DISCUSSIONS

In this section, we first evaluate the performance of our proposal through simulation experiments. We used QualNet 4.0 simulator [13]. We based our OLSR module on the code provided by Niigata University OLSRv2 project [14] with some modifications for supporting our proposed mechanism.

TABLE II
SIMULATION CONDITIONS.

scenario	channels	logical routing	channel switching
1	1	N/A	N/A
2	2	off	N/A
3	4	off	at source, at random
4	4	off	hop-by-hop
5	4	on	hop-by-hop

We built a grid network consisting of 100 nodes in the 1,000×1,000 m^2 region. We assigned four wireless network interfaces with omnidirectional antenna per node, ch1 (2.412 GHz), ch6 (2.437 GHz), and ch11 (2.462 GHz) assigned for real-time channels and ch14 (2.484 GHz) assigned for best-effort channel. A node can communicate with eight nodes in the diameter of 153 m at the rate of 54 Mb/s as lines for bidirectional links show. Radio signals transmitted by a node can interfere 24 nodes in the diameter of 289 m. We used the free space path-loss model with no shadowing and no fading. A FIFO buffer at IP layer has the capacity of 50,000 B.

As an application, we assumed VoIP traffic. A source node generated packets of 172 B consisting of voice data of 160 B and RTP header of 12 B every 20 ms, i.e. 64 kb/s CBR traffic. We measured the delay from a source to a destination and the delay jitter. We initiated 80 sessions between randomly chosen pairs of a source node and a destination node at randomly chosen time from 30 to 90 s in simulation time. Each session lasts for 60 s. A simulation run was terminated at 155 s in simulation time after all packets had reached to the destination node. We considered 10 traffic patterns, i.e. 10 sets of 80 source-destination pairs and their starting time.

To evaluate the effectiveness of our proposal, we consider five scenarios different in the number of available channels, their usage, and the way of channel selection. They are summarized in Table II. All of control packets of OLSRv2 and data packets of real-time applications are accommodated in a single channel in the scenario 1, whereas they have separated channels in the scenarios 2 through 5. In the scenario 3, the number of channels assigned to real-time traffic is increased from one to three. A real-time channel for a session is chosen at random at a source node. The scenario 4 is different from the scenario 3 in choosing a real-time channel with the highest available bandwidth in sending a packet at a source node and intermediate nodes. The scenarios 3 and 4 are similar to the proposal in [15]. Finally, the logical routing is conducted in the scenario 5.

Results on the average end-to-end packet delivery ratio, the average end-to-end delay, and the average packet delay jitter are shown in Figures 5, 6, and 7. The horizontal axis of these figures corresponds to the traffic pattern numbered in order of the average hop counts of physical paths. The vertical axis of the Figure 5 indicates the end-to-end packet delivery ratio averaged over 10 simulation experiments and of the Figures 6 and 7 corresponds to time. We can see that the average delay increases and the packet delivery ratio decreases by separating

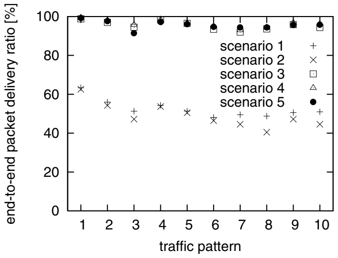


Fig. 5. Comparison of average packet delivery ratio.

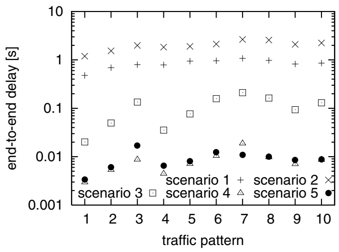


Fig. 6. Comparison of average delay.

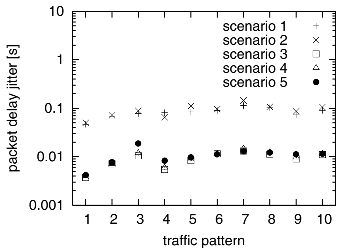


Fig. 7. Comparison of average delay jitter.

control and data channels by comparing the scenarios 1 and 2. The increase in the delay is for the longer packet length. It is shown that the packet delivery ratio is as high as 92% to 99% in the scenario 3, and the delay and the delay jitter become ten times smaller than those in the scenario 2 by having multiple real-time channels.

The delay can be further reduced in order of magnitude for the balanced usage of channels by the hop-by-hop channel switching in the scenario 4. To quantify the balanced channel usage, we introduce following two metrics. The first one is the variance σ^2 of transmitted data frames per channel,

$$\sigma^2 = \frac{1}{n}\sum_{i=1}^{n}(\bar{x} - x_i)^2, \tag{3}$$

where n is the number of nodes, x_i is the transmitted frames of node i, and $\bar{x}$ is the average among nodes. The smaller value of the variance indicates more balanced use of wireless channels. The average value of variance is 8.88×10^6 in the scenario 3 while it is 7.93×10^4 in the scenario 4.

The second one is the fairness index f of transmitted data frames per channel,

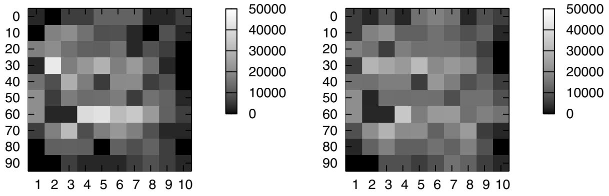
$$f = \frac{(\sum_{i=1}^{n} x_i)^2}{n\sum_{i=1}^{n} x_i^2} \quad (0 \leq f \leq 1). \tag{4}$$

The fairness index of 1 means that wireless channels are used equally. The average value of fairness index is 0.60 in the scenario 3 and it is 0.99 in the scenario 4. The maximum delay in the scenario 4 was 18 ms, which satisfies the requirement of Class A quality of ITU-T Recommendation G.144, i.e. 100 ms.

In Figure 8, we compare the scenarios 4 and 5 in the utilization of real-time channels in one simulation run. It is noticed that the nodes 32 and 65 are heavily loaded in the case without logical routing (Figure 8(a)), whereas the load is relatively distributed in the case with load balancing (Figure 8(b)). The average value of variance of transmitted data frames per node is 1.02×10^8 in the scenario 4 while it is 7.58×10^7 in the scenario 5. The average value of fairness index is 0.53 in the scenario 4 and it is 0.66 in the scenario 5. From these results, we can say that the scenario 5 effectively selects logical paths in order to avoid selecting busy nodes in the whole network.

V. PRACTICAL EXPERIMENTS AND DISCUSSIONS

In this section, we introduce the experimental system that implements our proposed mechanism and show results of practical experiments.



(a) Scenario 4.

(b) Scenario 5.

Fig. 8. Comparison of total number of transmitted MAC frames.

Fig. 9. The ad-hoc wireless relay node (Hitachi Information & Communication Engineering).

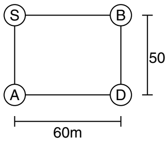


Fig. 10. Experimental topology.

A. Experimental system

We used the experimental system, the ad-hoc wireless relay node shown in Figure 9, to implement our proposed mechanism. The node has four wireless network interfaces which support IEEE 802.11b/11g MAC protocols and we used three interfaces in the ad-hoc mode. We configured one interface among the three for best-effort channel and the other two for real-time channel.

B. Experimental environment and discussions

Since we had only four relay nodes, we organized a simple square topology illustrated in Figure 10, where the node S is a source node, the node D is a destination node, and the nodes A and B are intermediate nodes. The solid lines indicate physical links. We used 64 kb/s CBR traffic. In the practical experiments, the source node S generated a new session every 5 s and sessions kept sending packets until the end of the experiment. At the beginning of measurement, the network interfaces were already up and the OLSRv2 was fully functional.

Figure 11 shows the received data rate, the expected data rate, and the delay jitter per session. Until about 35 s, the received data rate per session was as high as the expected receive data rate which is defined as 8,600 B per second, i.e. the

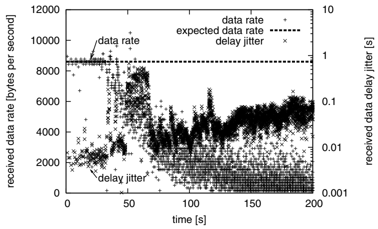


Fig. 11. Received data rate per session at the node D.

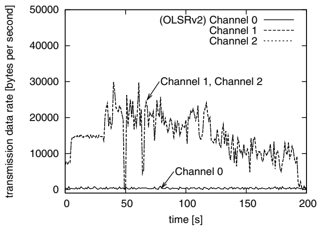


Fig. 12. Per channel transmission data rates at the node A.

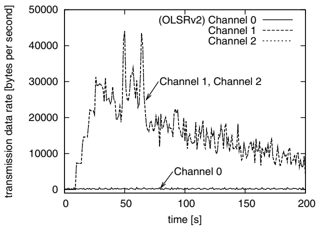


Fig. 13. Per channel transmission data rates at the node B.

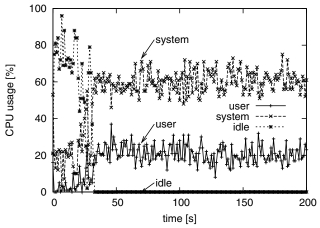


Fig. 14. Transition of CPU usage of the node S.

packet delivery ratio is higher than 98%. Although we could not measure the delay for inaccurate timer synchronization, the delay jitter was as small as 20 ms. We can see in Figures 12 and 13 that both intermediate nodes were used by the LR whereas the node A was the physical next hop node for the node D. The LR selected the node A as the intermediate node for the first two sessions and the node B for the next four sessions. Moreover, real-time channels were evenly used on a node by the SW. From 35 s, however, the received data rate per session suddenly deteriorated and the delay jitter exponentially increased. The reason for this can be explained by Figure 14, where the transition of CPU usage of the node S is depicted. The CPU idle ratio on the node S dropped to zero at 35 s and was kept zero since then. It implies that the drop of data transmission rate was caused by the full utilization of the poor CPU resource of the node S. We are still working to improve our modules to use CPU resource not so much.

VI. CONCLUSION

In this paper, we proposed a QoS-aware routing mechanism for real-time applications. By embedding bandwidth information in control messages of OLSRv2, a source node establishes the logical path satisfying application QoS requirements with a view of topology and bandwidth of the whole network. Through experiments on a simulator and a prototype, we confirmed that our mechanism could achieve the packet delivery ratio of about 95% at the end-to-end delay of about 10 ms in a grid network of 100 nodes by assigning three dedicated channels to real-time traffic and conducting logical routing. In addition, traffic was more evenly distributed over the whole network.

However, some issues still remain. We need to reduce the load on a node to avoid the system-dependent bottleneck. In addition, we need to conduct extensive evaluation including the scalability and comparison with other QoS routing protocols such as QOLSR [16].

REFERENCES

[1] J. Li, C. Blake, D. S. D. Couto, H. I. Lee, and R. Morris, "Capacity of ad hoc wireless networks," in *Proceedings of 7th Annual International Conference on Mobile Computing and Networking*, Jul. 2001, pp. 61–69.

[2] S. H. Shah, K. Chen, and K. Nahrstedt, "Available bandwidth estimation in IEEE 802.11-based wireless networks," in *Proceedings of 1st ISMA/CAIDA Workshop on Bandwidth Estimation (BEst 2003)*, Dec. 2003.

[3] L. Hanzo and R. Tafazolli, "A survey of QoS routing solutions for mobile ad hoc networks," *IEEE Communications Surveys and Tutorials*, vol. 9, no. 2, pp. 50–70, 2nd Quarter 2007.

[4] R. Guimaraes, J. Morillo, L. Cerda, J.-M. Barcelo, and J. Garcıa, "Quality of service for mobile ad-hoc networks: an overview," *Polytechnic University of Catalonia*, Jul. 2004.

[5] H. Badis, A. Munaretto, K. A. Agha, and G. Pujolle, "QoS for ad hoc networking based on multiple metrics: Bandwidth and delay," in *Proceedings of the 5th IFIP-TC6 International Conference on Mobile and Wireless Communications Networks*, Oct. 2003, pp. 15–18.

[6] S. Chakrabarti and A. Mishra, "QoS issues in ad hoc wireless networks," *Communications Magazine, IEEE*, vol. 39, no. 2, pp. 142–148, Feb. 2001.

[7] A. Adya, P. Bahl, J. Padhye, A. Wolman, and L. Zhou, "A multi-radio unification protocol for IEEE 802.11 wireless networks," in *Proceedings of the First International Conference on Broadband Networks (BROADNETS 2004)*, Jul. 2004, pp. 344–354.

[8] J. So and N. H. Vaidya, "Multi-channel MAC for ad hoc networks: handling multi-channel hidden terminals using a single transceiver," in *Proceedings of the 5th ACM international symposium on Mobile ad hoc networking and computing (MobiHoc 2004)*, May 2004, pp. 222–233.

[9] A. Raniwala and T. cker Chiueh, "Architecture and algorithms for an IEEE 802.11-based multi-channel wireless mesh network," in *Proceedings of 24th Annual Joint Conference of the IEEE Computer and Communications Societies*, vol. 3, Mar. 2005, pp. 2223–2234.

[10] P. Kyasanur and N. H. Vaidya, "Routing and link-layer protocols for multi-channel multi-interface ad hoc wireless networks," in *Proceedings of ACM SIGMOBILE Mobile Computing and Communications Review*, vol. 10, Jan. 2006, pp. 31–43.

[11] T. H. Clausen, C. M. Dearlove, and P. Jacquet, "The optimized link state routing protocol version 2 (OLSRv2)," *Mobile Ad hoc Networking (MANET) Internet-Draft*, Jan. 2008.

[12] K. Xu, K. Tang, R. Bagrodia, M. Gerla, and M. Bereschinsky, "Adaptive bandwidth management and QoS provisioning in large scale ad hoc networks," in *Proceedings of IEEE Military Communications Conference*, vol. 2, Oct. 2003, pp. 1018–1023.

[13] Scalable Network Technologies, Inc., "Creators of QualNet Network Simulator Software," http://www.scalable-networks.com/.

[14] Information and Communication Network Lab., Niigata Universitiy, "nOLSRv2," http://www.net.ie.niigata-u.ac.jp/~yowada/v2/.

[15] P. Kyasanur and N. H. Vaidya, "Routing and interface assignment in multi-channel multi-interface wireless networks," in *Proceedings of IEEE Wireless Communications and Networking Conference (WCNC 2005)*, vol. 4, Mar. 2005, pp. 2051–2056.

[16] H. Badis and K. A. Agha, "Quality of service for ad hoc optimized link state routing protocol (QOLSR)," *Mobile Ad hoc Networking (MANET) Internet-Draft*, Sep. 2007.