Efficient Routing Protocol to Select a High-Performance Route in Wireless Mesh Networks

Joo-Sang Youn, *Member, KIMICS*

***Abstract*—**In wireless mesh networks multi-rate technology environment, a mesh node can dynamically modify the data transmission rate on a particular link, in response to link distance, or more accurately, the perceived SNR ratio between neighbor nodes. In such networks, existing route selection schemes use a link quality metric. Thus, these schemes may easily result in the network being overloaded. In this paper, a new route metric is proposed; it considers both per-hop service delay and link quality at mesh nodes. In addition, the Load-Aware AODV (LA-AODV) protocol using the proposed metric is presented. The performance evaluation is performed by simulation using the OPNET simulator. It is demonstrated that the LA-AODV protocol outperforms the existing routing protocols using other existing route metrics in multi-rate WMN environment.

***Index Terms*—**Wireless Mesh Networks (WMNs), routing protocol, high-throughput, LA-AODV, multi-rate.

I. INTRODUCTION

As various wireless networks technology has evolved into next generation internet infrastructure, a key technology, wireless mesh networks, has emerged [1]. Wireless mesh networks (WMNs), where potentially-mobile mesh clients connect over a static multi-hop wireless network consisting of mesh routers, are viewed as a promising broadband access infrastructure for both urban and rural environments. It is also believed that the development of techniques for providing high-throughput and low-latency is important for many of the applications likely to be made possible by the introduction of WMNs. In WMNs, the relatively low spatial reuse of the single radio channel in multi-hop wireless environments, due to wireless interference, remains an impediment in the wide-spread adoption of WMN as the technology of access networks. Thus, as the number of nodes in single-channel wireless networks increases, it has been shown that network capacity decreases [2]. The multi-rate transmission scheme was introduced to overcome this problem. With the multi-rate transmission scheme, to obtain high-network capacity in multi-rate wireless mesh networks, it is necessary to find the result of the combined behavior of the medium access control protocol, routing protocol, and physical properties of the wireless network. In order to provide an understanding of how this combined behavior affects network throughput, several characteristics must be examined. Mesh nodes can utilize the flexibility of multi-rate transmissions in calculating appropriate range, throughput, and latency trade-off choices across a wide range of channel conditions. While this flexibility has traditionally been used in link conditions, it has recently been proposed for use in route metrics [8, 11]. However, these metrics have problems in congested networks, and a new route metric that considers traffic-load status in the network is necessary. This issue is described in section 3.

The main contributions of this paper can be summarized as follows. Researchers have proposed many route metrics to be used to discover a high throughput route between source and destination. However, these metrics do not consider queue delay in all mesh nodes over the end-to-end path. Hence, the problem of existing route metrics and an analysis of end-to-end service delay that affects routing decisions in multi-rate wireless mesh networks are presented. Based on this analysis, the general route cost for selecting an end-to-end route in such networks is derived. The traditional techniques used by existing ad hoc routing protocols select a route with minimum hop counter or the expected lowest cumulative link transmission time in terms of end-to-end throughput. This path tends to contain long range links that have low effective throughput and nodes with high queuing delay. However, in this paper a new route metric is proposed, to select routes with low end-to-end service latency. Therefore, the proposed route metric tends to

---

Manuscript received March 13, 2009 ; Revised May 18, 2009. Joo-Sang Youn is with Department of Multimedia Engineering, Dong-Eui University, Pusan, Korea (Tel: +82-51-890-1993, Email: jsyoun@deu.ac.kr)

avoid congested nodes and unreliable links when a routing protocol establishes high-performance end-to-end path. This results in an increase in overall network throughput.

The remainder of this paper is organized as follows. Section 2 describes previous work relating to multi-rate wireless mesh networks. Section 3 describes the motivation of our works, through analyzing the problems of using existing route metrics. Section 4 and 5 describe the new route metric and the proposed routing protocol, respectively. Section 6 summarizes the results of simulation studies. Section 7 presents the conclusion.

II. RELATE WORKS

Multi-rate transmission technologies, in the multi-rate wireless mesh model presented in this section, are based on the 802.11 standard [5]. The existing schemes for supporting multi-rate adaptation to dynamically switch data rates to match the channel conditions do this by leveraging information that has already been collected by the MAC and Physical layers. An alternate technique used in [4] performs active probing at the network layer in order to measure loss rates and estimate link speeds. However, this approach is unable to take advantage of the more advanced channel quality estimators, which are available at the lower layers. In addition, active probing techniques introduce additional network overhead proportional to the accuracy and rate at which they gather information.

III. MOTOVATION

In ad hoc networks with single-rate technology environments, early exiting protocols used a shortest path algorithms based on a hop-count metric to select effective paths However, even if the routing protocol that uses the minimum hop-count as a route metric are an excellent criterion in single-rate networks, where all links from the node to all its neighbor nodes are equivalent, they can not accurately capture the trade-off present in multi-rate wireless mesh networks. The problem of route discovery using the hop-count in such networks has previously been discussed in [8]. In [9], the Expected Transmission Count Metric (ETX) is proposed to select paths that minimize the expected number of transmissions required to deliver a packet from source to destination over single-rate links. To deal with multi-rate link environments through the ETX, in [10] the medium-time metric (MTM) is defined. The MTM essentially measures the time it takes to transmit a packet over multi-rate links. In [11], the Weighted7 Cumulative Expected Transmission Time (WCETT) is proposed as a route metric for route discovery in multi-radio multi-hop static wireless networks. The WCETT refers to the combination of the Expected Transmission Time (ETT) with ETX as a route metric. However, these metrics also take only link quality into account.

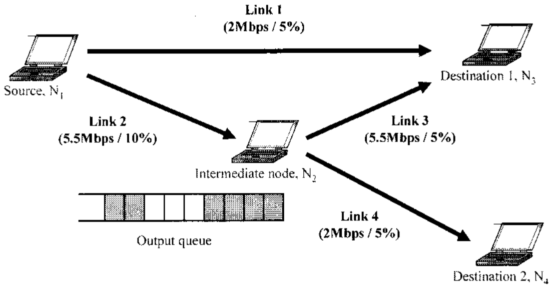


Fig. 1. Example of estimating the number of waiting packets. Output interface queue at the intermediate node has the 9 packets consisting of 6 packets waiting for transmission to the destination 1, and 3 packets waiting for transmission to the destination 2.

To understand the problem of the link quality based route metric, we analyze the problem through the topology shown in Fig. 1. It is assumed that all links are asymmetric. The transmission rate and loss rate of each link is also presented in Fig. 1. The link quality based route metric determines link cost as the following two parameters: (1) current bit rate in use, that is, the current modulation mode, and (2) current packet loss rate at the current bit rate for a data frame. It is assumed that N1 is the source node and wants to send a packet to N3. There are two possible paths: {N1, N3} and {N1, N2, N3}. When using the MTM, the link cost of link (1, 3), link (1, 2) and link (2, 3) is 4ms, 1.6ms and 1.5ms, respectively. Thus, the route scheme only using the link quality metric selects the path {N1, N2, N3} with the lowest cumulative value. However, if there are 9 packets, consisting of 6 packets waiting for transmission to destination node, N3, and 3 packets waiting for transmission to destination node, N4, in the output interface queue at intermediate node, the new packet that arrives at node N2 must wait in the queue for a considerably long period of time, resulting in significantly increased end-to-end delay on the path {N1, N2, N3}. It is believed that if the link bandwidth of the estimated path is admitted by any flow, the path {N1, N3} can be more effective than the path {N1, N2, N3} in terms of end-to-end performance. With the OPNET simulator [6], we perform the simulation with a simple topology shown in Fig. 1. In the simulation, the MAC layer protocol is IEEE 802.11 with a 550m carrier sensing range and multi-transmission rate according to link distance. The available rate on each link is also set from 1 Mbps to 11 Mbps. The simulation runs for 30s. The traffic pattern of each flow is designed as follows.

Table 1 Flow characteristics

Flow	Path	Packet size (bytes)	Packets per second	Bit rate (bps)
Flow1	$N_1 \rightarrow N_3$	512	50	204800
Flow2	$N_1 \rightarrow N_2 \rightarrow N_3$	512	50	204800
Flow3	$N_2 \rightarrow N_4$	1024	50	409600

As shown in the simulation results, since a link transmission time based route metric is not supported well in multi-rate wireless mesh networks, the throughput of flow 2, being mapped as higher throughput, actually decreases throughput by 50%. This is because the length of queue occupancy and queue delay of an output interface queue increase dramatically at the observed node (node N2), and causes the decrease in end-to-end throughput of flow 2. Therefore, even for the increased queue delay in the intermediate node, link quality based routing protocols cannot provide an accurate route with high throughput. This is due to the fact that in the existing route metric for wireless mesh networks, current performance such as per-hop queuing delay at each node is not considered at intermediate nodes along the end-to-end route. At 1 second, two flows (flow 1 and flow 2) on the source node are initiated toward two destination nodes, D1 and D2, respectively. Here, flow 1 uses the path {N1, N3} with high-link transmission time and flow 2 uses the path {N1, N2, N3} with low-link transmission time. Both flows consume 70 % of total channel capacity. As background traffic, flow 3 is initiated toward the destination node (N4) after 10 seconds. Fig. 2 show the time series traces for both queuing delay the source node, N1, and the intermediated node, N2, and Fig. 3 shows the end-to-end throughput of flow 1 and flow 2.

In Fig. 2, as expected, when using the link transmission time based route metric for a route discovery to search a route with high end-to-end throughput, flow 2 provides higher throughput than flow 2 until node N2 starts sending flow 3 to node N4. However, after starting sending flow 3, the throughput of flow 2 becomes less than that of flow 1. Thus, using only link transmission time based route discovery to provide high throughput can be too unstable, especially in a heavily loaded network. Fig. 3 shows that after flow 3 starts at 10 seconds, flow 2 results in up to 40% more end-to-end throughput than flow 1.

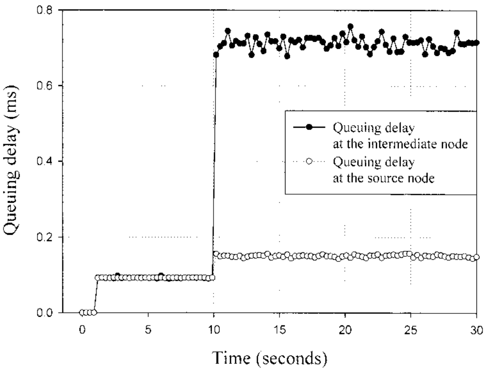


Fig. 2. Queuing delay at the source node and node N_2

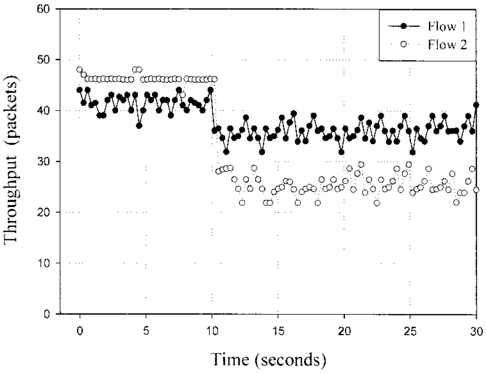


Fig. 3. Throughput of flow 1 and flow 2.

IV. NEW ROUTE SELECTION SCHEME

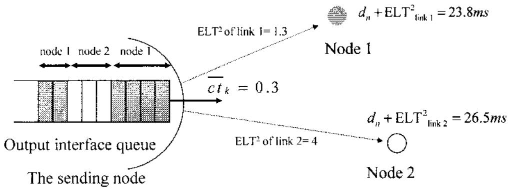
The network model of our work assumes that all mesh nodes are stationary and allow multi-rate operation. Also, each link operates at a different transmission rate according to the SNR ratio between nodes.

As discussed in the previous section, existing route metrics used to establish the end-to-end path are not efficient in multi-rate wireless mesh networks because they only measure the link transmission time, based on link quality and the reliability of a link. However, the proposed route metric takes the per-hop service delay, mean contention delay and link transmission time at the MAC layer into account. The per-hop service delay is defined as the time delay when a new arrival packet stays within the output queue before it is serviced by a wireless link. This value is determined with the number of packets waiting for transmission per link in the output interface queue and the link transmission time per link. In particular, with the predicted per-hop service delay of each node, more pertinent information of end-to-end service delay provided by the established end-to-end path can be created, than that of existing strategies.

In this works, with the per-hop service delay and link transmission time per link, a new route metric for route discovery is defined to select single-hop or multi-hop paths targeted for multi-rate WMNs. In addition, a new routing protocol using the proposed route metric is proposed to be used in such networks. In the proposed routing protocol, through the Hello message in AODV, the link state information generated by each node is transmitted to all neighbor nodes, this is used to estimate the quality of the link pair between neighbor nodes. A node must first calculate the link quality between neighbor nodes (mesh nodes) in mesh networks. The cost function for establishing a route combines two route costs, the network load-aware and link quality-aware route cost. The metric of each link also reflects the amount of channel resources consumed by transmitting the frame over a particular link. In the following subsections more details are provided, illustrating the proposed metric in detail.

A. ESDM: Expected end-to-end Service Delay Metric

The novel route metric, called the Expected end-to-end Service Delay Metric (ESDM), is proposed to allow any routing protocol to select a route with the lowest end-to-end service latency. The ESDM is defined as "network load-aware and link quality-aware end-to-end service delay", which is the end-to-end delay spent in transmitting a packet from source to destination. In order to estimate the ESDM value, the Expected Link Transmission Time (ELT2), which is the link transmission time to successfully transmit a packet on each link, is used initially. The ELT2 is similar to the MTM [8]. The MTM assigns a weight to each link, equal to the expected amount of medium-time it would take, by successfully sending a packet of fixed size S on each link in the network. The value depends on the link bandwidth and its reliability, which is related to the packet loss rate of a link. The difference between the MTM and ELT2 is the scheme which estimates each parameter to be calculated. With the estimated link transmission value, the ESDM is determined through multiplying the ELT2 plus the mean contention delay by the mean number of waiting packets in the output interface queue at each mesh node. It is assumed that each node is serviced with a first-in-first-out (FIFO) interface queue.



Destinations	The number of waiting packet	Link quality, ELT², (ms)	The mean contention delay (ms)	Per-hop service delay (ms)
Node 1	6	1.3	0.3	22.5
Node 2	3	4		

Fig. 4. Example of calculating per-hop service delay in the sending node. Output queue at the sending node has the 9 packets, consisting of 6 packets waiting for transmission to node 1 and 3 packets waiting for transmission to neighbor node 2.

Let d_n be the expected time spent in transmitting all packets waiting for transmission at node n, called the per-hop service delay. The per-hop service delay, d n, should take the expected service delay of any node such as queue delay, contention delay of an interface and transmission time of a link between node n and any neighbor node in the transmission range into account. With a given d_n, the ESDM of path, p, with h-hops, between source and destination, is estimated as follows:

$$\mathrm{ESDM}\ (p) = \sum_{n=1}^{h} \left(d_n + ELT^2_{(1-h),h} \right) \tag{1}$$

Where $\mathrm{ELT}^2_{(1\text{-h}),\text{h}}$ is the expected link transmission time on link i between 1-h and h. As a result, route selection using the ESDM finds the path with the lowest end-to-end service latency in terms of current traffic-load status in the network. In addition, a routing protocol using this metric can simultaneously perform traffic load balancing.

B. Per-hop Service Delay

Per-hop service delay is determined by the number of waiting packets and link transmission time per link between the node and its neighbor nodes. x neighbor nodes in the transmission range of node n is assumed. d_n is estimated as follows:

$$d_n = \sum_{i=1}^{x} \left(\overline{N}_i \times \left(\overline{ct}_k + \mathrm{ELT}^2{}_i \right) \right) \tag{2}$$

where $\overline{N}_i$ is the mean number of packets waiting for transmission to any neighbor node through link i, and is the mean contention delay at node n. Fig. 4 presents an example of calculating the per-hop service delay.

In order to estimate per-hop service delay, we have to estimate the four types of value which are the number of waiting packet per link, the mean contention delay of node n spent in the head-of-line packet to be transmitted to the physical layer, the expected link transmission time per link and the reliability per link.

1) The mean number of waiting packets

The mean number of waiting packets, $\overline{N}_i$, is estimated by the number of waiting data packets that use link i in the output interface queue. Thus, $\overline{N}_i$ is estimated per link. The link information used by an in-coming packet can be known through the value of the next hop (address) in the packet header before sending to the link layer. $\overline{N}_i$ is estimated through measuring the number of both queued packets and dequeued packets. The number of dequeued packets includes the number of packets successfully trans-mitted as well as the number of packets dropped due to exceeding the retransmission counter limit. The time-sliding window (TSW) estimator [3] is used to smooth the measured value. The TSW estimator is extremely simple. The TSW estimator operates as follows:

Upon each packet arrival,

$$\overline{N}_i = \frac{\alpha \overline{N}_i + 1}{T_{\mathrm{now}} - T + \alpha} \tag{3}$$

Upon each packet departure,

$$\overline{N}_i = \frac{\alpha \overline{N}_i - 1}{T_{\mathrm{now}} - T + \alpha} \tag{4}$$

where α is the time window length, which is measured in units of time. T_{now} is the time when a current packet is arrived or dropped and T is the time when a previous packet is arrived or dropped, respectively. Thus, $\overline{N}_i$ is updated each time a packet arrives or departs

2) The mean contention delay

The contention delay is defined as the time consumed for the head-of-line packet to be transmitted to the physical layer, and is used to estimate the overhead of the transmission in the contending area. The contention delay includes the period for successful RTS/CTS exchange, if this exchange is used for that packet. Similarly, if the initial transmission of the packet is delayed due to one or more collisions generated by other nodes within the transmission range, multiple numbers of back-off periods may also be included. The mean contention delay, $\overline{ct}_k$, is estimated as the running average contention delay of all packets belonging to the k-th packet transmitted at a node. The weighted moving average is used to smooth the estimated value. Therefore, the mean contention delay is updated as follows:

$$\overline{ct}_k = \beta \overline{ct}_{k-1} + (1-\beta) n_k \tag{5}$$

where parameter β is the weighting factor and β < 1, whose optimum value has been computed to be 0.7, following a comprehensive simulation under traffic conditions, and n_k is the contention delay achieved by the k-th packet. The initial vale, ct_0, is set to a value adding the slot-time of DIFS to the slot-time of the middle value between CW_{min} and CW_{max}. Moreover, if a node uses multi-radio, this value is estimated per radio.

3) The expected link transmission time

As defined above, $ELT^2_i(n)$ is first defined as the link transmission time spent by sending a packet over link i at node n. This measure is approximated and designed for ease in implementation and interoperability. The $ELT^2_i(n)$ of each link at node n is calculated as:

$$\mathrm{ELT}^2{}_i(n) = \left[O_{control} + \frac{S_p}{r} \right] \times \frac{1}{1 - R_i} \tag{6}$$

where the input parameters r and R_i are the bit rate in Mbs-1 and the frame loss rate of link i for frame size Sp respectively. The rate r is dependent on local implementation of rate adaptation between node n and its neighbor node and represents the rate at which the node would transmit a frame of standard size (Sp), based on current conditions. R_i is a local implementation and is intended to estimate the R_i for transmissions of standard size frames (Sp) at the current transmit bit rate used to transmit frames of size (r). The overhead of control is defined in [3].

4) Reliability of each link

The reliability of each link is estimated through the packet drop number. Here, the type of packet drop is divided into two types, control message drop and data drop. Only the accounting data drop is used to estimate the reliability of a link. The packet drop occurs in the output queue of a specific interface i and on a specific wireless link. However, in this paper, only the packet drop on a wireless link, called a collision drop, is taken into account. In the case of a collision drop, a packet is dropped by the sending node, when the MAC cannot receive any ACKs for the (re) transmissions of those packets due to consistently failing retransmissions during the MAC's retransmission count, 7, for the data packet. For convenience, the reliability, R_i, is computed in a straightforward manner as follows:

Interface ID	**Link ID (own node ID-destination ID)**	**The transmission rate**	**The reliability**	**Timestamp**
Interface 1	Link 1-2	r bit rate in Mbs^{-1}	Drop rate of link 1-2	Time
	Link 1-3	r bit rate in Mbs^{-1}	Drop rate of link 1-3	Time
	⋮	⋮	⋮	⋮
Interface 2	Link ID 1-2	r bit rate in Mbs^{-1}	Drop rate of link 1-2	Time
	Link ID 1-3	r bit rate in Mbs^{-1}	Drop rate of link 1-3	Time
	⋮	⋮	⋮	⋮
⋮		⋮	⋮	⋮

Fig. 5. Hello message structure. The bold item in the first row is the node's own interface ID information. The following rows are the neighbor node's information.

$$R_i = \frac{D_i}{L_i} \tag{7}$$

where D_i and L_i is the cumulative number of dropped packets and the cumulative number of transmitted packets on link i at node n, respectively.

V. ROUTING PROTOCOL USING ESDM

In this section, a routing protocol using the expected end-to-end service delay metric is proposed for WMNs with multi-rate multi-interface environments. This routing protocol is called the Load-Aware AODV (LA-AODV) protocol. The LA-AODV protocol is a modified version of AODV [5]. This has been modified extensively to improve performance, and to support the ESDM and multi-radio adaptation.

The LA-AODV protocol is based on basic AODV functionality, including route discovery and route maintenance. In addition, this protocol includes new mechanisms for ESDM maintenance. We assume that the link-quality is not symmetric. In considering link pairs between node a and node b, the transmission rate of the link pairs is the same, but the loss rate between the two links is different, indicating that the reliability of two links between node a and node b is different. First, in the LA-AODV protocol, route discovery uses ESDM. When a node receives a RREQ message, including both a source and a destination address, the node appends both its own address and the per-hop service delay in a RREQ message that is sent to neighbor nodes, it also appends the expected link transmission time for the link over which the RREQ message arrived. When a node sends a route reply, the reply carries back the complete list of per-hop service delay and the expected link transmission time for the route.

The LA-AODV protocol uses a proactive mechanism to maintain the table of link metrics for the link transmission rate and the reliability of all neighbor nodes. In order to obtain information regarding the transmission rate between a node and its neighbor nodes, and update the table of link metrics, the Hello message in the AODV protocol is used. In using the hello message, the information of the transmission rate of link i is appended onto the standard Hello message. In this paper, the algorithm for multi-rate decisions between nodes is available in [7]. The hello message structure is shown in Fig. 5. When a hello message is received, a node updates the link information of neighbor node transmitting the hello message in the table of link metrics.

VI. PERFORMANCE EVALUATION

To illustrate the effectiveness of the ESDM route metric, with comprehensive simulations, the LA-AODV protocol is evaluated and compared with other routing protocols based on the Min-HOP(MHOP) and MTM metrics. These routing protocols represent the performance of the routing discovery schemes based on MHOP route selection and minimum link transmission time route selection. For the simulations, we consider three scenarios; the first is a fully connected topology used to study the effects of node density, networks load, channel conditions, and node location, the second is a large topology of multi-rate ad hoc networks consisting of single-interface nodes and the last is a large topology which is the networks consisting of multi-interface nodes. All radios at all nodes use automatic multi-rate control. With automatic multi-rate control, the available rate between neighbor nodes can be set from 6 Mbps to 54 Mbps. RTS and CTS are both enabled. Each node is arranged such that several multi-hop routes to the destination are available. All topologies are random topologies. Simulations are conducted using the OPNET v11.5 simulator [12]. In the simulations, the TCP throughput, according to amount of traffic load in the network, and the distribution of path length, are studied.

A. Fully Connected Topology

In this scenario, the performance of the ESDM is studied using fully connected topologies in which all nodes are within radio range of each other. In these experiments, the number of TCP flows between a source-destination pair of nodes varies from 5 to 25 and there are 40 static mesh nodes. Each flow randomly chooses the nodes as sources and destinations in the networks. In this simulation, we can expect that, in the case of the MHOP metric, a routing protocol mostly selects 1-hop paths, regardless of the re-liability of a link. However, in the case of the MTM, a routing protocol selects a single-hop or multi-hop path according to the quality of each link and the ESDM based routing protocol selects a single-hop or multi-hop path according to traffic load and the quality of each link in the networks.

The simulation continues for 200s. The metric used in measuring the metric' performance is the average end-to-end throughput. The simulation results are presented in Table. 2. It has been proven from these results that the performance of the proposed LA-AODV protocol outperforms that of existing routing protocols using other metrics (MTM and MHOP) in terms of end-to-end throughput. As expected, in simulation with low load (5 TCP flows), throughput of both the MTM and MHOP is identical. This is be-cause both metrics almost select the same path and the current level of traffic load in the network topology does not result in saturation. However, in overall situations (in the case of 25 TCP flows), an improvement in end-to-end throughput (up to 200%) using the MTM based routing protocol compared with the MHOP based routing protocol is revealed. The improvement in end-to-end throughput of the LA-AODV protocol using the ESDM, compared with other metric based routing protocols, is shown in the simulation results. In particular, as the number of each flow increases, the full potential of the ESDM is revealed. The ESDM based path yields more than three times (up to 300%) the throughput of the MHOP based path and twice (up to 200%) the throughput of the MTM based path in higher traffic load conditions. This is because as queue delay increases at relay nodes, the LA-AODV protocol can select paths that consist of both low queue delay and high link quality. It is verified that using the ESDM almost provides optimal end-to-end throughput service.

Table 2. Performance of each service

Number of traffic flows	Average end-to-end throughput (Mbps)		
	MHOP	MTM	ESDM
5	10.35	12.88	13.56
10	7.46	9.56	12.36
15	2.78	4.57	8.45
20	1.46	3.38	5.58
25	0.54	2.85	4.78

B. Throughput in Multi-rate multi-interface Wireless Mesh Networks

To describe the performance of the ESDM in multi-rate multi-interface mesh networks, in this simulation, we assume that all nodes have two radios, which are composed of 802.11a and 802.11g radios. The 802.11a radio operates on channel 36 and the 802.11g radio operates on channel 10. Both radios use auto-rate operation. The available rate on both radios is also set from 6 Mbps to 54 Mbps. The simulation environments are the same as that of previous scenarios. The simulation results in terms of the average throughput of multi-interface case are presented in table. 3. As expected, the simulation results demonstrate an improvement in average TCP throughput of the LA-AODV protocol based on the ESDM, as compared with other metrics based routing protocols. In particular, as the number of each TCP flow increases, the full potential of the ESDM is adapted in multi-radio mesh environments. The average TCP throughput using the our protocol is up to 300% greater than the MHOP based routing protocol and up to 200% greater than the MTM based routing protocol in higher traffic conditions. Therefore, the ESDM consistently selects the highest throughput path available in the networks. It is also verified that the ESDM is close to providing high end-to-end throughput in multi-interface environments. The distribution of the path length of 40 TCP flows in such environments is illustrated in Fig. 6.

Table 3. The average throughput of all TCP flows in multi-rate multi-interface mesh networks

Number of TCP flows	MHOP	MTM	ESDM
5	19.85	19.43	20.58
10	10.67	14.47	17.67
20	4.56	6.56	13.47
30	1.46	3.36	5.67
40	0.78	1.89	4.13

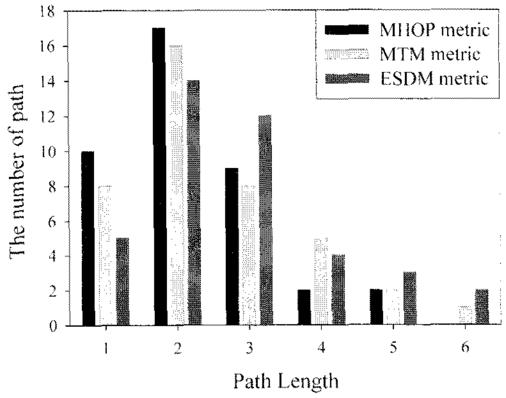


Fig. 6. The distribution of path length. Results of 40 TCP flows in multi-rate multi-interface mesh networks

The MTM usually selects 3-hop and 4-hop paths according to link quality. Longer paths yield increased throughput than shorter paths because the MTM path utilizes the extra medium time available in long paths. However, the ESDM usually selects 2-hop, 3-hop and 4-hop paths. This also means that load-balancing of traffic works well in multi-interface environments. When using ESDM, the selected paths tend to contain long range links that have effective throughput and a low packet drop rate, as compared with the MTM metric. These results demonstrate that the ESDM can select paths with high throughput in multi-rate multi-interface environments.

VII. CONCLUSION

In this work, it is demonstrated that existing route metrics only consider link quality as effective throughput in WMNs. In addition, they tend to increase overall network congestion. Thus the application has no way for improved performance under given network traffic conditions. In this paper, the ESDM is presented. This metric is proportional to the time taken to transmit a packet on a given link, including both queuing delay and contention delay at relay nodes. Also, this metric selects paths that have the highest effective throughput. In addition, a new routing protocol using the proposed metric, called the network load-aware AODV protocol, is presented. The simulation results reveal that the ESDM achieves significantly higher throughput and lower delay than alternative metrics. Up to 2.5 times more TCP throughput than with the MHOP or MTM metrics, is observed. The results demonstrate the importance of using per-hop service delay for selecting an end-to-end path with high throughput, and underscore the need for a route scheme that considers the current status of network load, in order to efficiently and accurately estimate end-to-end service latency.

ACKNOWLEDGMENT

This work was supported by Dong-Eui University Grant. (No. 2008AA202).

REFERENCES

[1] I. Akyildiz, X. Wnag and W. Wang, “Wireless mesh networks: a survey,” Proc. computer networks, Elsevier Science, no. 47, pp. 445-487, Jan. 2005.

[2] P. Gupta and P. R. Kumar, “The capacity of wireless networks,” Proc. IEEE Transactions on Information Theory, IT-46(2), pp 388 -404, March 2000.

[3] D. Clark and W. Fang, “Explicit allocation of best-effort packet delivery service, Networking,” IEEE/ACM Transactions on, Vol 6, issue 4, pp. 362-373, Aug. 1998.

[4] A. Adya, P. Bahl, J. Padhye, A. Wolman, and L. Zhou, “A multi-radio unification protocol for IEEE 802.11 wireless networks,” Proc. BroadNets, 2004.

[5] C. E. Perkins and E. M. Royer, Ad hoc Networking, Ad hoc On-Demand Distance Vector Routing, Addison-Wesley, 2000.

[6] The OPNET Modeler, http://www.opnet.com/products/modeler/home.html.

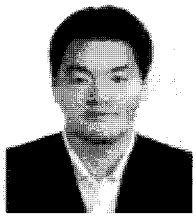
[7] B. Sadeghi, V. Kanodia, A. Sabharwal, and E. Knightly, “Opportunistic media access for multi-rate ad hoc networks,” Proc. MobiCom 02, pp 24-35, September 2002.

[8] B. Awerbuch, D. Holmer, and H. Rubens, “High throughput route selection in multi-rate ad hoc wireless networks,” Lecture Notes in Computer Science 2928, pp 253-270, 2004.

[9] D. S. J. D. Couto, D. Aguayo, J. Bicket, and R. Morris, “A high-throughput path metric for multi-hop wireless networks,” Proc. Wireless Networks, Vol 11, Issue 4, pp 419-434, July 2005.

[10] B. Awerbuch, D. Holmer, and H. Rubens, “High throughput route selection in multi-rate ad hoc wireless networks,” Proc. Wireless On-Demand Network Systems (WONS), January 2004.

[11] R. Draves, J. Padhye, and B. Zill, “Routing in multi-radio, multi-hop wireless mesh networks,” Proc. MobiCom 04, pp. 114-128, September 2004.



Joo-Sang Youn received the B.S., M.S. and Ph.D. degree in the Department of Electronics and Computer Engineering from Korea University in 2001, 2003 and 2008 respectively. His research interests include the QoS-aware systems, MAC protocol and routing protocol in mobile ad hoc/sensor networks and wireless network architecture for future Internet.