6-2009

Interference-aware routing protocol in multi-radio wireless mesh networks

Byoungheon SHIN

Yangwoo KO

Jisun AN
Singapore Management University, jisunan@smu.edu.sg

Dongman LEE

Interference-Aware Routing Protocol in Multi-Radio Wireless Mesh Networks

Byoungheon Shin Yangwoo Ko Jisun An Dongman Lee
Korea Advanced Institute of Science and Technology
Daejeon, Korea
{bhshin, yko, jisun, dlee}@kaist.ac.kr

ABSTRACT
Utilization of multiple radio interfaces increases throughput of wireless networks. Existing work proposes a multi-radio routing protocol exploiting link quality and channel diversity of a path. While an established path is deteriorated by interferences incurred by any changes in a network, and existing work does not detect the deterioration. In this paper, we propose an interference-aware multi-radio routing protocol detecting and resolving dynamic path deterioration in wireless mesh networks.

Categories and Subject Descriptors
C.2.2 [**Network Protocols**]: Routing protocols

Keywords
Multi-radio, wireless mesh networks, interference awareness

1. INTRODUCTION
Multiple radio interfaces give wireless networks a new opportunity to select radio-diverse multi-hop paths. Though hop count of a radio-diverse path is same as a single radio path, it provides higher throughput since it can significantly reduce packet drops by avoiding interferences [1].

Unlike single-radio cases, a multi-radio wireless network requires additional steps for routing: each node first has to know radios utilized by its neighbors, and it has to select an appropriate radio to reduce interference. Considering these factors, a multi-radio routing protocol selects a path that is best with respect to its routing metrics.

Several approaches have been proposed to increase throughput and scalability using multiple radio interfaces in wireless mesh networks (WMNs). Among these approaches, MR-LQSR [1] is one of outstanding multi-radio routing protocols. It extends an existing routing protocol in mobile ad-hoc networks (MANETs), Dynamic Source Routing (DSR), and selects paths considering both the Expected Transmission Time (ETT) and channel diversity of an end-to-end path. Since ETT and channel diversity vary due to several factors such as environmental obstructions and node status, a selected path can easily be deteriorated. One of the most critical factors leading to link deterioration is unexpected interference. Even though a new communication session exchanges packets across an existing path and incurs lots of interferences with one of radios included in the path, MR-LQSR would use the deteriorated path until it restarts a route discovery. Since the route discovery is triggered only when the source node receives a route error message due to a link failure, it may take quite long time for existing work to adapt to link deterioration.

In this paper, we propose an interference-aware multi-radio routing protocol that dynamically reconstructs a source-initiated path when radical link deterioration happens. It is based on MR-LQSR, but we add several new features to make it adaptive to interferences. We add a new data structure, neighbor ETT table, used for proactively detecting path deterioration. After a source-initiated route is generated, each intermediate node along the path periodically monitors the link quality of the link to its next-hop. It notifies deteriorated situations to the source node whenever its link gets significantly interfered and the source-initiated path should be reconstructed. The notification is delivered as an extension of RREP message.

The rest of this paper is organized as follows: In section 2, we introduce existing routing protocols utilizing multiple interfaces. Design considerations of our routing protocol are given in section 3. We describe details of the proposed protocol in section 4, and show simulation results from preliminary implementation.

2. RELATED WORK
Several approaches have handled how to utilize multiple radio interfaces in wireless networks.

Richard Draves et al. proposed Multi-Radio Link Quality Source Routing (MR-LQSR) protocol [1] utilizing a routing metric for measuring the quality of multi-radio paths. Each link calculates the Expected Transmission Time (ETT) with the Expected Transmission Count (ETX) [5], bandwidth, and packet loss. Let p be the packet loss rate combining both forward and reverse packet loss rate. Then the ETX is calculated as follows:

$$\mathrm{ETX} = \frac{1}{1-p}$$

To obtain a transmission time for sending a packet, Draves et al. considered the link bandwidth.

If the bandwidth is denoted by B (bps), and the packet size is denoted by S (e.g. 1024 bytes), ETT is calculated as:

$$\mathrm{ETT} = \mathrm{ETX} * \frac{S}{B}$$

CFI'09, June 17-19, 2009 Seoul, Korea.

This ETT value is used to compute the Weighted Cumulative Expected Transmission Time (WCETT). It is a weighted sum of end-to-end delay and the channel diversity of a path both of which are derived by ETT. In MR-LQSR, source nodes use WCETT as a routing metric selecting a path with the smallest WCETT. The detail of ETT and WCETT derivation is described in [1].

L. Villasenor-Gonzalez et al. proposed the Hierarchical OLSR (HOLSR) [2] that is derived from Optimized Link State Routing (OLSR) [3]. HOLSR organizes a hierarchy based on topology levels of nodes. Nodes with limited resource belong to lower level, and high-capacity nodes with multiple network interfaces are in higher levels. Gonzalez et al. proposed a hierarchy with three topology levels. Only level 3 nodes maintain the full topology of the network so that control overhead is much less than the flat OLSR. However, if a cluster head fails, communication within the cluster may be disturbed until a new cluster head is selected. This dependency on particular nodes is not desirable for MANETs.

Asad Pirzada et al. proposed the Multi-Radio AODV (AODV-MR) [4]. The routing table of AODV-MR contains the "network interface number" field to distinguish radios. During a route discovery, intermediate nodes forward Route Request (RREQ) over all interfaces except the one by which the RREQ is previously received. In this way, a multi-hop path contains a sequence of contiguously non-overlapping radios. However, AODV-MR focuses on the hop count and radio diversity on a path without considering the link quality.

3. DESIGN CONSIDERATION

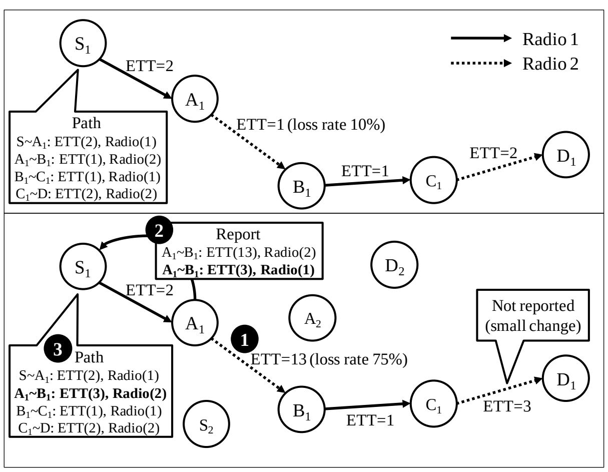

Figure 1. Detection of path deterioration and reconstruction of the path in multi-radio MANETs

3.1 Detection of Path Deterioration

Once MR-LQSR discovers a route, it does not utilize dynamic changes in quality of each link. However, we need a procedure to recognize that a path is deteriorated to reconstruct the path. Figure 1 shows a scenario that the intermediate node A_1 recognizes and reports the situation of path deterioration.

To determine deterioration of a path, a change in ETT should be compared with a threshold. The threshold should be carefully set considering its effect on the path quality (WCETT). If the path quality does not improve enough, small deteriorations needs not be reported. The node C_1 in Figure 1 shows an example of this case.

In addition, if a problem on a link is so temporary that its link quality recovers in a moment, the intermediate node needs not report this temporary deterioration. Thus, we need an appropriate level of tolerance to endure the short term deterioration.

3.2 Path Reconstruction

In addition to the link deterioration detection, we need a path reconstruction procedure which is triggered by intermediate nodes along a path. A simple way of reconstruction is to make the source node restart a route discovery. This approach is not desirable because it contains a flooding process to retrieve radios and link quality values of all possible paths generating high overhead. Instead, a cost-effective scheme for path reconstruction is required to solve this problem. If a link of a path causes a problem, only the link can be resolved rather than discovering a whole path. An example of the partial reconstruction is shown in Figure 2.

The concrete design of our proposed routing protocol is described in section 4.

4. PROPOSED SCHEME

Our routing protocol is based on MR-LQSR which optimizes DSR protocol. Thus, we utilize the link quality and the radio diversity factor used in MR-LQSR for our routing metrics as well. In addition, we add a new beaconing concept for detecting path deterioration.

4.1 Periodic Beaconing

In each node, ETT values and radios of its neighbors are obtained by a periodic beaconing. In MR-LQSR, the latest ETT can be calculated by measuring the number of beaconing messages broadcasted by each node every one second and the bandwidth using probe packet pairs [1]. We also set the beaconing interval to one second. For efficient management, each node maintains a table called the neighbor ETT table as shown in Table 1, and its detail is described in section 4.2. It stores the most recent ETT value of each neighbor, and the ETT value is updated whenever it receives a beaconing message from a neighbor and finishes calculating the new ETT. Before overwriting it, the node calculates a difference between the currently measured ETT and the last one recorded in the table. If the difference exceeds a threshold, the link is considered as deteriorated. And if the difference is a negative value and smaller than a negative threshold, the link is considered as improved.

Table 1. Neighbor ETT Table

Neighbor ID	ETT	Radio	isLinkUsed	Src ID (rev-next-hop, timestamp)
2	11	1	N	
4	1	1	Y	0 (0, 1242037723) , 8 (0, 1242037741)
4	7	2	N	
5	3	2	Y	1 (9, 1242037758)
…	…	…	…	…

The ETT is mostly affected by the loss rate of a link. It exponentially increases as the loss rate linearly increases. For 10Mbps radio with 1024 byte packet size, ETT increases by 4.2 milliseconds as the loss rate changes from 5% to 60%. Thus in our protocol, we set the threshold for determining deterioration as 4 millisecond for 10Mbps radio.

4.2 The Neighbor ETT Table

The neighbor ETT table is the core component for detecting path deterioration in our routing protocol. The latest ETT for every radio available in each neighbor node is stored and updated. After a source node initiates a route, each intermediate node updates "isLinkUsed" field of the link belonging to the path as "Y," meaning that the link is used by at least one source route. After starting transmission, source node ID, next-hop ID of the reverse path to the source, and the timestamp of the last successful transmission of a data packet are recorded in the "Src ID" field of the entry.

The timestamp in "Src ID" field is used for checking whether the link is recently used. If no data packet is passed through the link for a long time, the source node might finish the transmission or change the route using the other links. In this case, although the link is detected as deteriorated, the node needs not notify the situation to the source node. Thus, when a node detects deterioration on a link with "Y" value in "isLinkUsed" field, it first compares the recorded timestamp with the current one. If the difference between the two timestamps is upper 30 seconds, the link is considered as expired. Then the node updates "isLinkUsed" field as "N," deletes the source route information in "Src ID" field, and aborts notifying deteriorated situation to the source node. On the other hand, if the difference is under 30 seconds, the deterioration is notified to the source node. The way of notification is described in section 4.3.

In MR-LQSR, a loss rate of a link is measured by counting the number of received beaconing messages during a sliding time window (ten seconds) [1]. In our routing protocol, when the node no longer receives beaconing messages from a neighbor node for ten seconds, the neighbor node is regarded as disappeared due to any reason, and its entries are deleted in the neighbor ETT table.

4.3 Reporting Path Deterioration

When the link is detected as deteriorated (or improved), the node determines whether this situation should be notified or not by checking "isLinkUsed" and "Src ID" field, as explained in the earlier section. This notification message is called a "report." Report messages generated by intermediate nodes are a form of an RREP message. A report message contains a list of ETTs for all radios available on the link and is used to notify a source node that the link is interfered or gets better. Because DSR provides gratuitous RREP messages that do not require any RREQ messages, we utilize that format, but it is not related with the usage of the promiscuous mode in DSR [6].

After detecting path deterioration, the intermediate node sends a report to the next-hop on the reverse path by checking "Src ID" field of the table. The reason of maintaining the next-hop of the reverse path is because our routing protocol is a kind of source routing protocols. There is no way for the intermediate node to send some packets through the reverse path without receiving any packet that contains a source-initiated route.

Due to several factors such as environmental situations, systematic problems, and some abnormal application behaviors, a link may be temporarily deteriorated for a short time and recover the previous state. Then the node would rather leave the link until the temporary deterioration disappears than detect and report to the source node at once. To endure this short term deterioration, an intermediate node does not immediately send a report even if the change in ETT exceeds the threshold. It just forwards packets through the *potentially* deteriorated link for a specified time interval. If the transmission continues after the time, it considers the link as *obviously* deteriorated and sends a report to the source node. Small messages can be immediately delivered to a destination, but relatively bigger-sized data may be transmitted for a while (more than several seconds). Thus in our routing protocol, the enduring time interval is set to five seconds.

After sending a report, data packets from the source node might still pass through the deteriorated link. In this case, the source node might have determined this path is still the best one among others. Therefore, each node needs not send the same report twice or more times.

4.4 Path Reconstruction

In our routing protocol, a source node basically stores all RREP messages because each RREP contains all ETT values of links along the reverse path, and it can be used later for reconstructing a path. After a path is selected, path reconstruction is not performed until at least one report message is delivered. A path reconstruction procedure is thus triggered on demand by intermediate nodes. Whenever the source node receives a report, it replaces the previously stored RREP message of the same path and re-compares WCETT metrics to select a better path.

A source node of a path may act as an intermediate node in the other paths. Since it may forward report messages of which the destination is the other source node, those messages can be overheard and utilized in path reconstruction without directly receiving report messages from intermediate nodes on its source route.

In MR-LQSR, the WCETT value of a path can be cumulatively calculated by each intermediate node during the RREP forwarding as the hop count metric is cumulatively added in DSR. However, our protocol lets the source node calculate WCETT values using individual ETT values of all links. Because the hop count of a path cannot be very large in practical situations, this increase in size of RREP packet may not be a burden. In addition, intermediate nodes can benefit from this abundant knowledge of the source node by sending reports considering only its link to the next-hop on the path.

The source node restarts route discovery when it recognizes a severe deterioration over the whole path. When two-thirds of links are deteriorated for a path with more than 3 hops, the path is considered as severely deteriorated.

Since our routing protocol allows a source node to remember multiple paths to a destination maintaining RREP messages received during the previous route discovery, path can be reconstructed without performing route discovery even in case of link failure. Instead, the source node needs to check whether the remembered paths are out-of-date. One report message may affect multiple candidate paths stored in the source node. Then the partially updated paths are maintained removing the others. If there is no candidate paths remembered, or the candidate path is also unreachable to the destination, the source node performs the route discovery again.

5. EXPERIMENTAL RESULTS

To verify our preliminary idea, we perform a brief simulation with the topology similar with the one in Figure 1. Five nodes with 11Mbps 802.11 radio generate a multi-hop channel-diverse path and transfers FTP data, and the other nodes S_2 and A_2 generate traffic using the same radio of the intermediate node B_1. The main purpose of this experiment is to show the impact of radical interference and the benefit of interference awareness.

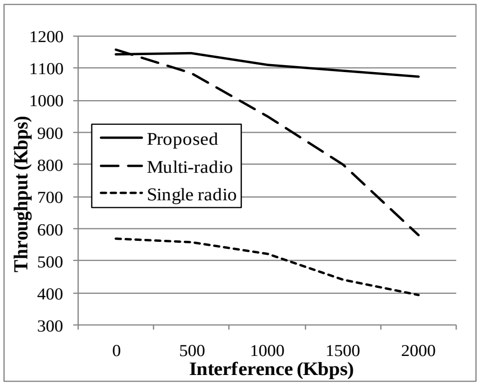

Figure 2. Throughput changes for interference levels

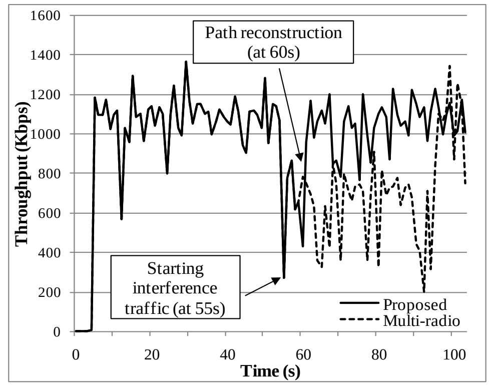

Figure 3. Throughput changes for 1Mbps interference traffic on a link

Figure 2 shows the impact of interference on each scheme, and Figure 3 shows the throughput changes for the interference traffic generation. We measured end-to-end throughput of a single radio routing (denoted by Single radio), a multi-radio routing without interference awareness (denoted by Multi-radio), and our proposed routing protocol considering radical interference (denoted by Proposed) with various interference levels and the result is shown in Figure 2. For evaluating interference awareness, we compared our interference-aware routing protocol with the Multi-radio scheme described in Figure 2. After generating 1Mbps CBR traffic as interference, our proposed scheme detected the path deterioration and changed the channel of the interfered link. As shown in figure 3, proactive detection of path deterioration occurred by interference is crucial in multi-radio wireless networks. Since our preliminary design of routing protocol in this experiment detects and resolves path deterioration dynamically, the end-to-end throughput is preserved.

6. CONCLUDING REMARKS

In this paper, we have presented a problem that a source-initiated end-to-end path in multi-radio wireless mesh networks can be intruded by interference. In order to take the unexpected interference into account, we suggested an adaptive routing protocol detecting deterioration and reconstructing the path.

Challenging issues exist that are yet unsolved in this paper. The threshold values in our routing protocol should be carefully considered by variable bandwidths, packet sizes, and loss rates and should be defined as relative values based on environmental changes. The greediness of path reconstruction may affect the optimality of the other paths. In addition, node mobility in MANETs can make the situation more dynamic. Consideration of these issues is our future work. We are working on the evaluation implementing the full version of our proposed scheme.

7. ACKNOWLEDGMENTS

This work was partly supported by the IT R&D program of MKE/IITA [2008-F-047-02, Development of Urban Computing Middleware] and [2007-F-038-03, Fundamental Technologies for the Future Internet].

8. REFERENCES

[1] Ricard Draves, Jitendra Padhye, and Brian Zill, “Routing in Multi-Radio, Multi Hop Wireless Mesh Networks,” in Proceedings of MobiCom’04, pp. 114-128, September 2004.

[2] L. Villasenor-Gonzalez, Ying Ge, and L. Lament, "HOLSR: a hierarchical proactive routing mechanism for mobile ad hoc networks," IEEE Communications Magazine, vol. 43, pp. 118-125, 2005.

[3] C. Adjih, E. Baccelli, and P. Jacquet, "Link State Routing in Wireless AD-HOC Networks," IEEE Military Communication Conference, vol. 2, pp. 1274–79, October 2003.

[4] Asad Amir Pirzada, Marius Portmann, and Jadwiga Indulska, "Evaluation of multi-radio extensions to AODV for wireless mesh networks," in Proceedings of the 4th ACM international workshop on Mobility management and wireless access, pp. 45-51, 2006.

[5] D. De Couto, D. Aguayo, J. Bicket, and R. Morris, “High-throughput path metric for multi-hop wireless routing,” in Proceedings of MOBICOM 2003, 2003.

[6] D. Johnson, Y. Hu, and D. Maltz, "he Dynamic Source Routing Protocol (DSR) for Mobile Ad Hoc Networks for IPv4," RFC 4728, http://www.faqs.org/rfcs/rfc4728.html, February 2007.