On-demand Multi-path Balancing in Wireless Mesh Networks

Cao Trong Hieu, Dae Sun Kim, Choong Seon Hong(*), and Youngcheol Bang(**), *Member, IEEE*
(*): Department of Computer Engineering, Kyung Hee University
(**): Korea Polytechnic University
$email : (hieuct, dskim)@networking.khu.ac.kr, cshong@khu.ac.kr, ybang@kpu.ac.kr$

***Abstract*—In recent years, while Mobile Ad hoc Networks still have many challenges to become popular because of dynamic topology and security vulnerabilities, Wireless Mesh Networks (WMNs) with static Transit Access Points (TAPs) are emerging as the best solution for wireless communication. Much of recent work in routing for Wireless Mesh Networks (WMNs) has focused on overhead reduction, performance improvement and security enhancement for "multi-channel, multi-path" environment using single or multi-radio. However, to the best of our knowledge, there is no current work considering the balancing between the numbers of multi-paths can be used and the needed transmission data in each communication session within the consideration of loss rate. This paper proposes the On-demand Multi-path Balancing protocol (OMB) with an effective algorithm to balance the number of multi-paths can be used and the needed transmission data in each communication session for Wireless Mesh Networks (WMNs) environment. In wireless communication, this balancing is very critical to reduce routing overhead and improve throughput which directly improve routing reliability. Using a threshold to choose the optimal number of disjoint paths and scheduling the transmission time for single radio nodes, we make our routing protocol perform much better. The simulation results show that OMB improves throughput and reduces overhead, especially in case of big size data transmission.**

***Index Terms*—Wireless Mesh Networks, multi-path routing, on-demand multi-path balancing.**

I. Introduction

WIRELESS Mesh Networks (WMNs) are believed to be the promising solution to build self-organized network in places where wired network's deployment is not available or costly, and serve as broadband wireless access to the internet [1].

In our paper, we classify mesh network into bi-level infrastructure as showed in Fig. 1. The backbone-level includes Mesh Routers (MRs) as relay nodes and several Gateways (GWs) to connect to Internet. The client-level contains wireless devices (laptop, PDA, Smart Phone...) which can only communicate with MRs or even can directly communicate with others (in ad-hoc mode). Backbone-level uses proactive routing thanks to unlimited energy and higher capacity to reduce routing delay, while client-level uses reactive routing to reduce overhead of periodically exchange routing information messages.

The efficiency of multi-path routing for communication is proved by many existing literatures and now becoming hot research topic that aims to assist IEEE standard for WMNs. However, after carefully survey the most up-to-date proposals, to the best of our knowledge, this is the first work considering the balance between the numbers of multi-paths can be used and the needed transmission data in each communication session with the consideration of packet's loss rate. For wireless communication, this balancing is very critical to reduce routing overhead and transmission time that can directly improve throughput and routing reliability. The reminder of the paper is organized as follows. Section II briefly reviews current routing techniques, especially focus on multi-path routing with single or multiple radios. The main part with adjustable path balancing for data transmission is proposed in section III. We show that our proposal using new scheme to drive routing protocol works more efficiently by simulation analysis in section IV. Finally, section V, some conclusions are discussed.

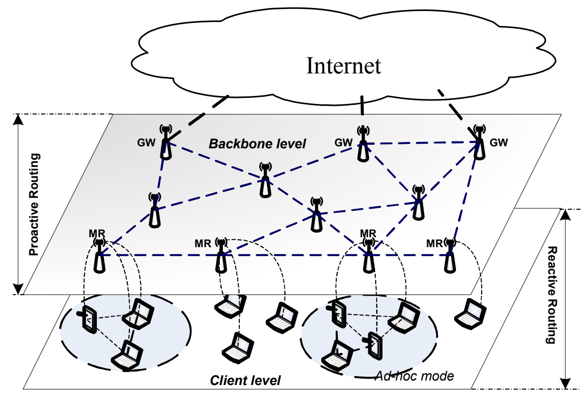


Fig. 1. Bi-level Mesh Architecture.

II. Related Work

The main goal of any routing protocol is to support effective communication. To reach this goal, many researches have proposed different routing protocols for wireless network as well as for specific wireless mesh network. Each routing protocol bases on routing metrics which are designed to achieve different targets. For example, some routing metrics capture the stability of a path, some concern about bandwidth of a path, and some focus on energy consumption. For WMNs, recently, researchers have proposed some link quality metrics such as 'Per-hop Packet Pair Delay" (PktPair) [2], "signal-to-noise-ratio" (SNR) [3], "Expected Transmission Count" (ETX) [6], "Per-hop Round Trip Time" (RTT) [4], and "Weighted

Cumulative Transmission Time” (WCETT) [5], to choose path with good quality such as high bandwidth, short transmission time and low loss ratio which can improve network capacity.

Consider multi-path routing in WMNs, a lot of existing literatures have proposed various solutions for routing problem [6][7][8][9][10]. TORA in [6] supports multi-path routing by using Directed Acyclic Graph (DAG), but it does not guarantee disjoint paths. Also, DSR [7] can not avoid using the same intermediate nodes for multiple routing. The Split Multi-path Routing (SMR) [8] and AODVM [9] (an extension to AODV)can solve this problem because duplicate RREQs are not dropped, but this is at the cost or more RREQs. AOMDV [10] is also an extension to AODV for computing multiple loop-free and link-disjoint paths which uses the notion of ”advertised hop count” to guarantee loop-freedom and uses a particular property of flooding to achieve link-disjoint routes.

Richard Draves et al. in [5] proved that ETX [11] performs very well with single radio multi-path, but in case of multiple radios, it dose not work well due to the following reason: in [11], the authors implemented their routing protocol using TestBed with single 802.11b wireless card. However, in case of multiple radios, it does not work well. For example, in the scenario with an 802.11a and an 802.11b radio per node, ETX will route most of the traffic on the 802.11b links. In the scenario with two 802.11b radios per node, ETX is again likely to select sub-optimal paths since ETX will not give any preference to channel-diverse paths. Therefore it will not derive full benefit from the availability of two radios. From those claims, [5] proposed new routing metric (WCETT) working with multiple radios, multi-channel protocol.

However, [5] did not utilize the efficiency of channel scheduling even though the cost of hardware upgrade for multiple radios is high. With an effort to improve performance of single radio multi-channel WMNs, we propose a novel routing protocol which takes into account the balancing between the amounts of data needed to transfer and the number of disjoint path serving simultaneously that has never mentioned before. Using the same channel scheduling policy in [12], by dividing time into slot, we coordinate channel usage to avoid collision and utilize multi-path transmission at the same time. Our new routing scheme is combined with our previous work in [13] to find multiple node-disjoint paths and limit the number of path’s candidates adaptable with the demand of the amount of data and variable follow the loss rate. The number of disjoint path which is used increases when the data size is big or the loss rate is high, that is the way the routing scheme reacts in on-demand manner.

III. Balancing Multi-path for Data Transmission

Our work inherits the probabilistic model in [11]. Let p_f and p_r denote the probability of packet loss in forward and reverse directions respectively. The expected number of transmissions, including retransmissions, is calculated base on p_f and p_r. The probability p that the packet transmission from x to y is not successful can be formulated as:

$$p = 1 - (1 - p_f)(1 - p_r) \tag{1}$$

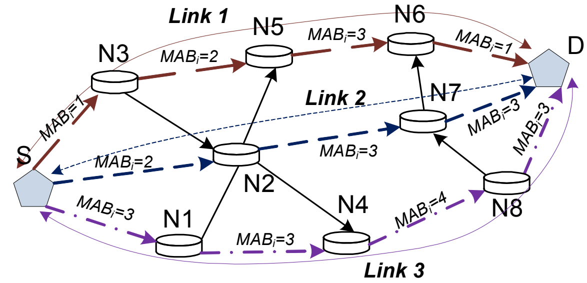


Fig. 2. An example for 3 link-disjoint paths.

The 802.11 MAC will retransmit a packet whose transmission was not successful. Let $s(k)$ is the probability that the packet will be successfully delivered from x to y after $k - th$ attempts:

$$s(k) = p^{k-1}(1 - p) \tag{2}$$

The expected number of transmissions required to successfully deliver a packet from x to y is denoted by ETX. It is also can be considered as a representative of loss rate (the more probability of packet loss, the more retransmission attempts):

$$ETX = \sum_{k=1}^{\infty} k.s(k) = \frac{1}{1 - p} \tag{3}$$

Eq. (3) implies that the ETX metric is bidirectional (the metric from x to y is the same as the metric from y to x). The ETX is used for further calculation of time’s threshold τ, a critical parameter to decide how many disjoint paths can be used for a data transmission session between two end nodes. To do that, we execute “Multi-path Finding Algorithm” in [13] to find m disjoint paths, and calculate the link speed of each path candidate. We use the same approach in [14] to evaluate the available bandwidth in each node. Here, the Maximum Unused Bandwidth (MUB) in Node i is calculated as:

$$MUB_i = C_i - \sum_j f_{ij} \tag{4}$$

with $\forall j \in$ neighborhood of i. C_i is the maximum bandwidth, or the capacity of the Node i, and f_{ij} denotes the traffic flow from Node i to neighbor Node j in bits/second. f_{ij} contains traffic generated at the Node i and transit traffic through that node. From Eq. (4), the Maximum Available Bandwidth (MAB), the remaining useable bandwidth, of Node i is defined as:

$$MAB_i = MUB_i - \sum_{j \in N_i} \sum_{k \in N_j} f_{jk} \tag{5}$$

In the next step, we sort path candidates by link’s speed γ_l with $l = \{l_1, l_2, l_3, ...l_m\}$ candidate links found in the previous step as illustrated in Fig. 2. The speed is assigned equal to the node speed which has lowest bandwidth among all nodes in this path.

$$\gamma_{l \in m} = \min\{MAB_{i \in l}\} \tag{6}$$

By simultaneously using multiple paths, the total speed of all links can be calculated as

$$\gamma_\Sigma = \sum_{l=1}^{m} \gamma_l \tag{7}$$

TABLE I
PSEUDO CODE FOR APS

Begin:
With the found m-disjoint paths:
Calculate $\gamma_{l\in m} = \min\{MAB_{i\in l}\}$;
Sort $\gamma_{l\in m}$ follow the reduction of link speed;
Calculate total speed γ_Σ, needed time T, threshold τ;
If $T \geq \tau$ use both m-disjoint paths
Else
{
for $l = 1, l \leq m, l++$;

$$T' = ETX \frac{M}{\sum_{l=1}^{m} \gamma_i}; // \; T' = T \text{ while } l = m$$

Compare and break while $T' \leq \tau$;
Use l disjoint paths;
end
}
End

Suppose, the amount of data needs to be sent from source to destination is M (bytes), the necessary time for data transmission when taking into account the loss rate is:

$$T = ETX \frac{M}{\sum_{l=1}^{m} \gamma_l} = ETX \frac{M}{\gamma_\Sigma} \quad (8)$$

If the amount of data is big enough or the loss rate represented by ETX is high, we can use all found m disjoint paths to utilize the total speed of all links. But in reality, the probability that the data size is small and ETX is usually greater but approximately equal 1 is very high, so we should use only fewer paths out of the m found paths for data transmission. To solve this problem, we define a time threshold τ to determine how many paths can be used on-demand of data size and adjustable following the packet's loss rate.

$$\tau = 3 \frac{M}{\sum_{l=1}^{m} \gamma_l} = \frac{3}{ETX} T = \beta T \quad (9)$$

Eq. (9) can be expressed as follows: for single-radio wireless communication, to reuse the frequency, the minimum spatial reuse distance is 3 hops. This key weakness causes the average bandwidth capacity divided by three, so that the transmission time also increases triple times. And for ideally, the transmission is successful without loss (ETX=1) causing value of τ as demonstrated. In common standard, packets will be retransmitted up to 7 times, so the value of β is in the range [3/7, 3]. Using Eq. (9), we propose a simple but very effective algorithm to calculate the needed disjoint paths named Adjustable Path Selection (APS) as showed in Table I. The value of T' is reduced by increasing the number of disjoint paths. From Eq. (8), logically, when the loss rate increases, more paths need to be used to reduce the transmission time.

IV. SIMULATION ANALYSIS

To evaluate the performance of proposed scheme, we have implemented a OMB module in the $NS-2$ [15]. The MAC layer is the IEEE 802.11a with the maximum speed of 54 Mbps. The backbone network is a grid network with the transmission range of 250 meters and interference range of 500 meters. We schedule transmission time into slots as the model in [12]. By dividing time into slots, OMB also coordinates channel usage among slots and schedules traffic flows on multi-paths to avoid collisions, and utilizes multi-path transmission at the same time. The channel scheduling in [12] works only with dual links while our channel scheduling can work with more than two links. We learn the affection of path length, distance (V) between two disjoint paths, and slot size in scheduling model to throughput and delay of OMB compare to Expected Transmission Count" (ETX) in [11] and Joint Multi-channel and Multi-path control (JMM) protocol [12]. To show the key point improvement of our proposed scheme, we do simulate our OMB with 2 disjoint paths ($l = 2$) and 3 disjoint paths ($l = 3$) as shown in Fig. 4.

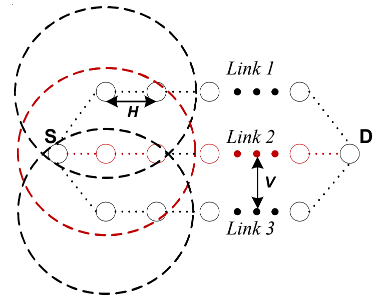


Fig. 3. Simulation model for backbone nodes.

A. Impact of Path Length

The network topology as showed in Fig. 4 with $H = 200$ meters and $V = 300$ meters is tested. We observe the end-to-end throughput from source gateway to destination by verifying the different path lengths (hop). Continuous 1024-byte packets are transmitted from source to destination. The results are shown in Fig. 5a. The ETX throughput decrease dramatically as the number of hops increases. While OMB with dual paths ($l = 2$) with single radio apparently performs worse than MCMP (two radios), the OMB with triple paths ($l = 3$) performs better than MCMP. The reason is by scheduling two non-adjacent paths (link 1 and link 3) operated in parallel while link 2 is idle and reversely, link 2 is active in the next time slot while link 1 and link 3 are idle, link 1 and link 3 do not interference each other.

B. Impact of Distance V

Because the backbone nodes are equipped with single radio only, it is obvious that the distance between two adjacent links will affect the performance of data transmission. We adjust the distance from 100 meter to 700 meters to see the reaction of end-to-end throughput. As showed in the Fig. 5b, both OMB ($l = 2$) and OMB ($l = 3$) throughput increase when the distance V increases. After V reaches over the interference range (500 meters), the end-to-end throughput increases sharply. Also, only OMB with triple links ($l = 3$) performs better than MCMP, which does not be affected by distance V thanks to doubly-equipped radios.

C. Impact of Data Size

As discussed above, the proposed scheme works very well with the big data size needed to transmit in a communication session. First, we send a 100 Mbytes data with the incensement of distance V as the same previous model. Next, we increase the data size to 500 Mbytes and compare with the transmission time of the first case. Even though the shapes of line in Fig. 5c and Fig. 5d are almost same, we can easily figure out that the needed time to transfer 500 Mbytes data is considerable larger than five times of one of 100 Mbytes. This evaluation proves that our declaration is reasonable.

D. Impact of Slot Size

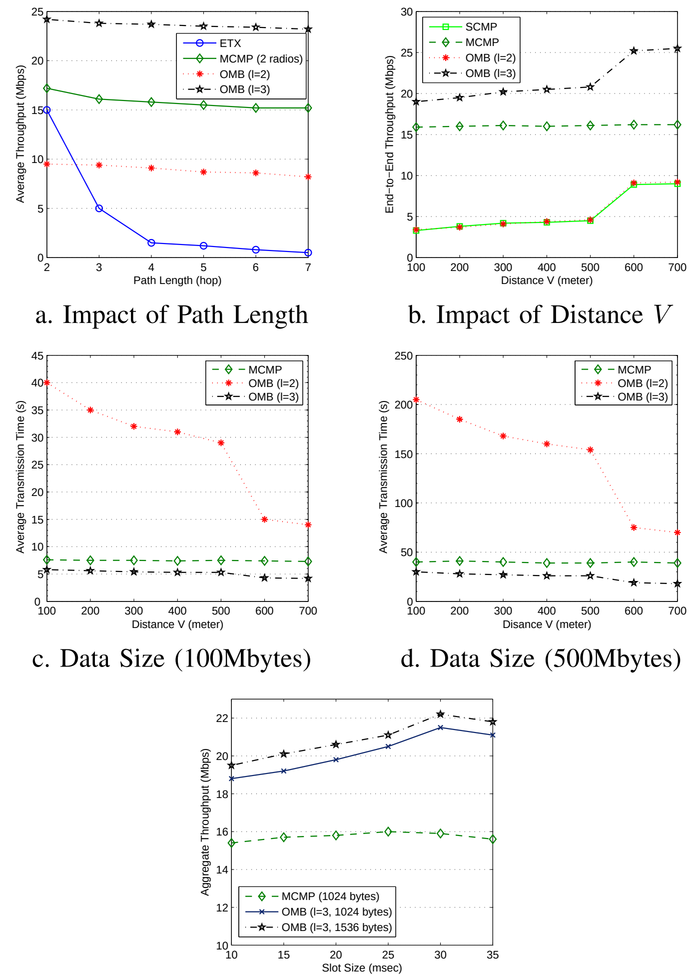
In time division method, slot size can influence the performance of routing protocol. If the length of slot size is too short, the channel switching overhead becomes considerable and degrades the system performance. In contrary, longer slot size may result in increased end-to-end delay as well as the buffer requirement at each node. To find the balance value, we vary the slot size from 10 milliseconds to 35 milliseconds with packet size of 1024 bytes and 1536 bytes. In the Fig. 5e, the results show that OMB ($l = 3$) performs much better than MCMP in both cases: 1024 bytes and 1536 bytes packet size. The figure also shows that at slot size of 30 milliseconds, the OMB reaches the best aggregate throughput while this case happens in MCMP with 25 milliseconds slot.

V. Conclusions

In this paper, we have shown that the WMNs can achieve good performance and utilize scheduling availability with only one radio card by carefully design multi-path routing protocol with multi-channel capacity. When the packet loss rate is high or the amount of data is large, the number of disjoint paths also needs to be increased on-demand to reduce transmission time. The proposed protocol especially works very well with bigger amount of data as well as bigger data packet size. Although the proposed protocol is affected by interference due to the chronically single interface problem, the experiment results show that OMB performs very well with triple disjoint links thanks for effective time scheduling.

Acknowledgment

This research was supported by the MKE under the ITRC support program supervised by the IITA" (IITA-2008-(C1090-0801-0002)). Dr. CS Hong is corresponding author.



a. Impact of Path Length

b. Impact of Distance V

c. Data Size (100Mbytes)

d. Data Size (500Mbytes)

e. Impact of Slot Size

Fig. 4. Simulation results

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