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End-to-end throughput improvement for single radio multi-channel multi-path wireless mesh networks: a cross layer design

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Abstract The distinguished feature of fixed backbone nodes in the wireless mesh networks (WMNs) can be utilized to design an efficient cross layer which cooperates routing and scheduling schemes for increasing end-to-end throughput. With only single radio nodes, by well designing the scheduling and routing schemes for multiple paths, we show that WMN can gain more throughput and reduce communication interference. Much of recent work has focused on those issues applied for "multi-channel, multi-path" environment using multi-radios that is costly and much more complex for implementation. Also, almost all of the proposals work on layer 2 or layer 3 separately that cannot support each other in performing efficiently. Instead, our paper introduces a cross-layer design with new routing algorithm that can balance the numbers of multi-paths and the needed transmission data in each communication session. We also propose a new channel scheduling and queuing models in MAC layer compatible with routing scheme and define a threshold with an effective algorithm to choose the optimal number of disjoint paths for routing scheme. The simulation results show that our multi-path routing scheme performs better than previous proposals in term of throughput improvement which can directly reduce the time of each communication session, especially in case of big size data transmission.

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1 Introduction

Wireless mesh networks (WMNs) are believed to be the cost-effective solution to build self-organized network for covering the places where wired network's deployment is not available or costly and serve as broadband wireless access to the internet [5]. 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. While seeking a more effective routing solution, we observed that using multi-paths with multiple interfaces is much more challenging in channel scheduling and consumes more cost. Besides, WMNs with cost-effective single interface nodes, which are major used currently, can improve network performance if we could distribute traffic into different paths on different channel and at different time slots. However, after carefully survey the most up-to-date proposals, to the best of our knowledge, this is the first work completely solving either routing or scheduling problem by splitting packet through multiple disjoint paths with adaptive channel scheduling to utilize the capacity of multi-path communication. The target of this paper is to improve network performance for backbone nodes which have only one wireless interface.

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The major motivation of this paper is how to distribute traffic to the destination (gateway) through different paths on different channels within delegated time intervals. To do that, we first propose a routing algorithm to find node disjoint paths for a communication session. After that, we evaluate path's speed of found routes by calculating maximum available bandwidth (MAB). The most distinguish contribution here is the consideration of the balance between the numbers of multi-paths that can be used and the needed transmission data in each communication session under the affection 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 number of selected paths are decided based on the *on-demand multi-path* scheme: the bigger size of data needs to be transferred, the more paths will be used. But how to use those paths simultaneously and efficiently with minimum inter-interference to increase end-to-end throughput? To solve that problem, we need to design a new MAC scheduling scheme which can support multi-path working simultaneously. Also, an adaptive queuing model and a packet forwarding strategy are given to help data deliver efficiently. The scheduling and queuing model are designed based on the fact that mesh nodes are stationary. Hence, once multiple disjoint paths are established, the pre-assigned channels within specific time slots can work well without the mobility consideration.

The reminder of the paper is organized as follows: Section 2 briefly reviews current routing techniques, especially focus on multi-path routing with single or multiple radios. The main part including cross-layer design and *on-demand multi-path balancing* (OMB) scheme mentioned above is presented in Section 3. We show that our cross-layer design works more efficient than existing proposals by simulation analysis in Section 4. Finally, Section 5 gives some conclusions.

2 Related work

Many researchers dedicated their ideas for multi-path routing protocol as well as multi-channel link protocols, but most of them approach those two problems separately. For the multi-channel MAC and link layer, authors in [6, 20] used single transceiver while authors in [4, 23] used multi-transceivers to design their protocols. The target is to improve network capacity, reduce collision, and contention among nodes.

For the routing layer, the main goal of any routing protocol is to support effective communication. To reach this goal, many literatures contributed different routing protocols for wireless network as well as for specific wireless mesh networks. Each routing protocol bases on routing metric which is 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" [15], "signal-to-noise-ratio" [10], "expected transmission count" (ETX) [8], "per-hop round trip time" [4], and "weighted cumulative transmission time" [9], 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 works have proposed various solutions for routing problem [14, 16–18, 22]. TORA in [18] supports multi-path routing by using directed acyclic graph, but it does not guarantee disjoint paths. Also, DSR [14] cannot avoid using the same intermediate nodes for multiple routing. The split multi-path routing [16] and AODVM [22] (an extension to AODV) can solve this problem because duplicate RREQs are not dropped. In this paper, we only deeply analyze some remarkable routing protocols which are applied for single radio, multi-path wireless mesh networks and directly related to our proposal.

In AODVM, the source node is responsible for maintaining alternate routes to the destination. Authors in [22] proposed the usage of so-called *reliable nodes* at the positions where multiple routes are not node disjoint. The motivation for deploying *reliable nodes* is to reduce the risk of nodes' failure at the bottleneck positions (where multiple routes use the same node for delivering data). However, the strategies to determine and deploy *reliable nodes* cost more overhead for the route discovery phase. Also, the hop-count-based metric is still used as the same as traditional AODV protocol; hence, AODVM does not change the performance of AODV significantly. Consequently, AODVM is not worth due to the extra implementation complexity compare to AODV. AOMDV [17] is also an extension to AODV for computing multiple loop-free and link-disjoint paths. It uses the notion of "advertised hop count" to guarantee loop freedom and uses a particular property of flooding to achieve link-disjoint routes. However, without a efficient route discovery strategy, this will get more RREQs flooding overhead. Also, the multiple paths are not ensured to be node disjoint as mentioned above. More importantly, both of them do not consider the MAC layer design to support delivering data efficiently.

Tam et al. in [21] give an excellent work in designing a joint cross layer for WMNs. By schedule traffic flows on multi-channels and multi-paths, authors in [21] showed that the overall network throughput can be improved significantly. However, they construct only two paths between two end nodes and model the scheduling scheme based on those two paths. The complexity of multi-channel link layer scheduling is high even though it deals with only two paths. Each node must communicate with its neighbors to get the information about available channels. Every node must be tightly synchronized and has to switch among available channels for delivering data packets (in case of single radio). In addition, the two paths are not guaranteed node disjoint that causes a bottleneck for traffic when transferring simultaneously. Taking into account all of those limitations, we propose a new cross-layer design that can work with more than two disjoint paths. Our new routing scheme first finds multiple node-disjoint paths and then limits the number of path's candidates adaptable with the demand of the amount of data and variable follow the loss rate. Once multiple paths are established, every node belonging to a specific path will work on the same channel so that the channel switching overhead is avoided. By dividing time into slot, we coordinate channel usage to avoid collision and utilize multi-path transmission at the same time.

3 Cross layer with OMB scheme

The design goal of our routing protocol is three-fold: First, we propose a routing scheme to find multi-paths to the destination node. After that, the path's speed will be calculated based on the estimation of available bandwidth. And then, by using *adjustable path selection* (APS) algorithm, the number of paths which can be used to achieve the most effective data delivery is calculated. Second, to support the proposed routing scheme, a specific MAC scheduling scheme is designed in Section 3.2. Also, we propose the queuing models that work with end nodes and intermediate nodes specifically. Third, the packet forwarding strategy and route maintenance are discussed. In this paper, a link is defined as the connection between two neighbor nodes, and a path is a set of links which connect two end nodes. Also, channels number i (i =1,2,...,N) are non-overlap channels, not a channel sequence.

3.1 OMB scheme and routing algorithm

First of all, we execute *multi-path finding algorithm* as shown in Table 1 to find m disjoint paths. The number of round request (RREQ) is equal to the number of neighbors (h) of source node (the maximum node disjoint paths cannot be greater than h). According to the algorithm, a path is formed when it satisfies the following conditions:

- It is the shortest path among remaining path candidates.
- It has the highest MAB (will be calculated below) among remaining path candidates.
- It is node disjoint with other path candidates.

Source node maintains the field *node's occupied status* in its routing table to exclude nodes already belonging to a path out of finding process next round. When a node belongs to an active route, this value of that node will be set to 1 to avoid to be chosen again (as the requirement of node disjoint path). Destination after chooses a route with a unique RREQ ID, it will unicast the RREP back to the chosen route. Destination will set all nodes belong to that route as occupied nodes. Next iteration, when received new RREQ ID, occupied nodes will discast those RREQs and stay idle. Only nodes which have *node's occupied status* = 0 will be candidates for a new path.

Table 1 Pseudo-code for multi-path finding algorithm

```
Initial:
    Node's Occupied Status = 0;
    Found Path = 0;
    Number RREQ = h;
    /* h is the number of neighbors of source node*/
Step 1
    Send RREQ_i to unoccupied neighbor nodes;
    Check nodes' MAB and Arrived HC_i;
Step 2
    If Arrived HC_i < Current HC_i;
        If Node Add == Destination Add
            Found Path ++;
            set Node's Occupied Status = 1;
            Number RREQ −−;
        else return Step 1
    else
        discast RREQ_i;
        set Node's Occupied Status = 1;
    finish
Step 3
    repeat Step 1;
    finish while Number RREQ == 0
End
```

Then, we calculate the expected number of transmissions for a path with α-hops for further using in the next step. The probabilistic model in [8] is applied in our paper with modification to work with multi-paths communication. For a link, 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_{loss} that the packet transmission from x to y is not successful can be formulated as:

$$p_{\text{loss}} = 1 - (1 - p_f)(1 - p_r) \tag{1}$$

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

$$s(k) = p_{\text{loss}}^{k-1}(1 - p_{\text{loss}}) \tag{2}$$

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

$$\text{ETX} = \sum_{k=1}^{\infty} k \times s(k) = \frac{1}{1 - p_{\text{loss}}} \tag{3}$$

Note that ETX in Eq. 3 is the value for a link (two adjacent nodes). For a path P_α with α-hops, we have:

$$\text{ETX}(P_\alpha) = \sum_{i=1}^{\alpha} \text{ETX}_i \tag{4}$$

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.

Another parameter needed for calculating τ is the MAB [7]. Hence, to calculate that, we calculate the maximum unused bandwidth (MUB) in node i first:

$$\text{MUB}_i = C_i - \sum_j f_{ij} \tag{5}$$

with $\forall j \in$ neighborhood of i ($i \neq j$). 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. And then, from Eq. 4, the MAB, the remaining useable bandwidth, of node i is defined, with N_i and N_j as neighbors of node i and node j, respectively, as:

$$\text{MAB}_i = \text{MUB}_i - \sum_{j \in N_i} \sum_{k \in N_j} f_{jk} \tag{6}$$

In the next step, we sort path candidates by path's speed γ_p with $p = \{p_1, p_2, p_3, \ldots p_m\}$ candidate paths found in the previous step as illustrated in Fig. 1. The speed is assigned equal to the node's speed which has lowest bandwidth among all nodes in this path.

$$\gamma_{p \in m} = \min\{\text{MAB}_{i \in p}\} \tag{7}$$

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

$$\gamma_\Sigma = \sum_{p=1}^{m} \gamma_p \tag{8}$$

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:

$$T = \sum_{p=1}^{m} \text{ETX}_p(P_\alpha) \times \frac{M}{\sum_{p=1}^{m} \gamma_p} = \sum_{p=1}^{m} \text{ETX}_p(P_\alpha) \times \frac{M}{\gamma_\Sigma} \tag{9}$$

In which $\text{ETX}_p(P_\alpha)$ is the expected transmission times on path p-th with α-hops as shown in Eq. 4. If the amount of data is big enough or the loss rate represented by ETX is high, we can use all m disjoint paths to utilize the total speed of all paths. 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. Here comes the role of parameter τ. A time threshold τ is defined to determine how many paths can be used on demand of data size and adjustable following the packet's loss rate.

$$\tau = 3\frac{M}{\sum_{p=1}^{m} \gamma_p} = \frac{3}{\text{ETX}} T = \beta T \tag{10}$$

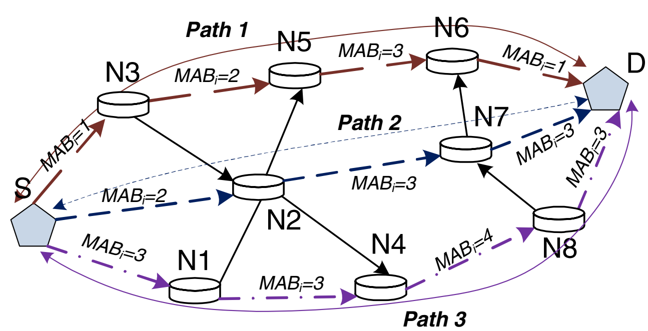

Fig. 1 An example for three node-disjoint paths

Equation 10 can be expressed as follows: For single-radio wireless communication, to reuse the frequency, the minimum spatial reuse distance is three hops. This key weakness causes the average bandwidth capacity actually divided by three, so that the transmission time also increases triple times. In ideal, the transmission is successful without loss (ETX = 1) so that value of τ is defined as in Eq. 10. In IEEE 802.11 standard, packets will be retransmitted up to seven times (ETX = 1 to 7), so the value of β is in the range [3/7, 3]. Using Eq. 10, we propose an effective algorithm to calculate the needed disjoint paths named APS as shown in Table 2. From Eq. 9, logically, when the loss rate increases, more paths need to be used to reduce the transmission time. Using this relation, the value of T' is adjusted in the algorithm by varying the number of disjoint paths. Once the threshold is defined, the path selection algorithm will use the most high speed path first ($p = 1$). The value of T' at $p = 1$ is then compared with the value of τ: If $T' \geq \tau$, then the second high speed path is used and so on until the condition $T' \leq \tau$ is satisfied. Using APS, the used paths are actually controlled by the relation of data size M and loss rate ETX.

3.2 Channel scheduling

When a node gets a chance to send data, it will execute *multi-path finding algorithm* (Section 3.1), gets the disjoint paths, and sends hello messages including channel assignment information to all nodes belonging to the paths. During the transmission session, all nodes belonging to the paths will act as forwarding nodes to the destination. N non-overlap channels are available for using (N can be specified based on specific standards) and all channels have the same bandwidth, so the packets transmitted on different channels do not interfere with each other. Currently, the *IEEE P802.11 Task Group S* continued working to issue IEEE 802.11s Mesh Networking Standard [1]. Therefore, there is no information about how many non-overlap channels that 802.11s can support. Because of that, in this paper, we assume that mesh network uses 802.11a with OFDM technology that provides enough non-overlap channels for proposed MAC scheduling scheme. We assume that each node is equipped with a single half-duplex transceiver. Also, a node can listen or transmit in only one channel at a time. A node can either transmit or listen, but cannot do both simultaneously. So when listening to one channel, it cannot carrier sense on other channels. Unlike our scheme, many other multi-channel MAC protocols require each node to have multiple transceivers that makes more complexity in channels and packets scheduling.

Nodes are synchronized, so that all nodes begin their beacon interval at the same time. All beacons are sent on a common default channel similar to IEEE 802.11 timing synchronization function [11]. After switching to a new channel, a node first remains silent for a duration equals to the maximum packet transmission time to avoid the multichannel hidden terminal problem which is resulted by loose time synchronization. Therefore, our protocol does not require very precise clock synchronization. After completing the session, nodes switch to their common channel for listening and contending a new transmission opportunity.

In each path, communicating nodes use the same channel so that they must follow the three-hop spatial reuse to avoid hidden and exposed node problems as shown in Fig. 2. Only nodes A and D can simultaneously use frequency f_1 at time slot T_{f1} because they

Table 2 Pseudo-code for APS

Begin:
With the found m-disjoint paths:
  Calculate $\gamma_{p\in m} = \min\{MAB_{i\in p}\}$;
  Sort $\gamma_{p\in m}$ 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 $p = 1, p \leq m, p++$;
    $$T' = \frac{M}{\sum_{p=1}^{m} \gamma_p} \sum_{p=1}^{m} ETX; // \; T' = T \text{ while } p = m$$
    Compare and break while $T' \leq \tau$;
    Use p disjoint paths;
  end
}
End

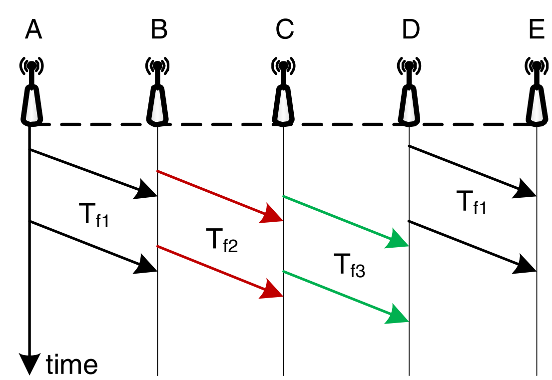

Fig. 2 Three-hops spatial reuse

are three hops apart. At the initial phase, all nodes use 802.11's CSMA/CA with RTS/CTS mechanism to contend for medium. After a node gets the channel access, it will delegate intermediate nodes working in an assigned channel through broadcast messages. Remind that all nodes out of the communication region can continue to compete the medium without interference.

All nodes in a path must use the same channel to send and receive data, so that there are four stages to schedule for intermediate nodes: *broadcast* (B), *transmit* (T), *receive* (R), and *idle* (I). Figure 3 shows an example for the channel schedule for three paths operating in non-overlap channels 1, 2, and 3, respectively. The source node can continuously switch to non-overlap channels for delivering packets, and the intermediate nodes will operate following the slotted time as scheduled. Node N_{i_Chj} is node number i which is operating in channel j (Chj) (note that $N_{i\_Ch1} \neq N_{i\_Ch2}$ because paths are node disjoint). Each path uses different non-overlap channel; by this way, the interference among paths is almost eliminated. For more disjoint paths, it is straightforward to rescheduling channels switching at only end nodes by inserting each time slot for an extra path.

Take a broader view, the Fig. 4 illustrates three representatives for three separate paths. Even they are close together, they can send or receive at the same time thanks to the non-overlap channel they are using. As figure showed, three different nodes N_{2_Ch1} (node number 2 working in channel 1), N_{2_Ch2}, and N_{2_Ch3} have the same slot's format and operating in channel 1, 2, and 3, respectively. For example, in the Fig. 1, nodes $N3$, $N5$, $N6$ use channel 1, nodes $N2$, $N7$ use channel 2, $N1$, $N4$, $N8$ use channel 3 to communicate following the time schedule in Fig. 3, and nodes $N1$, $N2$, $N3$ belonging to three different paths will be scheduled as in Fig. 4. This example illustrates three disjoint paths with three non-overlap channel case. It is straightforward to extend for more than three paths.

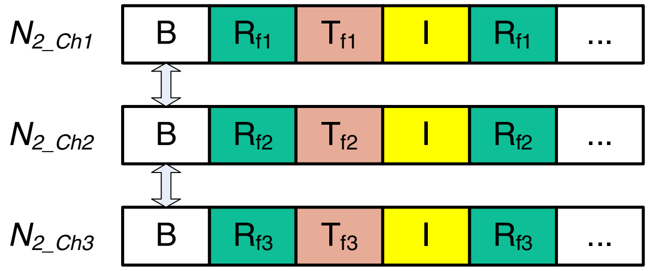

Fig. 4 Channel schedule for nodes in multi-paths

3.3 Queuing model

The queuing model illustrated in Fig. 5 is the example applying for three non-overlap channels. In general, the number of queues in each part is equal to the number of channels supported by each standard. Two queuing models are used for two kinds of backbone nodes: end nodes (source, destination) and intermediate nodes.

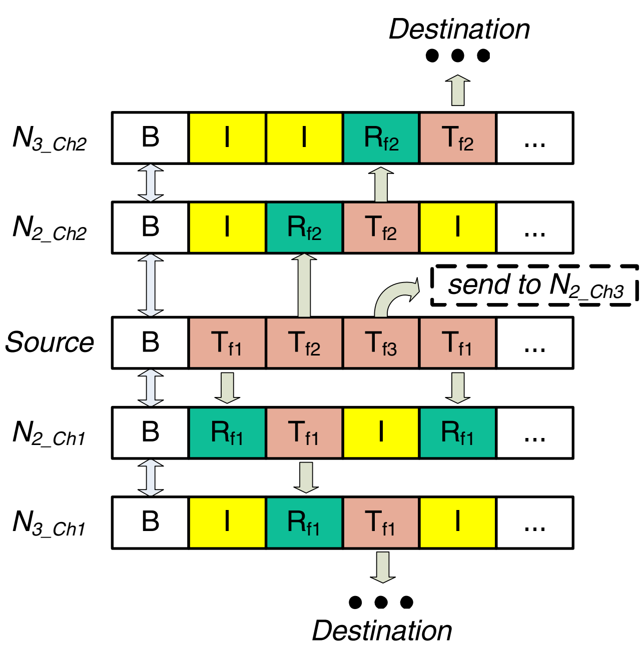

Fig. 3 Channel schedule for a path

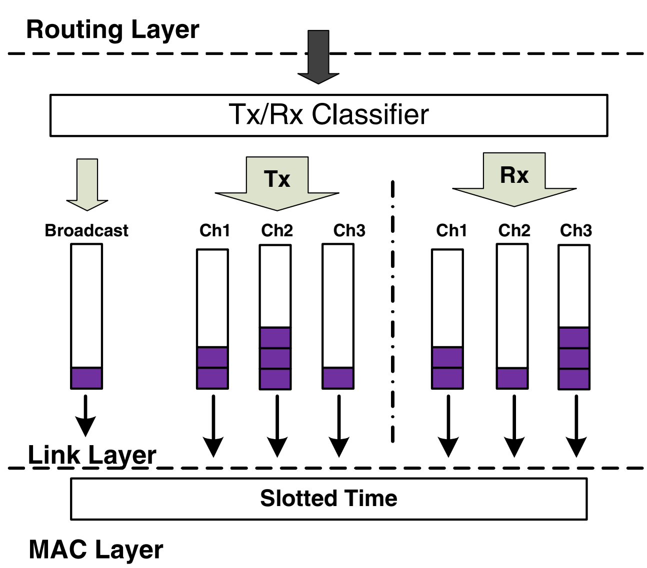

Fig. 5 Queue at two-end backbone nodes

The end nodes' queue deals with both three channels for transmitting packets on queue. Broadcast packets are in the broadcast queue, while unicast packets are classified into transmitting and receiving part as shown in Fig. 5. Each transmitting slot will serve one queue by switching to the channel of that queue, until the queue is empty or the slot expires. Remind that in case there are more than three disjoint paths, the extension of this queuing model is straightforward with N channels instead of three channels.

The communicating nodes after being assigned to a specific channel through broadcasting messages will work only in that channel in the end of transmission session. The queuing model for intermediate nodes is illustrated in the Fig. 6. It is an example of the queue model for nodes in a path transmitting on channel 1. By this way, the interference between parallel paths is avoided and all intermediate nodes in a path do not need to switch among channels as two end nodes must do.

3.4 Packet forwarding strategy

For currently using paths, the problem is how to fairly and simultaneously distribute packets to both paths. Traditionally, packets will be injected equally through those paths. When buffer overflow occurs at a specific path, the source node will stop to continue inject packets to that path until the congestion is over. However, in this paper, we use more precise method for effective packets delivery.

As discussed in the Section 3.1, the path speed γ_p evaluated in Eq. 7 will be used to decide the packet injection ratio. The packet injection ratio in each path is defined as follows:

$$r_p = \frac{\gamma_p}{\sum\limits_{p=1}^{m} \gamma_p} \tag{11}$$

which satisfies the condition $\sum\limits_{p=1}^{m} r_p = 1$. The path with higher speed will deliver more packets than the lower one following the ratio in Eq. 11. When congestion occurs and packets are dropped, the source node will retransmit the dropped packets through the current delivering path. This forwarding strategy is more efficient than equally distributing packet through multiple paths.

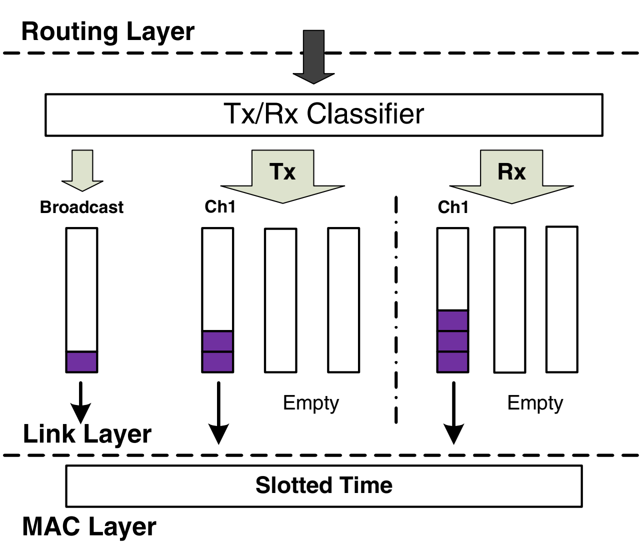

Fig. 6 Queue at nodes communicating on channel 1

3.5 Route maintenance and error

Each forwarding node must keep track of its continued connectivity to its active next hops. As discussed above, when the maximum number of retransmission attempts reaches seven times but the packet failed to reach the next hop, the connectivity of this link is broken. A route error (RERR) message will be unicast back to the previous node. A node initiates processing for a RERR message in these situations:

- If it detects a link break for the next hop of an active route in its routing table while transmitting data after trying route repair attempts unsuccessfully
- If it receives a RERR from a neighbor for one or more active routes
- If it gets a data packet destined to a node for which it does not have an active route

When an active route is unavailable due to link's breakage, the total path speed will be reduced. In response to this reduction, the most unused high speed route is used to supply more bandwidth for current communication. Once to be used, that route is assigned the same channel of the broken route and all nodes of broken (invalid) route stay idle. In the worst case, there is no more existing unused route, data will be delivered through the remaining paths. The invalid route is used to store previously valid route information for an extended period of time. An invalid route cannot be used to forward data packets, but it can provide information useful for route repairs and also for future RREQ messages.

Remind that the network is assumed to have multiple sources and multiple destinations. Only the involving nodes in the communication region have to follow the channel assignment by the specific source node. Nodes out of communication zone compete to get channel for data transmission as the same procedure discussed above.

4 Simulation analysis

To evaluate the performance of proposed scheme, we have implemented an OMB module in the *NS-2* [2]. The OMB module is implemented based on the modification of CMU Monarch project [3] and the extension described in [12]. The Monarch research group developed a module to support simulating multi-hop wireless networks complete with physical, data link, and MAC layer models in *Ns-2*. Holland et. al. [12] have extended that module in order to consider the effect of physical layer parameters in wireless communications. We have used the Rayleigh fading model as the path loss model described in [12]. The MAC layer parameters are modified following the IEEE 802.11a standard specification [13] with the maximum rate of 54 Mbps. The channel scheduling works with more than two paths compare to [21] which is designed to work with only two paths. The node's transmission range is 250 m and interference range is 500 m. First, we study the performance of route discovery, the impact of loss rate (based on the value of β), the impact of time slot size, and the impact of path length on end-to-end throughput. For this case, the backbone network is generated randomly by placing 100 nodes over a 2×2-km area. Then, to learn the effect of the distance (V) between two disjoint paths as well as the effect of the data size on throughput and delay of OMB, a grid topology with distance between two nodes in a path H and distance between two adjacent paths V in Fig. 7 is used. Finally, to study the effect of traffic load on network throughput, we gradually increase the data rate of 15 simultaneous flows randomly generated in the network. In the first case, we pick ten source-destination node pairs randomly and apply UDP flows with constant bit rate 54 Mbps at the source. Commonly, the switching delay between available channels in the source and destination nodes is actually very small compare to the transmission period. Hence, it can be ignored. The proposed OMB protocol is compared to AODVM in [22] in case of "single channel multi-path" and joint multi-channel and multi-path control protocol [21] in case of "multi-channel multi-path" (MCMP). Both AODVM and MCMP use two paths to deliver data simultaneously, but AODVM does not have supported MAC scheduling like OMB and MCMP. To show the key point improvement of our proposed scheme, we do simulate our OMB with two disjoint paths ($p = 2$) and three disjoint paths ($p = 3$). Figure 7 illustrates the case when routing scheme found two and three paths, respectively. As mentioned above, all nodes out of communication region of current S and D node will use the same procedure to compete channel for communication, so that multiple sources multiple destinations can operate simultaneously. The simulation results that we show are the geometric means over 50 simulation times.

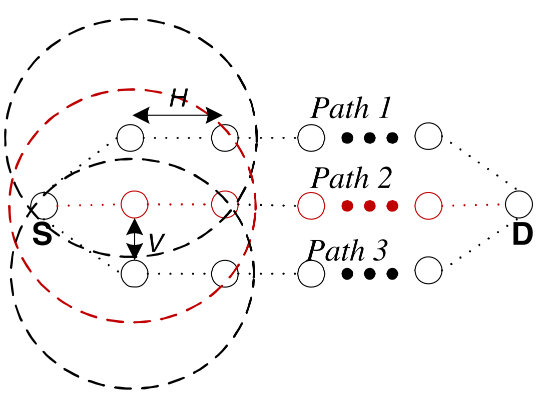

Fig. 7 Example of grid topology for backbone nodes

4.1 Tradeoff between multiple disjoint paths discovery and data delivery efficiency

We observe average route discovery time to study the trade off between multiple disjoint paths and the efficiency of data delivery. The OMB route discovery time is compared with that of traditional AODV [19], AODVM [22], and MCMP (uses two radios) in the Fig. 8. As shown in the figure, in all cases, the discovery time increases sharply when the number of hops (path length) between source and destination increases. This is because the more intermediate nodes in the path, the more medium access contentions will occur that causes more time consumption. For each protocol, AODV performs the fastest because it only finds single path and the first arrived RREQ is used to send RREP backward to source node. For MCMP which operates with two radios, each radio has responsible to find one path, so that the time to find two paths is also faster than OMB. The number of different RREQs sent by OMB is limited by the number of source's neighbors because it prefers to find node-disjoint paths. Hence, the average time to find multi-paths of OMB is still better than AODVM that allows duplicated RREQs retransmit. Although OMB takes longer time to discover multi-paths than that of AODV and MCMP,

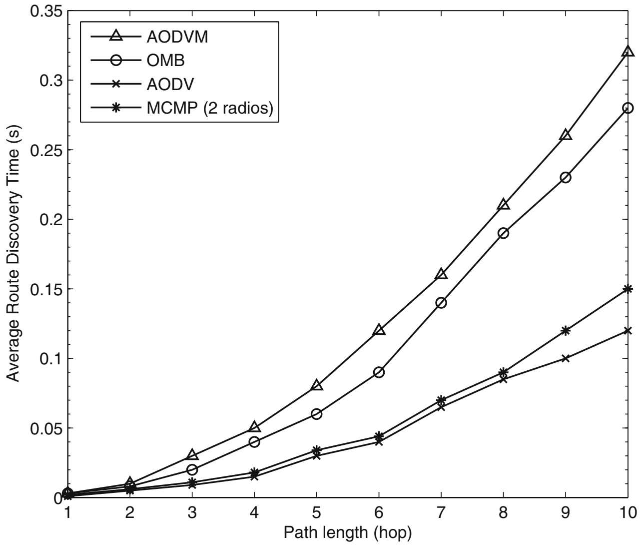

Fig. 8 Average route discovery time

it is acceptable compare to the noticeable achieved throughput of OMB using those paths for delivering data. The following studies will prove the throughput improvement.

4.2 Impact of β

To study the impact of β, we adjust the loss rate by changing the ETX value and also insert different data sizes to observe the reaction of OMB. The packet size is adjusted from 512 to 1,536 bytes and the observed throughput is estimated on average. When the data size is small and the loss rate is low, the threshold τ will limit the routing scheme that choose fewer paths. However, when data size is increased or loss rate is high, routing scheme will find more paths. So that even the average throughput reduce when ETX is high, the reduction is sharp only at ETX = 4 (Fig. 9). The proposed on-demand routing scheme reacts well in case the number of retransmissions is high; more paths then will be used to compensate for high loss rate. The throughput increases in proportion to the number of disjoint paths which are using. Consequently, under the condition that the retransmission reaches seven times, the average throughput still reaches 14 Mbps with OMB (three paths; over 50% throughput of an ideal case (25 Mbps) when ETX = 1).

4.3 Impact of slot size

In time division scheduling, slot size can influence the performance of routing protocol. If the length of slot size is too short, the channel switching overhead

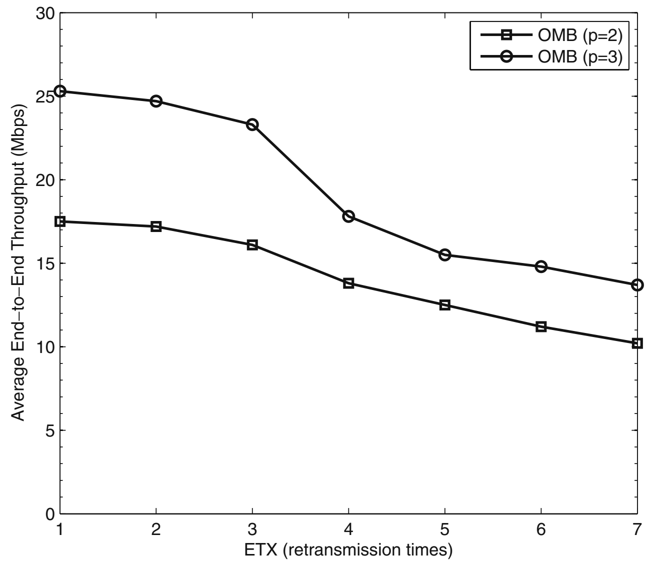

Fig. 9 Impact of β

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 to 35 ms with packet size of 1,024 and 1,536 bytes. In Fig. 10, the results show that OMB ($p = 3$) outperforms MCMP by almost 25% in both cases—1,024 and 1,536 bytes packet size. The reason is that for the usage of three node disjoint paths with the support of designed MAC scheduling and packet delivering strategy above, the total throughput

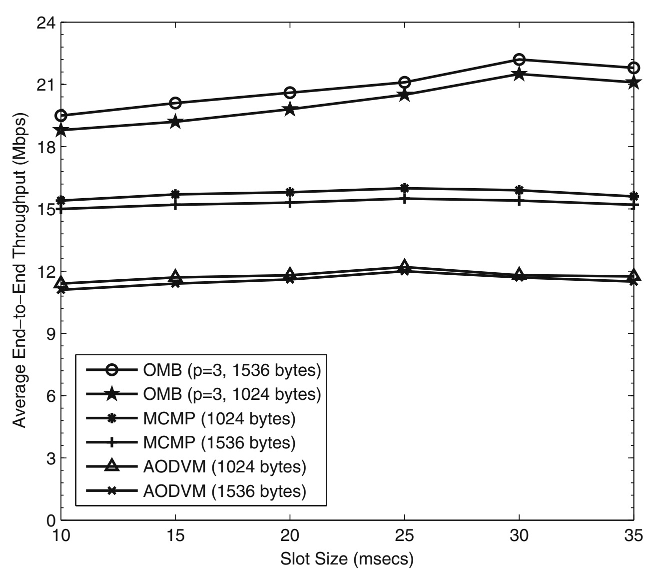

Fig. 10 Impact of slot size

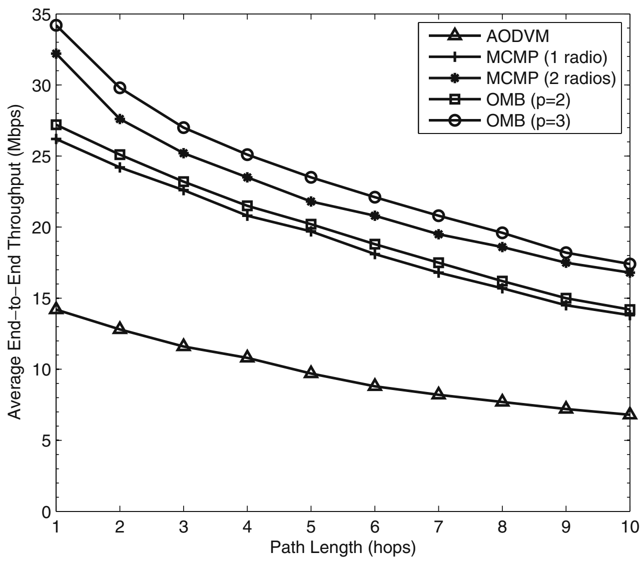

Fig. 11 Impact of path length

of OMB is sharply increased. Also, thanks to the well-designed MAC scheduling for the two paths in the MCMP protocol, it apparently performs better than the AODVM protocol with two paths without supported MAC scheduling. The figure also shows that at slot size of 30 ms, the OMB reaches the best aggregate throughput (approximately 22 Mbps) while this case happens in MCMP and AODVM with 25 ms slot (approximately 16 and 12 Mbps, respectively). Hence, to get the best performance, OMB should use 1,536 bytes packet size and time slot 30 ms for data transmission.

4.4 Impact of path length

In this experiment, we observe the end-to-end throughput from source to destination under the variation of the path length (hops). The MCMP protocol is tested with one radio and two radios equipped per node. The purpose is to compare the effective of multiple radios node to single radio node with supported MAC scheduling. The results are shown in Fig. 11. The throughput in all cases decreases dramatically as the number of hops increases. The throughput of OMB with two paths ($p = 2$; approximately 27 Mbps, 14.2 Mbps at one and ten hops path length, respectively) performs a little bit better than MCMP (one radio; approximately 26 Mbps, 13.8 Mbps at one and ten hops path length, respectively). Also, the OMB with three paths ($p = 3$) performs better than MCMP (two radios; approximately 34.2 Mbps, 17.4 Mbps compare to 32.2 Mbps, 16.8 Mbps at one and ten hops path length, respectively). The reason is when the multi-path performs under the control of proposed channel schedule, the interference between two adjacent paths is eliminated. In case of AODVM, as mentioned above, it does not have supported MAC scheduling so that the throughput is downgraded noticeably even it also uses two disjoint paths to transmit data simultaneously. This experiment proved the capable in throughput improvement of single radio with non-overlap channel compared to multiple radios nodes.

4.5 Impact of distance *V*

In this experiment, we study the effect of the distance between two adjacent paths to the performance of multi-path routing. The grid topology as shown in Fig. 7 is tested. We adjust the distance from 100 to 700 m to see the reaction of end-to-end throughput. As shown in the Fig. 12, in both cases, the throughput has slightly increased trend when the distance V increases except in the case of AODVM. When V is smaller than interference range (500 m), the average end-to-end throughput of ETX drops significantly due to high interference between two adjacent paths. After V reaches over the interference range, the end-to-end throughput of AODVM increases sharply (almost 40% from 9.5 to 14.9 Mbps). The reason is that AODVM uses single channel multi-path without an effective scheduling scheme and the throughput can only increase when two adjacent paths no longer interfere each other. On the contrary, thanks to well-designed scheduling schemes, both MCMP and OMB are not affected much by distance V, but OMB ($p = 2$ and $p = 3$) has higher

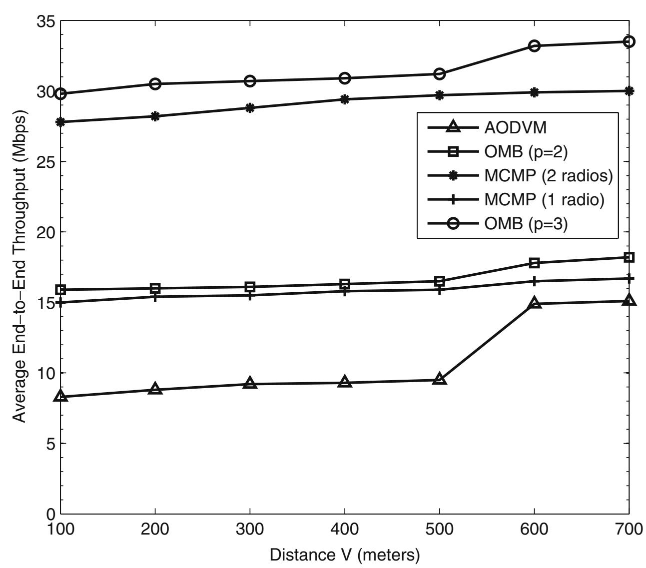

Fig. 12 Impact of distance *V*

average throughput than MCMP (one radio and two radios), respectively, at any distance.

4.6 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. To prove that, first, we send a 100-Mbyte data over different distances V from 100 to 700 m. Next, we increase the data size to 500 Mbytes and compare with the transmission time of the first case. The Fig. 13 shows that in case of 100 Mbytes, the OMB performs better than MCMP (one radio) but worse than MCMP (two radios). But for the case 500 Mbytes, OMB outperforms MCMP (two radios). Also, we can easily figure out that the needed time for OMB to transfer 500-Mbyte data is considerably smaller than five times for the case 100 Mbytes. This phenomenon can be explained as when data size is large, OMB will use more paths following the proposed APS algorithm to transmit data. This means OMB performs better in case of bigger amount of data need to be transmitted. In addition, we observe that the distance V between two paths takes much effect on the throughput of AODVM. This result agrees with the previous experiment (impact of distance V) result. Consequently, AODVM only can perform better when $V \geq 500$ m (Fig. 14).

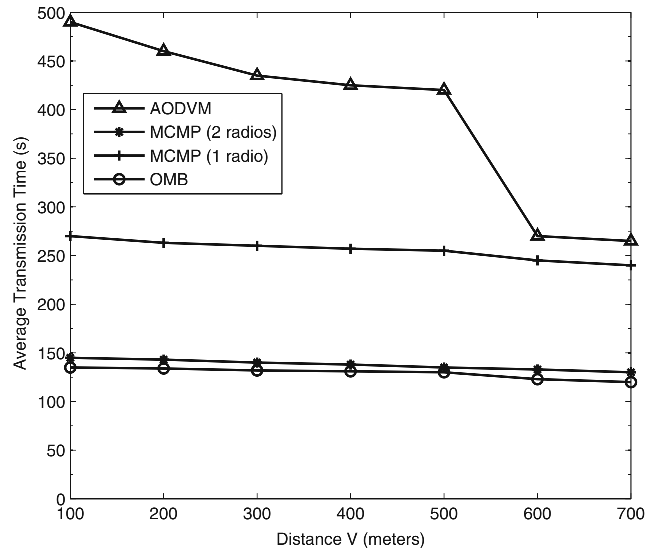

Fig. 14 Data size (500 Mbytes)

4.7 Impact of traffic load

In this scenario, we adjust the data rate of the 15 flows from 10 to 50 pkts/s with the packet size 1,024 bytes to study the impact of traffic load on the network throughput. Figure 15 shows that when the traffic load increases, the achieved network throughput of all routing protocols is also increased. However, it does not increase at the expected rate with increasing loads. Indeed, network congestion and collision occur more frequently when the network has simultaneous flows with high traffic loads. For AODVM, the network throughput increases very slowly with increasing loads because without support MAC scheduling for multi-path, the packet drop rate is high due to network's congestion and collision. While OMB ($p = 2$) performs a little bit better than MCPM (one radio), OMB ($p = 3$) gains

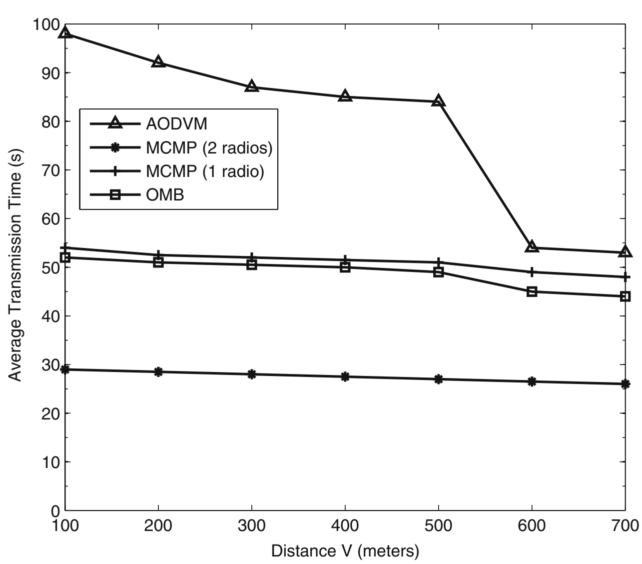

Fig. 13 Data size (100 Mbytes)

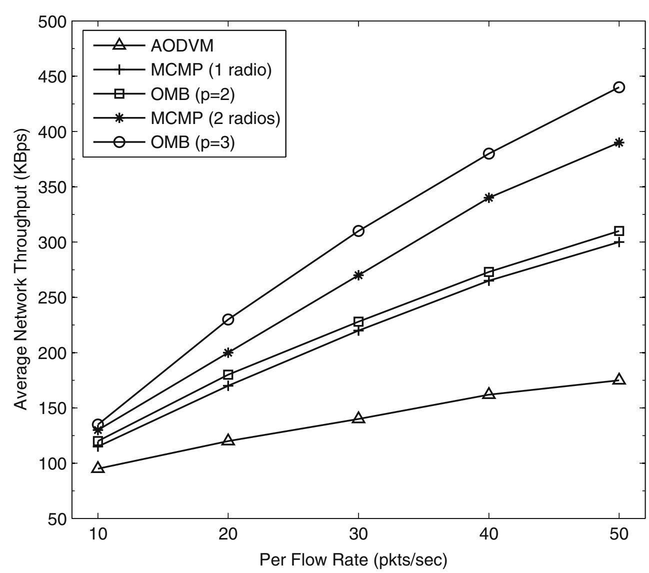

Fig. 15 Impact of traffic load with 15 simultaneous flows

a noticeable network throughput compare to MCMP (two radios). The achieved throughput improvement is from 5% to 20% depending on different traffic loads thanks to the efficient MAC scheduling and routing protocol.

5 Conclusions

Recently, researchers are trying to deal with multiple interfaces problem because it apparently can provide more bandwidth capacity than single interface. However, in this paper, clearly, we have shown that the WMNs can achieve good performance and utilize scheduling availability with only one wireless 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, more disjoint paths should be used to reduce transmission time. For practicality, we considered the implementation of our protocol based on 802.11a specifications. The proposed protocol especially works very well with bigger amount of data as well as bigger data packet size. The well-designed scheduling scheme can avoid interference, which is the chronically single interface problem, between two adjacent paths, so that the aggregate throughput is noticeably increased as shown in the experimental results.

However, as mentioned above, it takes a little more time for multiple route discovery as the trade off for throughput improvement. Also, the number of node disjoint paths can be found more or less based on the node density. Therefore, in the future, we will study the effect of node density in the network to the proposed protocol and implement the designed cross layer in our testbed system to study the performance of OMB in the real network.

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