A Novel Traffic Splitting Policy for Performance Improvement in Wireless Mesh Networks

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Abstract—**Wireless mesh networks are expected to play an important role in the next-generation wireless communication systems as it can provide wide coverage and scalable broadband Internet access services. However, as more traffic is injected into the network it may lead to throughput degradation, packet loss and longer transmission delay. In this paper, we argue that network performance can be improved by cross-layer design over multiple layers and load balancing based on service types. Correspondingly, a novel traffic splitting policy which can potentially utilize diverse paths for transmitting traffic flows of different service types from the same router has been proposed and investigated. Such a policy is able to balance traffic load, ideally aggregate capacities across multiple paths and leverage diversity among the paths to achieve low packet loss and more stable throughput.**

I. INTRODUCTION

Wireless Mesh Network (WMN) is a multi-hop wireless network composed of connected mesh router for the purpose of e.g. providing Internet access. WMNs are typically based on IEEE 802.11 due to its distributed nature and ease of implementation. The throughput of such a network is not a fixed quantity, but depends on the efficiency of the Medium Access Control (MAC) protocol used, path loss and signal fading, interference generated by other routers etc. Furthermore, as the numbers of stations and traffic flows increase, the probability of collision may increase dramatically, leading to degraded network performance. On the other hand, WMNs are expected to provide optimized capacity to clients and Quality of Service (QoS) to certain number of flows despite possible congestion status of the network. These requirements lead to the task of performance improvement of WMNs more challenging.

To improve the performance of a WMN, various approaches can be introduced, from MAC and routing enhancement, to load balancing and cross-layer design. In addition to MAC mechanisms and routing protocols themselves, routing metrics are also of significance in order to find most suitable path and forwarding nodes between source nodes and their destinations [1]. A well-selected metric should cover adequate information about the link or path. Each router in the network selects the best path according to the properties contained in routing metric. Due to the co-existence of many interacting parameters such as network load, link transmission rate, intra-flow and inter-flow interference, and link dynamics, the design of efficient routing in WMNs remains a challenging task, from the perspective of cross-layer design. Currently, most cross-layer design approaches consider solely how to use layer 1 or layer 2 information for layer 3 routing optimization [2, 3]. With these approaches, traffic flows with diverse service types may not benefit from the optimal routing path owing to the un-awareness or disharmony between routing metrics and flows' own traffic features.

Load balancing is another efficient approach to resolve the congestion problems in WMNs. It can be achieved through path-based load balancing, gateway-based load balancing or mesh router-based load balancing [4]. In path-based load balancing, the traffic is distributed across multiple paths. In gateway-based load balancing, the load is balanced either among all Internet gateways (IGWs) or a few selected gateways [5]. Load balancing can also be carried out at the mesh routers over the wireless backbone. However, *traditional routing* strategy with load balancing intends to *direct all traffic flows as a whole to another less loaded path* if the ongoing path could not satisfy the requirements [1, 3, 6], without distinguishing the *types of services*. This strategy may lead to a potential threat that many traffic flows are suddenly redirected to the same path, causing performance degradation on that specific path. Furthermore, as a consequence of this strategy, mesh routers may switch paths frequently back and forth, leading to so-called ping-pong effect with poor service continuity.

In this paper, we propose and investigate the performance of a novel routing strategy which incorporates both cross-layer design and load balancing. By collaboration across layer design over multiple layers, improved network performance is expected. More specifically, the congestion information derived from layer 2 serves as an indicator to initialize load balancing, and the load balancing routing scheme is achieved by separating flows into different available paths, according to their traffic types. This method is referred to as traffic splitting. With our proposed traffic splitting policy, traffic load is distributed over the entire network, resulting in multifold benefits: (a) excessive congestion inside the network is avoided; (b) the network capacity is optimally utilized; (c) packet loss is decreased and total network throughput increased; (d) greater benefit is achieved for the re-directed traffic flows.

The rest of this paper is organized as follows. Sec. 2 reviews some related work. In Sec. 3, we present our traffic splitting policy for efficiently load-balancing over different paths, while the simulation results are observed in Sec. 4. In Sec. 5, we further study factors that affect the results, and based on this study a more detailed algorithm is described in Sec. 6. Finally, the paper is concluded in Sec. 7.

II. RELATED WORK

In this section, we discuss briefly recent work regarding performance analysis of wireless mesh networks, and various proposals for enhancements in WMNs, including load balancing and cross layer design.

In [7], the authors derived a model to eliminate the effect of hidden/exposed nodes in multi-hop wireless networks. They investigated the throughput starvation of flows and showed that the minimum contention window has a more profound effect on mitigating flow starvation than exponential back-off mechanism and RTS/CTS control procedures. [8] observed that in wireless mesh networks the limited number of gateway nodes could be the bottleneck of the entire network. The authors presented a formal study on the delay and throughput of the gateway nodes. They modelled the gateway nodes as independent M/D/1 queue stations, and derived closed-form solutions for the bottleneck delay and throughput with liner and grid topologies.

A major concern about using IEEE 802.11 in WMNs is its inherent unfairness at the MAC layer when used in multi-hop wireless networks. Existing solutions to this problem either do not efficiently resolve this unfairness, or require modifications to the MAC protocol. [9] proposed a co-ordinated congestion control algorithm that achieved max-min fairness over unmodified 802.11 MAC layer. The overhead measurements showed that their algorithm was indeed feasible, and it did yield significantly better performance than existing mechanisms. [10] also proposed algorithms to reach fairness across multi-hop flows for achieving better performance. They measured the available bandwidth as the inverse of per-packet MAC contention and transmission time. Each router then ran a proportional max-min fair bandwidth sharing algorithm to divide this measured bandwidth among the flows passing through it.

There are also many studies for enhancing network performance by distributing the traffic load among the whole network. [3] proposed a routing metric with load balancing for wireless mesh networks. Quantitative and qualitative analyses showed the significance of the proposed scheme, compared with existing similar schemes. In [5], the authors proposed a novel technique that elegantly balanced the load among the different IGWs in a WMN. The point of attachment of an active source is switched among gateways, depending on the average queue length at the IGW. However, without considering cross layer issues, their schemes can not efficiently explore other protocol layer parameters.

In summary, there is a large body of work on improving the multi-hop wireless mesh network performance. However, few of these solutions address the problems from the perspective of cross layer design considering both layer 2 and layer 4, and from load balancing perspective considering service types. Different from the related work, we employ a traffic splitting policy which takes into account parameters in other protocol layers, path capacity, congestion condition, different service types, to balance the load among the whole network to obtain high aggregation throughout.

III. THE PROPOSED TRAFFIC SPLITTING POLICY

In this section, we develop a traffic splitting policy under heavy loaded conditions to provide load balancing in WMNs. The scheme uses congestion status and traffic types as the input for routing decision.

A. Motivation

According to the basic principle in traditional routing protocols, a routing decision is made to find the least-cost path from source to destination, no matter it is based on hop-count or other metrics. Correspondingly, once a proper route from the source node to the destination node is established, all traffic flows will be transmitted through the same route until the routing decision is updated, regardless of which type of traffic is being carried. The main idea behind our traffic splitting policy, however, is to distribute traffic flows of the *same* source destination pair among *different* routes according to network congestion status and traffic types, so that better load balancing and channel utilization can be achieved.

B. The proposed traffic splitting policy

In our earlier work [11], a routing scheme which could redirect certain types of traffic to other paths under heavy traffic load has been proposed. In addition, depending on the average MAC layer utilization and network transmission queue length, a combined metric is used to measure the congestion status at each router. In this paper, we further develop the traffic splitting routing policy, which is expected to utilize resources in the whole network more efficiently. The proposed routing policy is shown in Fig.1.

As showing in the figure, when more traffic flows are pumping into path 1, instead of redirecting all traffic flows to a better path we will split certain traffic to go through another path, while the rest is still kept on the original path. In other words, this splitting policy has been designed in such a way that different traffic types from the same router may select different paths towards the Internet gateway.

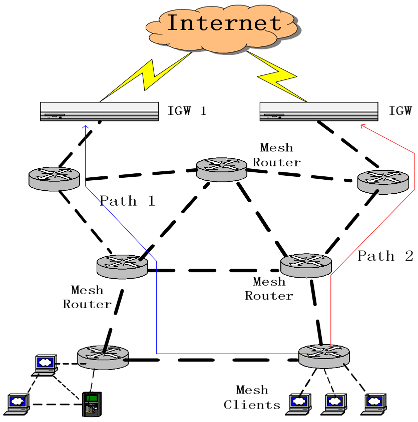

Fig. 1. Illustration of traffic splitting in a wireless mesh network.

IV. SIMULATION CONFIGURATION AND OBSERVATION OF THE RESULTS

In this section, we carry out extensive simulations to evaluate the performance of our proposed routing scheme using network simulator, ns2. We also provide observation of the simulation results and performance comparison between traditional routing and our proposed routing policy in terms of aggregate throughput and packet loss ratio.

A. *Simulation configuration*

In the simulations, we use a small-scale multi-hop wireless mesh network as an example to evaluate the performance of the proposed routing scheme. As shown in Fig. 2, there are 20 Mesh Routers (MR) consisting of the backbone of the wireless mesh network. Stations 1, 2, 3 are connected to MR 11 and station 4 is connected to MR 1. Two gateways, MR 5 and MR 20 are connecting to the Internet. All communications are based on 802.11 DCF. The transmission range is 250 m and the carrier-sensing range is 550 m. In addition, the distance between any two neighboring nodes is set as 200 m. The simulation duration is 300 s. The channel datarate is set to be 11 Mbps.

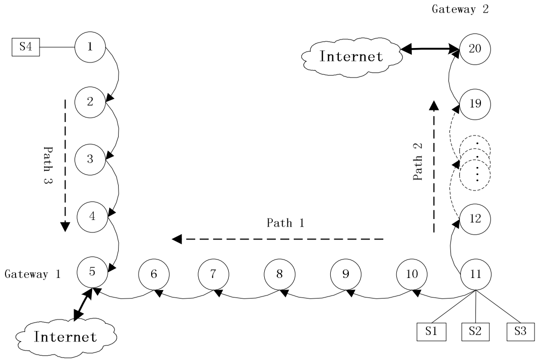

Fig. 2. Simulation topology of a WMN.

At MR 11, connecting stations send heterogeneous traffic. Two UDP flows and one TCP flow go through the network from gateway MR 5 or MR 20. At MR 1, a TCP flow is also generated from station 4 to go through the network. In order to saturate the network the traffic generated at source node in a manner that as soon as a packet is transmitted to destination node, another packet is ready for transmission.

In a heavily loaded wireless mesh network, clients may inject more traffic into the network than it can support. In our case, mesh clients S1, S2 and S3 generate more traffic than the saturation throughput.

TABLE 1
PROPOSED TRAFFIC SPLITTING POLICY VS. LEGACY ROUTING PROTOCOL.

		Legacy routing		Splitting policy	
	Src	Dest	Next hop	Dest	Next hop
TCP1	S1	GW1	MR10	GW1	MR10
TCP2	S4	GW1	MR2	GW1	MR2
UDP1	S1	GW1	MR10	GW2	MR12
UDP2	S1	GW1	MR10	GW1	MR10

Ad hoc On-Demand Distance Vector Routing (AODV) [12] is adopted in our simulations. Under the guiding of the legacy AODV, the heterogeneous traffic flows go through the network in the way as shown in columns 3 and 4 of Table 1. That is, all types of traffic go through the same path towards the closest gateway. Different from the legacy routing protocol, our proposed policy allows different types of traffic flows to be transmitted over different paths, even though they are covered from the same mesh router, as shown in columns 5 and 6 of Table 1. For instance, the traffic splitting policy tries to split UDP1 to travel along path 2 towards the Internet through gateway 2 when path 1 is heavily loaded, while other TCP and UDP flows are still using the original shortest path, i.e. path1. We could also split another type of flows, as described in the next subsection.

B. *Observation of simulation results*

Three cases are studied in our simulations. For our proposed traffic splitting policy, we modify the legacy AODV so that the routing decision is not only based on hop count, but also traffic load and service type. With this modification, we are able to split certain traffic flows into other path while the rest is still kept in the existing path, when the current path suffers from heavy traffic load. In our simulation, the split flow could be TCP traffic or UDP traffic, as specified below.

- Case 1: Traffic flows transmit based on the traditional routing protocol.
- Case 2: The traffic splitting policy is applied, where one UDP traffic flow is split to path 2.
- Case 3: Instead of splitting UDP traffic, one TCP traffic flow is split to go through path 2.

The observed simulation results based on these 3 cases are presented in what follows.

Case 1: Two UDP traffic flows and one TCP traffic flow generate from MR 11 and one TCP traffic flow generates from MR 1. Under the instruction of AODV, all flows transmit through gateway MR 5 since compared with gateway MR 20, gateway MR 5 has shorter hop count to the two source nodes.

As shown in Fig.3, in the heavily loaded network, we can observe that not all of the four traffic flows get opportunities to transmit. Indeed, the TCP flow from MR, TCP 1, 11 did not obtain any throughput. Due to the capacity limit and many competing stations on the same channel, although two UDP traffic flows are able to capture the channel, they have to share the bandwidth and each of them could only get limited throughput owing to time division of occupying the channel and packet collision during the competing. Considering TCP 2, the same reason of single channel limit and common gateway router shared with the rest of traffic flows leads to TCP 2 reasonable throughput.

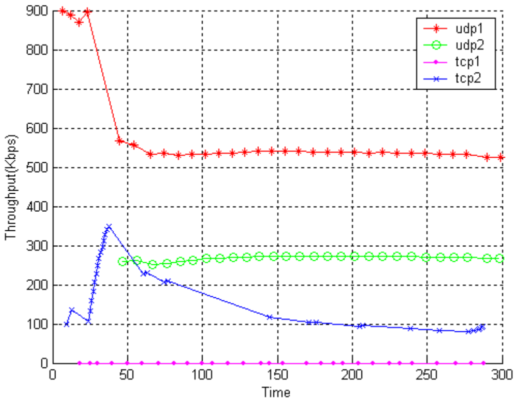

Fig. 3. Throughput of traffic flows in Case 1.

Case 2: By using our proposed traffic splitting approach, as the congestion condition on the current path reaches certain level, one UDP traffic flow is split to another path to attach the Internet through gateway, MR 20. As known from [13], in a chain topology the throughput of the traffic around 6 hops away from the source will converge to approximately 1/7 of the throughput that a single-hop transmission can achieve. For illustration of the throughput result, we take the observation of the achievable throughput of each traffic flow.

As shown in Fig.4, the split UDP traffic obtains much higher throughput gain and the total throughput is significantly improved. This is because that the split UDP flow transmitted along the new path has got much higher throughput compared with in Case 1. In Case 1, as the two UDP flows go through the same route, they have to compete to get to access the channel. In addition, owing to link capacity limit in path 1, it will be more difficult for the UDP flows to capture the channel. In Case 2, besides the split UDP flow another UDP flow also gets higher throughput as there is less traffic flow competing for the limited channel capacity. For the traffic flow of TCP 1, it still does not get any throughput due to the failure of competing with UDP traffic flows at the router.

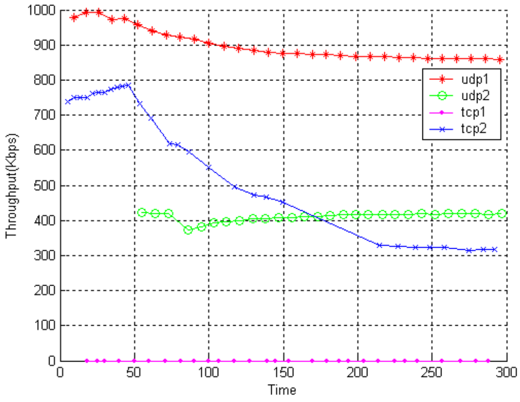

Fig. 4. Throughput of traffic flows in Case 2.

Case 3: Instead of splitting UDP traffic flow we redirect TCP traffic flow to the adverse path in this case. As shown in Fig.5, two UDP traffic flows are able to obtain stable throughput. However, the split TCP traffic flow still can not get any throughput. TCP traffic exhibits properties that it will send more and more packets to the network as long as there is enough bandwidth, and vice versa. After unsuccessfully competing with two UDP traffic flows which go through the same router, TCP traffic loses opportunities to access the channel to transmit any packets.

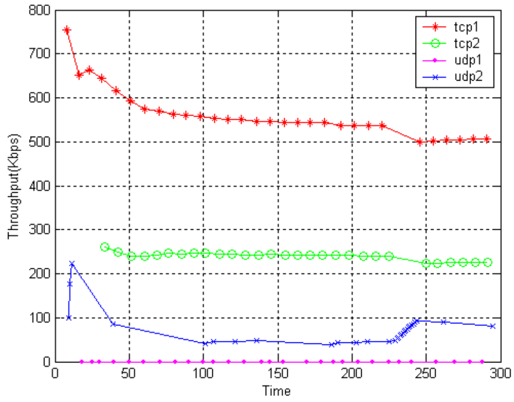

Fig. 5. Throughput of traffic flows in Case 3.

C. *Summary of the simulation result*

Comparing with the original routing strategy we observe that our proposed policy presents higher aggregate throughput. Table 2 illustrates that in Case 1 with the traditional routing protocol the aggregate network throughput is only 843 Kbps. However, in Case 2 with our proposed traffic splitting policy the aggregate throughput could reach 1526 Kbps, which is far higher than with the traditional routing. Although in Case 3 we also split certain traffic to another light loaded path, due to the service type of the split traffic the aggregate throughput we can achieve is only 788 Kbps, which is lower than in Case 2 and even lower than in Case 1. As a consequence, we do not recommend traffic splitting for TCP flows. Instead, rate control should be introduced to TCP traffic.

Table 3 shows packet loss ratio result of UDP traffic flows in three cases. Since the TCP traffic flow provided with retransmission mechanism, the dropped packet will be retransmitted if an ACK is not received within timeout. Due to this fact we do not consider the packet loss ratio of TCP traffic flow. It is observed that two UDP traffic flows in Case 2 get moderately less packet loss than in Case 1 and 3. The probability for successful packets transmissions in Case 2 is higher, nearly extra 10 percent of sending packets are able to achieve, indicating the reliability of data transmission is improved significantly.

TABLE 2
INDIVIDUAL AND AGGREGATE THROUGHPUT OF DIFFERENT FLOWS.

Throughput(Kbps)	UDP1	UDP2	TCP1	TCP2	Aggregate
Case1	525	225	0	93	843
Case2	858	340	0	321	1526
Case3	506	199	0	83	788

TABLE 3
PACKET LOSS RATIO IN THE THREE CASES[1].

Loss ratio (%)	UDP1	UDP2
Case1	87.12	89.82
Case2	78.19	80.67
Case3	87.44	90.63

V. FACTORS AFFECT THE OBSERVED RESULTS

In this section, we study a few factors that affect the network performance introduced by the splitting policy, e.g. the effects by competing stations, hidden terminal and traffic intensity. The performance of three cases will be also compared.

A. *Effect by the number of competing stations*

Traffic generated by many mesh clients has to compete for channel access at the router. The number of stations will influence the contention probability to obtain the channel. Collisions experienced by each source node suffer from packet loss during transmissions. The collision rate signifies the contention level in the channel, and it follows that higher packet

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[1] As the aggregate source datarate of total traffic flows is much higher than the maximum chain throughput the channel could provide, a large amount of packets will be dropped. If we set the source datarate lower, the packet loss ratio will be much lower.

loss implies less coordination among the competing source nodes. With the proposed traffic splitting policy, some traffic flows will be split to another path. Consequently, the number of competing stations along the congested path will relatively decrease, leading to lower collision probability. With less collision, the overall network performance is improved.

B. *Effect by hidden-terminals*

A fundamental issue in multi-hop wireless networks is that performance degrades sharply as the number of hops traversed increase. In addition to carrier sensing preventing simultaneous transmissions of adjacent hops within the carrier-sensing range of a node, the hidden terminal problem could also decrease system throughout. *However, hidden terminal problem happens only when the hidden terminals have packets to transmit.* With the number of flows increasing on the path, the hidden terminal problem will become even worse. Especially, in a heavily loaded route, more hidden terminals would be active, leading to more serious performance degradation.

By applying our traffic splitting policy, the traffic load on path 1 is reduced. Correspondingly, the effect of the hidden terminal problem on that path will be relieved. In Fig. 6, we could observe that, with the traditional routing in Case 1 and one of the traffic splitting methods in Case 3, most packet loss happens at MR 11, and the packets are dropped fewer and fewer at the remaining routers to the destination direction. It will also hold this principle in Case 2. We could find that packet loss happens in this case at two directions, and packet loss occurs relatively less than in Cases 1 and 3. What is more, compared with the routing scheme in Cases 1 and 3, the proportion of the packet loss at these nodes decreases dramatically with our proposed policy, which means that both these two paths enjoy higher delivery ratio. The total packet loss ratio among these nodes in Case 2 is far less than in Cases 1 and 3. Consequently our traffic splitting policy greatly eliminates the effect of the hidden terminal in a heavily loaded routing path.

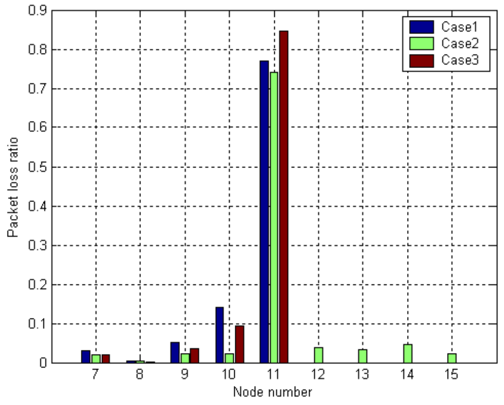

Fig. 6. Distribution of packet loss ratio among the nodes.

C. *Effect of traffic intensity*

If more traffic is injected into the network than it can support, it will lead to a congestion problem. For multi-hop wireless mesh networks, if heavy traffic load is transmitting from the first hop, the throughput will decrease as the number of hops increases.

It has been shown in [13] that in a chain topology the traffic flow could not get a sustainable stable throughput until 6 hops away. It is the result of carrier sensing and hidden-terminal problem which imposes the limitation on channel spatial-reuse and increases the chance of link failure. From the view point of MR 5, when the traffic started at MR 11 reach MR 5 which is 6-hop away from the source node, the total generated throughput more than saturation at first node will decrease approximately to 860 Kbps at the 7th node, which is nearly 19% of one hop saturation throughput. If the traffic generated at MR 11 does not reach the saturation throughput, but more than 860 Kbps, the received traffic at MR 5 will be also 860 Kbps. So we could conclude the network sustainable capacity is 860 Kbps from the view point of MR 5. This is also true for the whole network or even worse if the flow traverse more than 6 hops.

Guided by this principle, in Fig. 7, it is true at MR 11 that all stations compete for getting access to the same channel. Assuming that in Case 1 under the same condition each traffic generated by the three stations is more than 860 Kbps, then only 860 Kbps could be received. Actually, since TCP 2 generate at station 4 will also go through MR 5 which shares the channel, and TCP 1 comes from the same router with UDP 1 competes to access the channel which leads to packet collision. Indeed, the throughput of path 1 obtaining at MR 5 is 750 Kbps. In contrast in Case 2, as the split traffic transmit from path 2, additional 860 Kbps capacity could be achieved on another path. Although in Case 2 the throughout obtained at MR 5 decreases, from the two curves of Case 2 in Fig. 7 we could observe that the total throughput on both path 1 and 2 in Case 2 is much higher than the one obtained in Case 1. The proposed policy admits almost twice as much traffic as the legacy routing protocol could sustain.

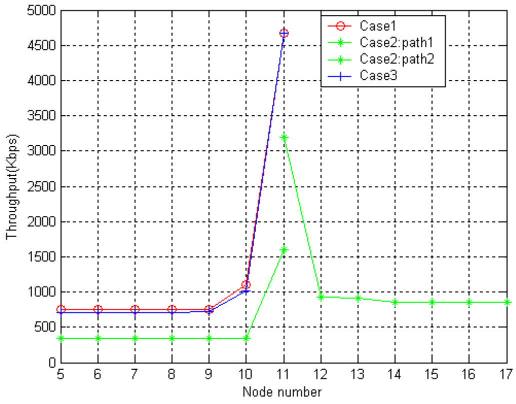

Fig. 7. UDP throughput at different MR in the presence of TCP flows.

Considering these mentioned issues and the earlier conclusion, if more traffic is trying to go through path 1 on which ongoing traffic flows have filled full of the saturation throughput, it should be rejected subject to the network capacity constraint. But if we switch some traffic flows into path 2 which assumes to be relatively lightly loaded, there will be no such capacity limitation, then we could achieve more aggregate throughput by utilizing the resources of path 2.

D. Unfairness among TCP flows

Most of the factors lead to TCP unfairness can be tracked back to unfairness of the IEEE 802.11 MAC protocol. However, the greedy behavior of TCP and its poor interaction with the MAC layer further exacerbate the unfairness situation. Compared with UDP, the adaptivity of the TCP traffic gives it high throughput in a lightly loaded environment and low throughput in a congested environment. In both cases, TCP traffic will have a very low TCP packet loss because of its retransmission scheme.

Generally, TCP tries to send more packets when the network is lightly loaded, and vice versa. There are also periods in which TCP traffic is completely stopped. In our scenario, TCP 2 starts earlier to send packets than TCP 1. We could observe that TCP 2 achieves stable throughput while TCP 1 gets no chance to transmit. As TCP 2 catches the channel and path 3 is lightly loaded, its congestion window size will become larger and larger, sending as more packets as it could. Conversely, TCP 1 fails to transmit due to the unsuccessful competition with UDP flows, and then back-off mechanism aggravates the failure of its transmission. Compared with TCP 2, the contention window of TCP 1 becomes larger and larger, so TCP 1 loses the opportunity while trying to send packets again. This explains the reason for very low throughput of one of the TCP flows in these cases.

VI. DETAILED ALGORITHM DESIGN

Based on the above observations and performance analyses, we design the traffic splitting algorithm with more details as follows.

As mentioned in Sec. 3, when the traffic load condition on the path measured by the combined metric reaches certain pre-defined value, we split certain number of traffic flows from the ongoing path to another one. However, we did not distinguish traffic type when we split the flow to another path, i.e. both UDP and TCP can be split. Through simulations studies, we conclude that, usually, UDP traffic flow will be taken to split to another path if congestion happens. As a consequence, the split traffic flow will get better throughput, and the aggregate network throughput will significantly increase. This performance is improved at the cost of more resource utilization in the newly directed path. Meanwhile, we do not recommend to split TCP traffic, because TCP flow will generate little traffic in the heavy traffic loaded condition. Instead, rate control policy is applied on TCP flows.

The detailed traffic splitting algorithm is shown in the following diagram.

***Algorithm**: Traffic splitting policy*

```
Begin
  At each mesh router
    If the value of the combined metric < Threshold
      Admit this node and follow the original shortest path routing protocol
    End if
    If the value of the combined metric ≥ Threshold
      Inform all the mesh routers by
        Sending a Congestion_Notify message using multicast
    End if
  Upon receiving a Congestion_Notify message
    For each path to the gateway
      Select the lightest loaded path from all available paths
    End for
    Check service type
    If it is UDP
      Then split the traffic flow
    End if
    If it is TCP
      Then apply rate control policy
    End if
End
```

VII. CONCLUSIONS AND FUTURE WORK

In this paper, we presented a novel traffic splitting policy to improve the performance of wireless mesh networks. We study the impact of number of competing stations, hidden terminals, and traffic intensity on the network performance. Through these reasonable and practical analyses, a traffic splitting routing algorithm is proposed. The simulation results demonstrate that our splitting policy can moderately reduce packet loss and significantly increase aggregate network throughput compared with the legacy routing protocol. The great benefit is achieved by the split traffic flow with the aid of better utilizing the resources in the whole network. As our future work, a large-scale network will be tested and rate control on TCP traffic will be studied.

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