A Framework of Distributed Dynamic Multi-radio Multi-channel Multi-path Routing Protocol in Wireless Mesh Networks

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Abstract— **Wireless Mesh Networks (WMNs) have gained a lot of attention recently. Many efforts are made to design proper routing protocols for WMNs. Existing multi-radio multi-channel routing protocols utilize only one path for transmission, and some multi-path routing protocols consider only single channel situation, in which multi-path routing won't improve end-to-end throughput efficiently. In our paper, we propose a framework for distributed reactive routing protocol in WMNs, which utilizes multi-radio multi-channel technique, as well as multi-path transmission strategy. Dynamic channel assignment is used to avoid the inter-flow and intra-flow channel competition and interference. Our protocol establishes and maintains two or more channel-dimensional disjoint paths, and then every data flow is splitted into multiple paths, in order to increase the total end-to-end transmission throughput. Demo and NS2 simulations are carried out for the evaluation of the performance of our proposed protocol comparing with AODV and other related routing protocols. It is shown our proposal can increase end-to-end throughput significantly.**

I. Introduction

Recently, the Wireless Mesh Network (WMN) [1] becomes popular and important in wireless technology and industry fields. WMNs are believed to be a promising technology to offer high bandwidth for wireless access to the Internet. In the infrastructure of a typical WMN, fixed wireless mesh routers and gateways are highly connected together in a ad-hoc manner. Mesh routers are practically Access Points (APs) equipped with functionalities of IEEE 802.11 standard series [2], e.g. 802.11a/b and 802.11g, where normal wireless devices can connect for communication services. Mesh routers performs not only as a role of data aggregator, but also as a role to relay data to gateways. WMN gateways are devices with high bandwidth that can provide internet connections to routers. Data flows can be formed in multi-hop manner from wireless devices through each mesh routers to the gateways, or to other mesh routers and devices in other areas.

WMN infrastructure benefits from large coverage of multi-hop wireless connections, but it also suffers channel competition and collision problems. Because of half-duplex property of radio antenna, one network radio cannot transmit and receive at the same time, the capacity of transmission link can only achieve a half of basic MAC layer rate. Broadcast nature of the wireless medium makes nodes work in common communication channel, therefore nodes have to wait for other nodes that are occupying the channel, and then compete with each other for next chance. If two nodes in each other's transmission range and in the same channel transmit at the same time, there will be collision. It is difficult to avoid transmission collisions, although some mechanism like RTS/CTS are invented to fix the hidden terminal problem resulting in reduction of throughput.

Multi-channel technique can significantly avoid transmission competition and collision in the same channel. Orthogonal channels use non-overlapping frequency bands, thus there is no interference among them, for example, in IEEE 802.11a there are 12 orthogonal channels. Routing protocols assigning diverse channels to each hop of data flow can reduce intra-flow channel interference and competition therefore can improve end-to-end throughput times. Radio is a network function with antenna that can switch and transmit data in a specified channel, and wireless devices are able to equip two or even more radio which are working in different channels, to make full-duplex transmission and provide more efficient routing.

Multi-path routing strategies are also designed to split and transmit data through two or more different paths to destination simultaneously. However, multi-path routing cannot achieve times of throughput as we expect since inter-/intra-flow channel competition and interference. Therefore we propose a novel framework for multi-channel and multi-path routing protocol in WMNs which use both techniques.

The rest of this paper is organized as follows: In Section II we will briefly compare different routing strategies in WMNs then propose the motivation of our work. In Section III we will explain our protocol and algorithm in detail. Section IV is the part of simulations showing evaluation of our proposal. Conclusion and future work will be mentioned in Section V.

II. Motivation

We initially compare some existing routing strategies, from the aspect of number of paths and radios, thus our motivation of this novel framework, which is to utilize multi-radio and multi-path strategy in order to improve flow end-to-end throughput in WMNs, will be carried out.

A. Comparisons of Routing Strategies

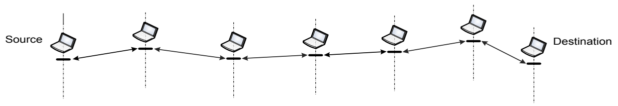

Fig. 1. Single Radio Single Path

1) SRSP(Single Radio, Single Path): Among a great number of routing protocols, it is common to use a single-radio and single-path routing method, e.g. Dynamic Source Routing (DSR) [3], Ad-hoc On demand Distance Vector routing (AODV) [4]. In this case, packets travel along the chain of nodes toward their destinations and all nodes are working with one radio in the same channel, as shown in Figure.1. Successive packets on a single chain may interfere with each other causing channel competition and collision in the MAC layer. Ideally end-to-end throughput could achieve at most 1/3 of the effective MAC layer data rate, since at one time, among any three continuous nodes only one can make transmission in the same channel.

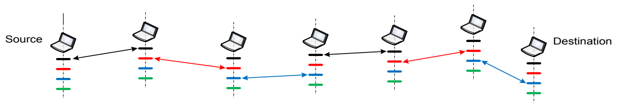

Fig. 2. Multiple Radio Single Path

2) MRSP(Multiple Radio, Single Path): Some researchers have proposed multi-channel/multi-radio solutions using more channels/radios to receive and send data in different channels simultaneously, such as [5], [6] and [7]. In this scenario, an ideal multi-channel/multi-radio routing protocol could help achieve end-to-end throughput almost as high as the effective MAC data rate. Considering the scenario in Figure.2, a assume that the MAC protocol can always select an appropriate radio and schedule perfectly. At time slot 1, the first node transmits the first packet to second node on channel 1. At time slot 2, they can transmit at the same time using different radios as well. If radio resources are enough for MAC protocol, every node can continuously inject one packet every time slot.

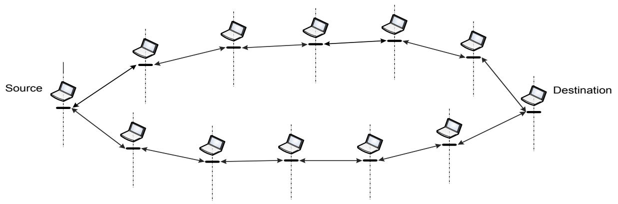

Fig. 3. Single Radio Multiple Path

3) SRMP(Single Radio, Multiple Path): In multi-path routing, packets are split into two or more disjoint paths to destinations, like SMR routing [8], and AOMDV [9]. In Figure.3, there are tow paths, each of which performs the same as the SRSP. Hopefully, twice end-to-end throughput can be achieved. However, broadcast nature of wireless medium degrades throughput significantly since all nodes are still working in the same channel, especially the first and last node, which are mostly the bottle neck nodes. Consequently, practically SRMP routing protocols help make limited improvement of throughput.

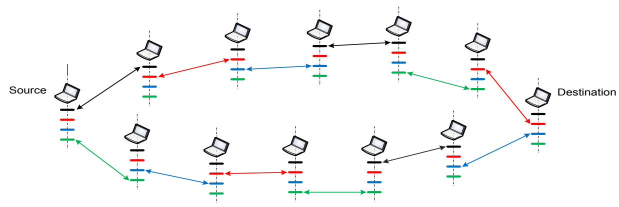

Fig. 4. Multiple Radio Multiple Path

4) MRMP(Multiple Radio, Multiple Path): Ultimately, we show a protocol using a multi-radio MAC protocol combined with multi-path can overcome every issue we mentioned above. In MRMP scenario, the ideal MAC end-to-end throughput can be as high as the effective MAC data rate multiplying the number of paths. Figure.4 shows a case in which a routing protocol can split data flow properly and radios used in transmission are enough and well assigned by the MAC protocol. At time slot 1 of this case, one node transmits a packet along the upper path to next node on a channel, and simultaneously, another node in the lower path also transmits a packet to its successive node. At time slot 2, still all nodes can keep receiving packets using one radio from previous node, while forwarding to next nodes with the other radio at the same time. Therefore, this achieves an end-to-end throughput twice as full MAC data rate.

B. Related Work

To our knowledge, JMM protocol[10] is the only protocol utilizing multi-channel technique and multi-path strategy in WMNs. JMM divides the time into slots, and coordinates channel usage among slots using a receiver-based channel assignment and schedules transmissions along dual paths. JMM efficiently increases the performance by decomposing contending traffic over different channels, different time, and different paths. However, JMM protocol could not dynamically assign channels upon changeful network status. Also it is centralized algorithm, which requires high amount of controlling messages exchanges inducing high overhead. According to this, we propose a novel routing protocol dynamically utilizing multiple radios of each node and multi-path strategy upon current network status. Every node will select optimal channel and radio based on latest one-hop neighbor information, and the route establishment are in distributed manner.

III. Framework of Proposed Routing Protocol

Challenge in our framework is how to set up two or more optimal paths with different channel assignment diverse enough to make no intra-path and inter-path influence to improve the throughput of the transmission. Our distributed algorithm for each WMN router will be discussed in detail in this section.

A. Assumptions and Definitions

We assume each mesh router can have maximum N radios working in N orthogonal channels perspectively. This is not limited to current standards, which means our proposal can be adapted to future standards easily. WMN routers connect together as a homogeneous networks with bi-directional links, and we define two words to evaluate a path.

- **Topology-dimensional Disjoint paths**: From the view of network topology, there is no graphical joint nodes of two paths. In other words, they share no node in common.
- **Channel-dimensional Disjoint paths**: From the view of channel assignment, if a node is involved in two or more paths of the same flow, it will be assigned to make two radios work in different radios, therefore different channels, for each path. This means even if paths are graphically joint, but at the joint, different radios are assigned, and there will be no channel competition and interference there.

B. Routing Algorithm

Our scheme mainly bases on origin AODV, a reactive routing protocol which uses a broadcast route discovery mechanism and relies on dynamically establishing route table entries at intermediate nodes. Our approach modifies some bits in the hello messages of AODV protocol in order to make each router know the channel usage status of its neighbors. Also, some bits and frames of RREQ/RREP are changed slightly, and the abandon and rebroadcast mechanisms of the AODV RREQ are changed to meet the need of the new scheme.

Node Id	Relationship	Channel Usage List
4	Myself	00101…
2	CS	11001…
3	CS	11010…
5	CS	00001…
7	CS	01100…
Total Channel Usage Index		23213…

Ch#1	Ch#2	Ch#3	Ch#4	Ch#5 …
0	0	1	0	1 …

1 ~ Occupied by data flow
0 ~ Idle

Fig. 5. Channel Usage List

1) Channel Usage List and Modified Tables: We predefine Channel Usage List showed in Figure.5 which is maintained by each node. It stores the channel usage status of the node itself and its 1-hop neighbors. As the figure shows, node will choose the least channel#4 to rebroadcast the RREQ. Also AODV routing tables are modified a little adding radio info. AODV routing discovery table is used to store path info temporarily to temporarily store the first path info and to help construct the second path.

2) Path Discovery: The Path Discovery process is initiated whenever a source node needs to communicate with another node for which it has no routes in its routing table. The source node used flood mechanism such as AODV routing protocol. The modified RREQ carries more information about its path ID. The RREQ flooding is as shown in Figure.6. The first RREQ with path_ID=1 will choose the least used channel to broadcast, related bit in routing discovery table will be modified. After a short random period, the second RREQ with path_ID=2 will be broadcasted in the second least used channel, so as the following RREQ if more paths are used. This makes sure the second path of same flow won't use the same radio as the first path at this node. Note that our algorithm guarantees channel-dimensional disjoint characteristic of the paths of same data, by using discovery table, as the first priority. The topology-/channel-dimensional disjoint characteristic of paths of different flows can be guaranteed if radio resource is enough, which means it will be treated as the second priority.

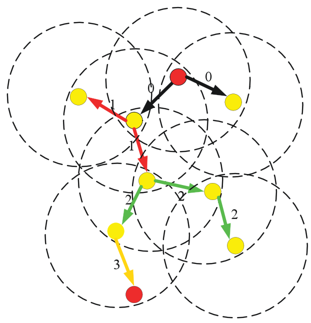

Fig. 6. Flooding RREQ

Each neighbor either satisfies the RREQ by sending RREP back to the source, or then rebroadcasting the RREQ to its own neighbors. To choose an optimal channel for rebroadcast is one of the key issues in the proposed scheme. As each node is maintaining its Channel Usage List, it clearly knows the channel status of itself and its 1-hop neighbor nodes. Therefore it will select the least used channel to rebroadcast the RREQ.

3) Reverse Path Setup: A node records the address of the neighbor from which it received the first copy of the RREQ in case that it will set up a reverse path. These reverse path route entries are maintained for at least enough time for the RREQ to traverse the network and produce a reply to the sender. Besides, the abandon mechanism of RREQ is a bit different from the one in AODV. When an intermediate node receives a RREQ if it has already received a RREQ with the same broadcast id, source address, and also the radio, or the RREQ is from one of its next hop node, it recognize the RREQ as a redundant one and does not rebroadcast but drop it. Algorithm is showed in Figure.7

4) Forward Path Setup: Once the destination node received the RREQ, it replies the RREP. Then the RREP trace the vectors in each node to reach the source node. This is the way of setting up the forward path from all nodes back to the source. Addition to AODV routing protocol, reverse path setup duration is accompanying the channel status table maintenance. Once RREP reach a node, the node has to broadcast a channel announce message (CAM) which contain the channels it used for receiving and forwarding the RREP to its neighbor nodes. All of the neighbor nodes received the CAM and then use it to update its Channel Usage List.

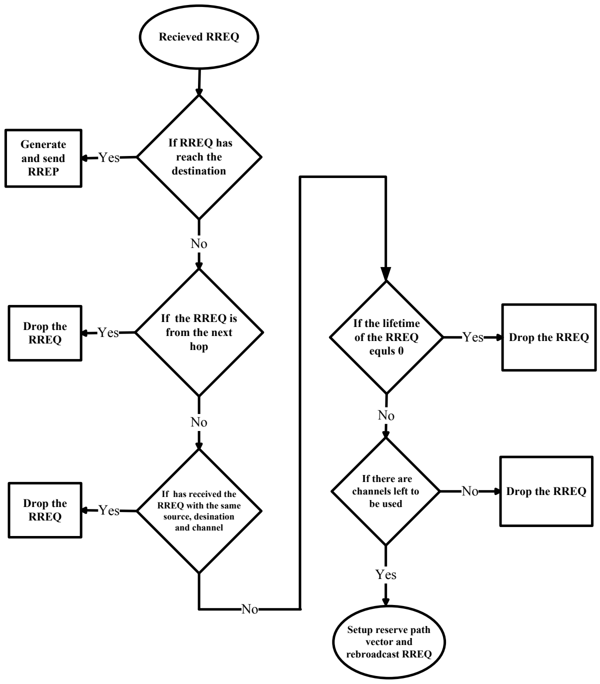

Fig. 7. Procedure of RREQ

5) Multi-Path Maintenance: After the path initialization, in ideal situation, we can get two or more paths in the wireless mesh network. A special calculation will be done to select two or three of the paths for data transmission simultaneously. Dynamic maintenances based on the quality of WMNs are still in consideration.

6) Data Transmission: Data is divided into several concurrent flows, and be transmitted to the destination simultaneously. Currently in dual paths, packets with odd ID number is sent to path 1 and packets with even ID number is sent to path 2. Also we can use improved scheme that we assign packets to paths based on the practical bandwidth of each path from feed back, which utilizes network resource better.

IV. Simulations

A demo based on our algorithm was developed to discover routes in a virtual network. Routers are placed in a grid in where only the four routers around are considered as neighbors.

A. Simulation Without Interference Flow

In this evaluation scenario the network starts from an idle state and there is no other concurrent flows.

1) Path Discovery: Figure.8 contains some of the paths our demo discovered while the virtual network contains not any other interference flow, which is evaluated in the NS2 platform in the next step. Links with different color mean the different radios, and they show the routing path from the source node to the destination one with specified hop counts.

Origin AODV routing is used in SRSP scenario, and for MRMP Scenario, we use our proposed protocol. In the SRMP scenario, we simply use the same paths as MRMP but all nodes

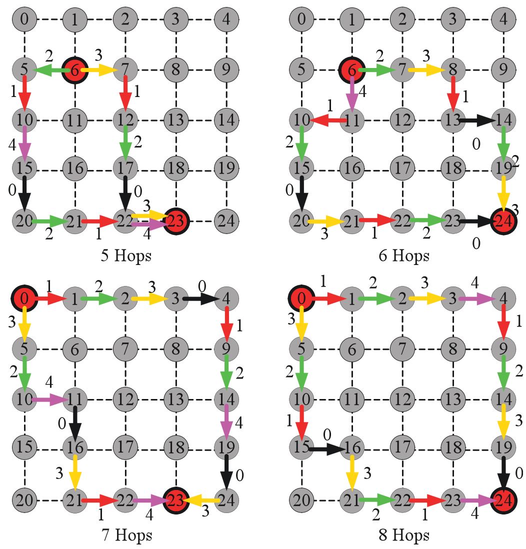

Fig. 8. Protocol Demo Showing Channel Assignments and Paths

with only one channel. For the MRSP scenario, we selected the shorter path in MRMP as the only optimal path and same channel assignments are used.

2) Simulation Performance related to Hops: We analyze the details of the four scenarios on the trends of them related to the hops. The tested topology is a 7x7 grid. 802.11a at 6Mbps rate and UDP traffic are used. We utilize 5 channels and radios. Figure.9 compares the throughputs of the four scenarios.

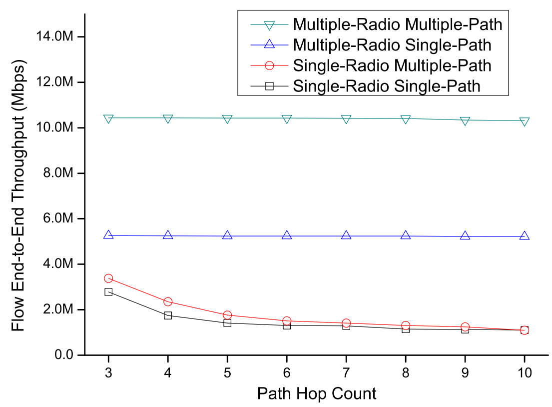

Fig. 9. Performance In Idle Network Scenario

MRMP has the best throughput performance. It could achieved an about 10 Mb throughput. MRSP could also provide a high throughput at about 5 Mb, a half performance of the MRMP scenario, because it uses only one path to transmit data between the source and destination. Scenarios with single radio have a poor performance because the channel competition and interferences intra-flow in a single channel scenario will seriously affect the capacity of the throughput. Meanwhile, if the number of the radios is enough for the assignment in multiple channel scenarios, the decreases of the throughput along with the increase of the hops will not impact the throughput and each hop is transmitting at maximum speed. SRSP could only achieve about 1 Mb throughput, which is about 1/10 of the MRMP scenario, and SRMP do not make any enhancement on the throughput comparing to SRSP even if it uses multi-path, since the intra-/inter-path channel competition and interference could not be reduced when single channel is used.

B. Simulation with interference flow

1) Path Discovery: In order to verify whether our proposal still works well if it already exists other flow in the network, as shown in Figure.10, we simulate a interference transmission flow from node 2 to node 22, and then we simulate a data flow from node 6 to node 18. Throughput of each flow by AODV and our proposal are tested.

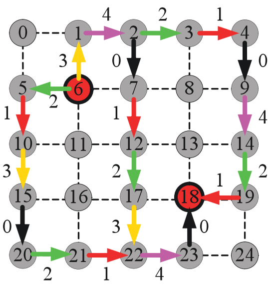

Fig. 10. Paths Discovery in Scenario with Concurrent Flow.

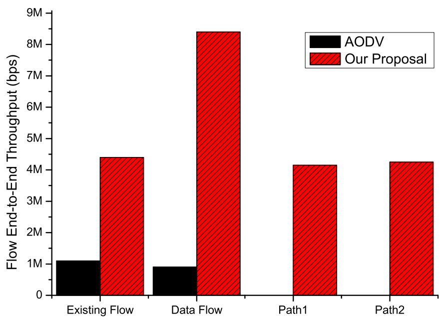

Fig. 11. Protocol Performance in Scenario with Concurrent Flow.

2) The Enhancement of Throughput: We evaluated this scenario in NS2, comparing with origin AODV. According to the existing flow, channel competition and interference cause performance reduction for origin AODV protocol working in one channel and one path. For this reason, by using AODV, from the Figure.11, the data flow could only achieve 802 Kb throughput, and the interference flow can achieve nearly 1Mbps. On the other hand, the throughput of the flow based one our proposal changes little by the interference flow. If our proposed routing protocol is used for data flow and interference flow, both of them can achieve very high throughput. For the data flow, it is divided into two paths, and as we can see path 1 and path 2 can achieve 4Mbps throughput. This shows that our proposal also have a better performance comparing to other scenarios in the network if the radios resources are still enough and they are well allocated. The reason is that the dynamic path establishing mechanism and channel selection of our proposed protocol make routes more flexible when some of the channels in the network are occupied.

V. CONCLUSIONS

In this paper, we proposed a framework for a multi-radio and multi-path routing protocol based on origin AODV for Wireless Mesh Network systems. The protocol can dynamically establish multiple paths with diverse channel assignment, which are topology-dimensional and channel-dimensional disjoint for data transmission, and the routing initialization works in a distributed manner. JAVA demo and NS2 simulations are carried out to evaluate our proposed protocol compared with other routing strategies: SRSP, MRSP and SRMP. Our proposal can make significant enhancement on achievable throughput in WMNs if the network is initially idle, and it performs still better than AODV in scenarios where there is also other concurrent ongoing flow. In future we are planning to make more evaluation on scenarios with heavier traffic and make optimization, because the exhaustion of radio resources will impact our propose much. Also routing discovery overhead and delay will be relatively worse than other protocols. We will also mathematically modeling and we hope implement on QualNet4.0 and even real testbed.

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