

Multipath Routing over Wireless Mesh Networks

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Abstract

Wireless Mesh Networks (*WMNs*) are self-organized multi-hop networks, which have been widely deployed to provide wireless Internet access. *WMNs* forward data via omni-directional antenna. Consequently, the performances of *WMNs* are always limited by interference. Multipath routing, however, can also take advantage of broadcast nature of omni-directional radio to improve performance. To the best of our knowledge, tens of multipath routing protocols have been designed over wireless networks for different purposes up to now, but few of them have been evaluated on real testbed.

We extend *SRCR* into multipath routing protocol for a multi-radio, multi-channel network with *Click* and evaluate it on the testbed consisting of twenty nodes. Our contributions are twofold. First, we verify interference between different channels. Results show that channels of *IEEE 802.11b* interfere with each other due to *close interface effect*. But, channels at *2GHz* and *5GHz* bands can work simultaneously without any interference.

Second, we conduct a series of experiments to investigate how path metric, path selection scheme, and other parameters affect the throughput of our implementation. It turns out that path selection scheme is the most important factor determining throughput and throughput can be largely increased if node disjoint scheme is adopted instead of link disjoint scheme. Cache and query frequency can only slightly affect mesh network performance. These results are valuable to gradually improve multipath routing protocol design in future.

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1 Introduction

Wireless Mesh Networks (*WMNs*) are self-organized multi-hop wireless networks, which consist of mesh routers and mesh clients. Mesh routers communicate with each other via wireless link and make up backbone network to provide service for clients. Special routers called gateways perform bridge functionalities to integrate wireless mesh network into the existing wired network. Routers are usually stationary with power supply. Mesh clients can be stationary or move around the area covered by wireless signal. Clients directly talk to routers in infrastructures *WMNs* architecture. In Client *WMNs* architecture, clients take the responsibility to relay data for others. We only focus on data transmission among mesh routers in this thesis.

Today, *WMNs* are widely deployed as the last mile of the global network but also turn into the network bottleneck. On one hand, interference and signal attenuation largely degrade the performances of *WMNs*. Moreover, wireless links are unreliable and variable over time, which also decreases mesh network throughput in some extent. On the other hand, data traffic blooms with the development of network technologies, which impose great challenges on *WMNs*. For instance, applications involved with high quality videos or 3D objects cost a large amount of bandwidth. In addition, peer-to-peer data sharing also greatly contributes to the increasing network traffic.

To ease the bandwidth bottleneck, many techniques have been proposed for wireless mesh network, such as multi-channel design, rate adaptation, power control, directional antenna, and so on. These techniques that can directly or indirectly increase the throughput of mesh network will be presented as follows.

Firstly, multi-channel design can greatly reduce or even eliminate interference of wireless networks. *IEEE 802.11a* standard theoretically provides twelve orthogonal channels, which can be used to send data simultaneously. Although evaluation results in [SM10] show that non-overlapping channels of *802.11a* interfere with each other due to *close interface effect*, multi-channel design potentially reduces interference. Many papers are published on channel selection and channel assignment. To fully investigate the gain of

multi-channel design, multi-radio has been proposed, hoping that network throughput can linearly increase with the number of network interfaces. *MIMO* is a classic application scenario of multi-channel and multi-radio. In short, multi-channel design is a promising technique to improve the performance of wireless mesh network, especially for multi-radio networks.

Secondly, rate adaptation dynamically selects data rate according to link quality to increase throughput. Currently, *IEEE 802.11a* standard supports a series of rates from *6Mbps* up to *54Mbps*. Higher data rate can increase throughput by several times but tolerate less interference. Rate adaptation adjusts data rate according to signal attenuation and interference, since they are the two main reasons for packet drop. If packet drop is caused by signal attenuation, data rate has to be reduced. Otherwise, senders can continue sending data at the current rate. So far, many researches have been done on rate selection and link quality measurement.

Thirdly, power control changes network connectivity as well as signal interference by tuning transmit power. Different from that of sensor network, power constraint is not a critical issue for wireless mesh network, for routers are stationary with power supply. The point is that lower transmit power will produce less interference, which can increase the overall capacities of *WMNs*. Traditional protocols leverage *CSMA* to coordinate transmissions. Nodes have to keep quiet if they sense ongoing transmissions. In other words, fixed power model with on and off states are employed. In [MBmWH01], Monks et al. extend fixed model into bounded power model, in which, nodes can start a new transmission with minimum power provided it will not disturb ongoing transmissions. As an application of power control, bounded power model allows more concurrent transmissions, which will increase the overall throughput.

Lastly, directional antenna can also reduce interference greatly. Networks working with directional antenna should be carefully designed and routers should be placed in position. Directional antenna may complicate network deployment, but still can be adopted in some scenarios for high throughput.

Multipath routing is also an efficient way to directly improve network performance. Multipath routing is special because it works on a upper layer and decides on which techniques aforementioned to work cooperatively with. Nevertheless, multipath routing protocols are more suitable to wireless networks than single path protocols. Single path routing protocols in *WMNs* may not provide enough bandwidth due to signal attenuation and interference. Additionally, path discovery may be initialized frequently because of unreliable wireless link, which burdens mesh network with protocol traffic. In contrast, multipath routing protocols can take advantage of broadcast nature of omnidirectional radio and fully exploit resource redundancy and path diversity of wireless networks to increase throughput. They maintain multiple paths for every pair of nodes and broken routes can be recovered by shifting to another path without generating any protocol overhead.

With the development of *WMNs*, tens of multipath routing protocols have been proposed aiming at increasing reliability, reducing latency, increasing throughput or reducing overhead. Section 2 will give a literature review on these multipath routing protocols.

To design a multipath routing protocol for a multi-channel multi-radio network, we first evaluate interference between different channels on the real testbed located in Prince George's Park Residence, National University of Singapore. Although *802.11b* claims that it has three non-overlapping channels and *802.11a* has twelve, our measurement results show that channels of *802.11b* are interfered with each other due to *close interface effect*. Luckily, channels of *802.11a* and *802.11b* can work simultaneously without any interference.

Next, we conduct a series of experiments to investigate how path metric, path selection scheme, and other related parameters affect the throughput of our multipath routing protocol. *SRCR* protocol used in *Roofnet* is extended into multipath routing protocol for a multi-channel multi-radio network in our implementation. Multipath routing protocol can choose *ETT* or *WCETT* in [DPZ04] as metrics to measure path cost and produce link disjoint or node disjoint paths. Measurement results show almost 30 percent node pairs perform better with multipath routing protocol than two single path

routing protocols running on two set of interfaces independently. It turns out that path selection scheme is the most important factor determining network throughput. The throughput can be largely increased if node disjoint scheme is adopted instead of link disjoint scheme. However, neither node disjoint scheme nor link disjoint scheme considers interference between selected paths at source nodes. This interference correlation can degrade the performance of multipath routing protocol. In future, non-interfered multiple paths should be selected for simultaneous transmissions.

The reminder of the thesis is organized as follows. In Section 2, we give a literature review on multipath routing protocols and relevant techniques. Implementation details of our multipath protocol are presented in Section 3. Then, we evaluate the performance of the new protocol and compare it with a single path protocol. Corresponding results are shown in Section 4. Section 5 summarizes this thesis and points out possible research directions in future.

2 Literature Review

An efficient multipath routing protocol for multi-channel, multi-radio wireless networks usually jointly integrates with channel assignment, power control, and rate adaptation. For instance, in [LRG10], Luo et al. propose to take power level and data rate as link properties, which play important role in route computation. In other words, routing protocols for wireless mesh networks prefer cross layer design because network layer has to know exactly what happens on lower layers to react wisely. The upper layer can retransmit packets if collision leads to loss. But, data rate has to be lowered if signal attenuation is the cause of loss.

This section mainly provides an overview on multipath routing protocols and related techniques such as channel assignment scheme, power control, and rate adaptation. Section 2.1 classifies multipath routing protocols into four categories according to their advantages. Traffic distribution, as a special component of multipath routing protocol, is shown in Section 2.2. Section 2.3 summarizes research progresses on channel assignment scheme. Section 2.4 briefly introduces rate adaptation and power control.

2.1 Multipath Routing Protocol

Bandwidth incompatibility between wireless and wired network motivates the development of multipath routing as well as related techniques. Single multi-hop path usually cannot provide bandwidth as high as wired route due to signal attenuation and interference. Plus, several clients compete for the limited bandwidth provided by mesh router. Multipath routing can increase bandwidth by involving more resources to serve clients. Several inter-domain protocols for wired networks also adopt multipath routing scheme, such as Multi-path Interdomain ROuting (MIRO) in [XR06] and Yet Another Multipath Routing Protocol (YAMR) in [GDGS10].

Compared to wired networks, wireless networks are more suitable to adopt multipath routing. First, broadcast nature of omni-radio enhances connectivity between routers, which is helpful in discovering multiple paths between source and destination. Second, multi-channel and multi-radio design largely exploit the benefits of multipath routing.

Third, multipath routing protocol can reduce protocol overhead, because broken path can be easily replaced with alternative paths without flooding new query packets.

As Tsai and Moors say in [TM06], multipath routing qualifies a range of advantages such as high reliability, reduced latency, balanced load, and aggregated throughput, which will be described as follows.

- High reliability

Multipath routing is much more resilient to packet loss than single path routing. Reliability can be easily enhanced by sending out redundant information over a set of paths. For instance, video can be encoded into multiple descriptions and these descriptions traverse over different paths to destination. If several descriptions are lost for some reason, destination may still be able to decode received descriptions into the original video. Gálvez et al. also propose to generate multiple paths that are far away from each other in measure of physical distance in [GRS11]. Then, this proposal can be more resilient to the regional failure in which nodes in a certain area fail at the same time.

- Reduced delay

The latency can be reduced mainly because senders can simply shift to backup routes for data transmission in multipath routing, once path breakage is detected. But, single path routing has to initialize costly path discovery procedure and wait until a new route is discovered. Moreover, multipath routing can potentially reduce path discovery frequency as well as protocol overhead.

- Balanced load

Sources in multipath routing have the opportunity to dynamically balance data among network by scheduling transmission over multiple paths. Ideally, all the traffic can spread evenly over the whole network. Overall throughput can be increased by avoiding congested nodes and balancing traffic load.

- Aggregated throughput

Throughput can be aggregated linearly by transmitting data simultaneously over carefully selected paths. This property is particularly beneficial when single path cannot satisfy bandwidth requirement. Multipath routing provides one way for

applications relying on high-bandwidth to run over wireless networks.

With the development of wireless networks, tens of multipath routing protocols have been proposed that can be broadly classified as (a) reliable multipath routing protocol, (b) delay-aware multipath routing protocol, (c) minimum overhead multipath routing protocol, and (d) hybrid multipath routing protocol. Reliable multipath routing protocols are proposed in [WZ04], [WZ09], [GGSE01], [HKS09], [GGSE01], [CGHT11], [GRS11], and [Mos05]. Delay-aware multipath routing protocols are proposed in [LG00], [SJM01], and [MD01]. Minimum overhead multipath routing protocols are proposed in [JLR08], and [LW05]. Hybrid multipath routing protocols are proposed in [YW06], [LRG10], [OIM09], [WH01], and [DYX11]. Table 1 summarizes the main features of these multipath routing protocols.

	Category	Route discovery	Traffic distribution	Allocation granularity	Route maintenance	Motivation /Application
<i>RMPSR</i>	Reliability	Multiple nearly disjoint primary paths with alternative paths connecting destination and intermediate nodes	Two paths	Per packet	Initialize route query when connectivity is lost	Low loss rate video applications
<i>IWM</i>	Reliability	Two node disjoint paths with minimum concurrent packet drop probability	Two paths	Per packet	n/a	Robust video applications
<i>SMP-DSR</i>	Reliability	Best path as primary path and alternative path to be the best among paths disjoint with primary path	Multiple paths if necessary	Per packet	Route error (<i>RERR</i>) is sent back to clear broken routes	Fault tolerant applications
<i>SMS</i>	Reliability	Multiple partial disjoint shortest paths	Multiple paths	n/a	Route error is transmitted to invalidate routes	Multimedia Applications
<i>[HKS09]</i>	Reliability	Shortest delay path and multiple best paths excluding each intermediate node on shortest delay path	Not specified	n/a	Intermediate nodes salvage packets with alternative paths	Increase reliability
<i>SDMR</i>	Reliability	Spatially disjoint paths	Two paths	Per packet	Refresh its topology graph and compute new paths	Spatially disjoint without geography information
<i>SMR</i>	Delay-aware	Shortest delay route and its maximally disjoint path	Two paths	Per packet	<i>RERR</i> is sent back to clear broken routes	Build maximally disjoint paths
<i>AOMDV</i>	Delay-aware	Link disjoint paths	Single path	n/a	<i>RERR</i> propagates towards nodes having a route via the failed link	Discover disjoint path without source routing
<i>DPMR</i>	Minimum Overhead	Node disjoint paths	Multiple paths	n/a	n/a	Geography multipath routing

Table 1: Summary of multipath routing protocols

2.1.1 Reliable multipath routing protocol

Reliability is enhanced in multipath routing protocols using backup paths. Hence, reliable multipath routing protocols differ mainly in how to choose multiple paths. Generally there are two opposite directions. One is to choose disjoint paths. The other one

tries to reuse links of high quality.

Disjoint paths provide two significant advantages. Firstly, single failure can only destroy one route. Secondly, interference are potentially reduced in some extent. Hence, disjoint paths are suitable to simultaneous transmissions.

Split MultiPath-Dynamic Source Routing Protocol (*SMP-DSR*) selects the best path that is disjoint with primary path as the alternative path. Intermediate nodes can salvage packets with their alternative paths to increase reliability. Since alternative path is usually longer than primary path, route will become longer and longer as *SMP-DSR* runs. Moreover, *SMP-DSR* abandons the rest of good links on primary path if primary path is broken. In other words, disjoint backup path cannot utilize network resource efficiently.

Further, Wei and Zakhor propose to choose alternative paths satisfying disjointness requirement and develop a multipath extension to Dynamic Source Routing (*DSR*) in [JMB01] called Robust Multipath Source Routing Protocol (*RMPSR*) in [WZ04]. In *RMPSR*, destination collects all the query packets within a time window and builds multiple sets of paths. Each set contains primary path connecting source and destination and alternative paths connecting destination and intermediate nodes. Disjointness of primary paths from any two sets, formally defined as ratio between the number of shared nodes and the number of nodes of shorter path, should be lower than a predefined threshold. Destination will send back reply packets via primary paths to source and alternative paths to corresponding intermediate nodes. Because of disjointness evaluation, data following different primary paths will not cause heavy interference and high loss rate. In addition, alternative paths can salvage packets when primary paths go down to increase reliability.

Finally, Wei et al. take interference into consideration and concentrate on selecting two best paths for video streaming in Interference aWare Multipath Routing Protocol (*IWM*) in [WZ09]. To preserve the quality of video, concurrent packet drop probability (*PDP*) of two paths is computed to guide path selection. They take concurrent trans-

mission among interfered links into consideration and creatively group interfered links into independent sets. Consequently, *PDP* can be accurate to reflect reality and two best paths will be truly selected to enhance reliability.

Mosko, however, argues that disjoint paths limit route reliability in [Mos05]. Mathematical analysis in this paper shows that lifetime of mesh construction is much larger than that of disjoint construction. Several papers also propose to reuse links of high quality to increase reliability, which form the second category of reliable multipath routing protocols.

In Shortest Multipath Source Routing Protocol (*SMS*) proposed in [ZHAA07], source keeps all the paths with the least hop as primary paths. Once link failure is detected, source can forward packets with other primary paths excluding failed link. Primary paths may share some nodes, so that single link failure may break several paths. Although *SMS* is not resilient to frequent link failure, it fully exploits links of high quality.

Braided scheme is another way to reuse good links by generating multiple partial disjoint paths. A thorough comparison between disjoint scheme and braided scheme is presented in [GGSE01]. To be accurate, compared schemes include idealized disjoint, idealized braided, localized disjoint and localized braided. Simulation results in this paper show braided schemes are much more reliable than traditional node disjoint schemes in case of node failures.

Kajikawa et al. creatively combine the ideas of *SMP-DSR* and *SMS*, which belong to two different categories to eliminate their own limitations in [HKS09]. Destination selects the best paths, which exclude each intermediate node on primary path as backup paths as idealized braided in [GGSE01] does. Backup paths turn out to be much shorter than those of *SMP-DSR* and can be used to recover from any single failure immediately.

Different from aforementioned protocols, Spatially Disjoint Multipath Routing Protocol (*SDMR*) in [GRS11] finds spatially disjoint paths without the help of location information. *SDMR* is proposed to be resilient to regional failure (Nodes in a certain area fail

at the same time). In *SDMR*, Gálvez et al. define *node distance* as the number of hops of the shortest path connecting nodes. Distance between node and path is minimum *node distance* from node to any nodes on a path. *Path distance* is the sum of distances between each node on one path and the other path. *SDMR* simply finds two paths with the largest *path distance*. Simulations show that *path distance* and Euclidean distance are highly correlated, which means *SDMR* successfully picks up spatially disjoint paths without location information.

2.1.2 Delay-aware multipath routing protocol

Delay-aware multipath routing protocols maintain backup routes to realize fast recovery from failure. After link breakage is detected, backup path will be used to forward data until better routes are discovered. In this way, end-to-end delay caused by waiting for route reconstruction will be eliminated.

Backup routing protocol proposed in [LG00] takes advantage of neighbors to salvage packets. During path discovery procedure, nodes that are not on the primary route overhear route reply (*RREP*) packets, and store direct sender of *RREP* as next hop to destination in alternative route table. In case of link failure, packets will be broadcasted so that neighbors with alternative path to destination can relay it around the broken link. Alternative routes are used to forward data between source and destination before new primary route is discovered. Therefore, time to wait for route construction is eliminated and delay is reduced.

Split Multipath Routing Protocol (*SMR*) proposed in [SJL01] chooses paths that are maximally disjoint with primary path as backup paths. Specifically speaking, route followed by the first query will be chosen as primary path for its low delay. A set of paths, which are maximally disjoint with primary path, are also replied as alternative paths. Maximal disjointness guarantees the rest of paths are still valid when primary path is broken somewhere so that disjoint paths can simplify route recovery and decrease latency.

Similarly, Ad hoc On-demand Multipath Distance Vector Protocol (*AOMDV*) construct-

s link disjoint and loop-free paths in single route discovery, which potentially reduces route discovery frequency. Simulation results show that *AOMDV* can reduce protocol overhead and end-to-end delay.

2.1.3 Minimum overhead multipath routing protocol

To reduce protocol overhead, nodes are allowed to receive query packets for a short interval and filter out unnecessary queries in [JLR08]. Queries with larger hop count will be discarded first. Then, queries are dropped following the descending order of the number of shared links with others until all routes are disjoint with each other. Protocol overhead is reduced by filtering out redundant queries. Finally, at most two node disjoint paths will be selected for data transmission.

Geography routing is another method to reduce overhead in large scale networks, which is applicable to multipath routing as well. Li and Wu assume every node knows its location and propose a Node Disjoint Parallel Multipath Routing algorithm (*DPMR*) in [LW05]. Source chooses a set of neighbors closer to destination and neighbors initialize greedy forwarding procedures every s seconds one after another. If node is occupied by other routes it will refuse to forward query packet to guarantee node disjoint.

2.1.4 Hybrid multipath routing protocol

DSR is extended into a node disjoint multipath routing protocol in [WH01]. They define correlation factor of two paths as the number of links connecting these two paths and filter out paths with high correlation factor. In addition, path length is also bounded referring to the length of primary path. Similarly, Yong et al. place two constraints on selected paths, namely, path quality measured in *WCETT* and interference measured as the number of interfering path in [DYX11].

Moreover, Yang and David develop a multipath extension to shortest path routing protocol in [YW06]. The authors relax forwarding rule applied in shortest path routing protocol. Instead of picking up node with the lowest cost to destination as next hop, first rule allows to select a group of nodes as next hop, if these nodes have lower cost to destination. Additionally, second rule allows to forward query to nodes with higher cost

to destination temporarily, provided that two-hop neighbors have lower cost. These two rules generate safe and loop-free *deflection paths* of the shortest path.

Ohara et al. novelly apply Maximum Adjacent Ordering (*MA*) algorithm and generate a family of multipath protocols in [OIM09]. It is proved that these protocols maximize performance in term of parameter used in *MA* algorithm. For example, if aggregate capacity is adopted as parameter, the multipath routing protocol generated will provide the highest network capacity.

2.2 Traffic Distribution

Multipath routing protocols basically consist of three elements, namely, path discovery, path maintenance, and traffic distribution. Path discovery specifies how to find paths connecting source and destination. To be accurate, path discovery involves with how to flood query packets and how to response query packets. Path maintenance deals with link failure. Traffic scheduling is the main issue in traffic distribution.

Traffic distribution is a critical component of a multipath routing protocol. Common sense implies multipath routing can balance traffic load significantly better than single path routing. Yashar and Abtin, however, show that load distribution of multipath routing is almost the same as single path routing unless a large number of paths are chosen in [GK04]. They assume each node generate traffics at a particular rate to destinations, which are uniformly distributed over the area in the proof. But, traffic distribution plays an important role in balancing load if network traffic is unbalanced.

Basically, traffic distribution includes distribution strategy and allocation granularity. Smart distribution strategy can split traffic load properly and give the fullest expression to the advantages of multipath routing. Round robin and randomization are two simple ways to distribute traffic, but not efficient. Wang et al. distribute data in proportional of the good throughput of paths in [WKC09]. Ali et al. propose weighted load fairness on packet level and call level in [ACA09]. Data is diverted to paths whose loads are lower than expected. In [LWD00], Wang et al. split load according to round trip time (*RTT*) and simulation results show *RTT* based load balance scheme reduces

queue size, end-to-end delay, and loss ratio regardless of *TCP* or *UDP*. Tsirigos and Haas study how to distribute data fragments on multiple paths in presence of frequent topological changes in [TH01], so that the probability of recovering original data at destination is maximized. The basic idea lies in sparing more on the path with lower failure probability. In [SBR06], Channel Aware Multipath Metric (*CAM*) of selected paths is re-computed referring to load distribution to get optimized distribution strategy.

Allocation granularity, as the other component of traffic distribution, determines scheduling unit. For instance, *SMR* schedules data on packet level, which is flexible for load balance. In contrast, packet level schedule may produce many out-of-order packets. In [ACA09], Ali et al. divert connectionless traffic on packet level and connection-oriented data on call level, which is friendly to *TCP*. Applications related with video streaming prefer to consider structure of media data while deciding on allocation granularity.

2.3 Channel Assignment

Channel assignment strategies can be classified into three categories which are static, dynamic, and hybrid. Static channel assignment allocates channel based on metrics such as network connectivity or channel diversity. It is usually adopted when channel switching cost is high or the number of orthogonal channels is less than the number of interfaces. Moreover, static channel assignment does not need any coordinations. Channels, however, cannot adapt with data traffic, which may limit network performance. Dynamic channel assignment allocates any channel to network interfaces at any time. Nodes can communicate with each other when they share at least one common channel. Dynamic channel assignment needs coordination to maintain connectivity and schedule data transmission. Channel diversity can be fully exploited at the expense of complicated coordination mechanism. Hybrid scheme is comprised of static and dynamic strategies. In this scheme, some interfaces, called fixed interfaces, adopt static channel assignment. The rest communicate via fixed interfaces and choose channel dynamically.

Channel Assignment	Reference	Proposal
Static	[DZLS09]	Gateways statically assign channels by propagating channel sequences
	[ZKTN10]	Assign channel to reserve connectivity and also reduce potential interference
Dynamic	[RC05]	Links with high traffic load are assigned clean channels first
	[WYT ⁺ 06]	<i>JCAR</i> assign channel and select path according to <i>CCM</i>
	[WKC09] [JDN01]	Allocate channels in greedy manner Channels are classified into data channel and common channel. RTS/CTS works over common channel to avoid collision with data. Nodes decide on data channel via communication over common channel
	[JL11]	Minimize the number of channel required while providing enough bandwidth
Hybrid	[Kya06]	Fixed interfaces are assigned with least used channel and switchable interfaces calculate metric <i>MCR</i> to select channel
	[Kya05]	Fixed channel is allocated as a well-known function result of identifier and switchable interfaces adjust to fixed channels of its neighbors for communication
	[LKKV11]	Assign channel according to multicast tree and try to minimize the number of channels provided bandwidth is satisfied

Table 2: Summary of channel assignment schemes

2.3.1 Static channel assignment

Gateways predetermine channels by propagating channel sequences in [DZLS09]. Channel sequences are carefully chosen to reduce interference between links on the same path. Generally, nodes sharing the same number of hops away from a gateway are assigned with the same channel so that broken routes can be easily recovered with cross links. Gateways take different channel sequences to reduce interference between paths. This channel assignment is proposed to maximize throughput from nodes to gateways.

In [ZKTN10], Zhang et al. studied greedy channel assignment. Potential interference edges set of link e is defined as all edges, which may interfere with e under certain channel assignment, to separate interference from channel assignment. As superset of

interference edges set, potential interference edges set bounds interference of network. Potential interference set of maximum size comes first for channel assignment and nodes in selected set are processed following the descending order of node degree. If nodes on the same link are allocated with different channels, either node has to replace its channel with that of the other node or both nodes replace channels with the least used channel.

2.3.2 Dynamic channel assignment

Wang et al. simply allocate channels in greedy manner in [WKC09]. Idle channels are assigned first. If all the channels are busy, channels that are not used by one-hop and two-hop neighbors will be reused.

Similarly, Raniwala and Chiueh propose to greedily assign the least used channel to links burdened with the highest traffic load in [RC05] in case that channel interference degrades link capacity. They maintain status of channel assignment of neighbors within K hops and dynamically adjust channel according to traffic load and channel utilization.

Jang and Lee design channel allocation algorithm to minimize the number of required channels while enough bandwidth is provided in [JL11]. They assume K -shortest paths are given for each source and destination pair. First, channels are allocated for all the shortest paths. In this procedure, allocated channels, which have extra bandwidth or cause no interference, will be reused. Then, links with no channel are sorted in descending order in term of their interference set size and channel rearrangement assigns these links with channel C if they do not have a neighbor using channel C .

In [JDN01], Jain et al. change channel to eliminate packet collision under high load. They classify channels into common channel and data channel. *RTS/CTS* packets are transmitted on common channel to avoid collision with data. Sender and receiver sense channels to pick up clear channels. At last, they exchange selected channel list via *RTS/CTS* and switch to the ideal channel, which is clear to both of them.

Channel assignment is performed as a component of routing protocol in [WYT⁺06]. They define channel utilization as the ratio of time occupied by a particular channel to

the total time consumed in sending a certain amount of data. In fact, channel utilization measures channel diversity in quantity. They also comp up Channel Cost Metric (*CCM*) in which *ETT* is weighted by channel utilization. Channel is dynamically assigned to minimize *CCM*, which potentially increases the overall throughput.

2.3.3 Hybrid channel assignment

Hybrid channel assignments classify interfaces into fixed interfaces and switchable interfaces and apply different channel allocation schemes on two kinds of interfaces. Channels of fixed interfaces are statically predetermined and will not change for a long time. In contrast, switchable interfaces change their channels frequently to exploit channel diversity.

Kyasanur first uses well-known functions of node's identifier to calculate channels for fixed interfaces in [Kya05]. Node can easily obtain channel information of their neighbors. Switchable interfaces simply switch to fixed channels of its neighbors for communication. Well-known function scheme does not worry about channel agreement but cannot exploit channel diversity efficiently.

Later, he abandons well-known function scheme and proposes to assign the least used channel to fixed interfaces according to channel utilization of one-hop and two-hop neighbors in [Kya06]. Channel utilization status is obtained from periodical broadcast on all channels. Additionally, Multi-Channel Routing (*MCR*) metric, which integrates channel switching cost with *WCETT*, is designed to guide channel switch for switchable interfaces. *MCR* dynamically chooses channels for switchable interfaces in a simple but reasonable way.

In [LKKV11], Lim et al. design channel assignment in a bottom to up way to increase channel utilization for multicast. Multi-channel can reduce interference with no doubt. Sender, however, has to forward same data many times to neighbors using different channels in multicast. As a result, channel utilization is quite low and overhead is huge. To solve this problem, they periodically broadcast fixed channel information as well as link quality of all channels. So a new joined member adjusts its channel to avoid

interference with its parent or grandparent but shares the same channel with its siblings. Hopefully, multicast tree is expanded without generating additional data traffic.

2.4 Rate Adaptation and Power Control

Rate adaptation is to choose maximum rate allowed by environment for data transmission. Truly, rate adaptation can increase throughput by several times. A large amount of work has been done on rate selection criteria. Moreover, Chou and Misra apply rate adaptation on broadcast in [CM05]. They allow nodes to broadcast more than one time to different subset of neighbors at different rates instead of the lowest rate. Hopefully, latency of broadcast procedure can be reduced due to concurrent transmissions.

Transmit power management and cooperative transmission are two promising research directions of power control. Wireless mesh networks can benefit from transmit power management. For example, Monks et al. generalize traditional *on/off* power model into bounded power model in [MBmWH01]. Nodes in the generalized model will estimate a maximum power, which will not disturb ongoing transmissions. If the estimated power is larger than that required to complete a coming transmission, node will start the new transmission in proper transmit power. Compared to traditional model, bounded power model allows more concurrent transmissions, which potentially increases the overall throughput. Cooperative communication takes advantages of wireless broadcast nature to save power or increase transmission range and data rate. Khandani et al. model cooperative senders as virtual antenna array to save power in [KAMZ03] and Sriram and Raghupathy implement virtual multiple input single output (*VMISO*) with cooperative senders to increase throughput in [LS09].

3 Multipath Routing Protocol Implementation

We develop a multipath routing protocol based on *SRCR*. *SRCR* is chosen because it is a source routing protocol. So, we can easily realize accurate path control over the whole network, which is important to leverage multi-radio design. In addition, we also introduce *WCETT* to measure path cost for the sake of multi-channel strategy. As one kind of multipath routing protocol, our implementation can also be divided into three elements. First element is path discovery, in charge of finding routes for a particular node pair. Path maintenance, as second element, is responsible for the detection and recovery of broken path. The last element, traffic distribution, focuses on how to distribute network traffic among multiple paths. This chapter describes these three elements in detail.

SRCR is a link table driven source routing protocol for *Roofnet* developed by *MIT*. Routes are computed with *Dijkstra* algorithm based on link table. Link table records detailed information of known links, such as link quality, expired time, and so on. Link quality is measured in Expected Transmission Time (*ETT*) and calculated based on periodical probes. To increase the efficiency of probe mechanism, probe packets also include information of links connecting sender and its neighbors. Receivers of probes retrieve link information and update corresponding entries of their link tables. With the help of probes, nodes can learn all links within two hops.

SRCR starts path discovery procedure when node does not have adequate link information to compute a path. Source broadcasts route request (*RREQ*) packet to destination over the network. *RREQ* records partial path that it traverses. On receiving *RREQ*, node first updates link table with link information learnt from *RREQ*. Then, if forwarding rules are satisfied, node will append itself to partial path and re-broadcast *RREQ*. Destination computes path to source and sends back route reply (*RREP*) packet. On the arrival of *RREP*, source refreshes its link table and runs algorithm again to find a path to destination.

We extend *SRCR* into multipath routing protocol for a multi-radio multi-channel wireless network in our implementation. Basically, link table is replaced with routing table

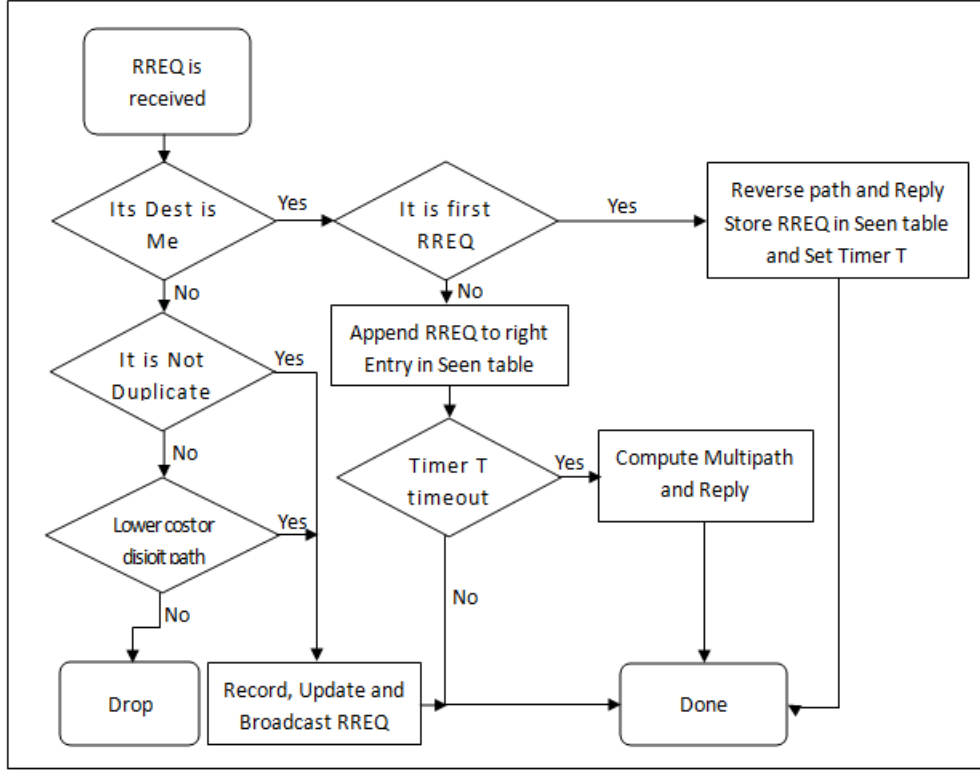


Figure 1: Flowchart for handling RREQ

and query mechanism is modified for multi-channel and multiple interfaces. The modified protocol consists of three elements, namely path discovery, path maintenance, and traffic distribution. Implementation detail will be presented in the following subsections.

3.1 Path Discovery

In multi-radio networks, we model interfaces into virtual nodes. Each interface has its own *IP* and *MAC* addresses and performs in the same way as node in single path routing. Moreover, all the interfaces of a node share another same *IP* address, which can be viewed as node address. Essentially, our protocol implementation is a multipath extension to *DSR*. Source can precisely determine sequence of interfaces each packet traverses by setting route in the packet header.

First of all, we explain when to initialize path discovery because it affects protocol overhead as well as the effectiveness of path selection. Frequent path discovery will generate heavy overhead. In the opposite, stale routes on routing table cannot be updated on time. Path discovery is started immediately if it is the first time to query a path to a

particular destination. Later, query to the same destination within a lower bound will be canceled to reduce overhead. Routes to a certain destination off a upper bound will be marked as invalid and nodes are forced to start query procedure if all routes become invalid. If time spent lies between the lower bound and the upper bound, path discovery will be initialized only when all the paths to the destination in routing table are broken.

Figure 1 shows how to handle *RREQ* in detail. When a node receives *RREQ*, it first checks whether the destination of *RREQ* is current node or not. If receiver is not the destination of *RREQ*, it will check whether *RREQ* is duplicate or not. *RREQ* identified by a new sequence number will always be forwarded. In addition, if *RREQ* qualifies lower cost or comes from different incoming links, node also broadcasts it via all the interfaces. Otherwise, the receiving node will drop it. On the other hand, if node is destination of *RREQ* and it receives *RREQ* with same source and sequence number for the first time, it will send back reply immediately by reversing path contained in *RREQ* to reduce end-to-end delay. At the same time, a timer is initialized so that destination can trace all the coming queries within a predefined time. Once timer expires, destination will select multiple query packets based on certain criteria and reply them.

Figure 2 presents flowchart for handling route reply (*RREP*) packets. On the arrival of *RREP*, nodes first check whether *Error Flag* is set or not. When *Error Flag* is clear, *RREP* is an ordinary query reply packet. Intermediate nodes need to forward it to the next hop specified in the packet header. Finally, source receives reply packet and retrieves path from it for data transmission.

3.2 Path Maintenance

We leverage *RREP* packets to deal with broken link. Whenever node forwards data, it always checks whether next hop is still its neighbor or not. If next hop is no longer in its neighbor list, which means link between current node and next hop is broken, node will construct route error (*RERR*) packet including broken link information and send it back to source. *RERR* is the same as *RREP* except that *Error Flag* is set. Intermediate nodes will delete routes that contain broken link and pass *RERR* to source.

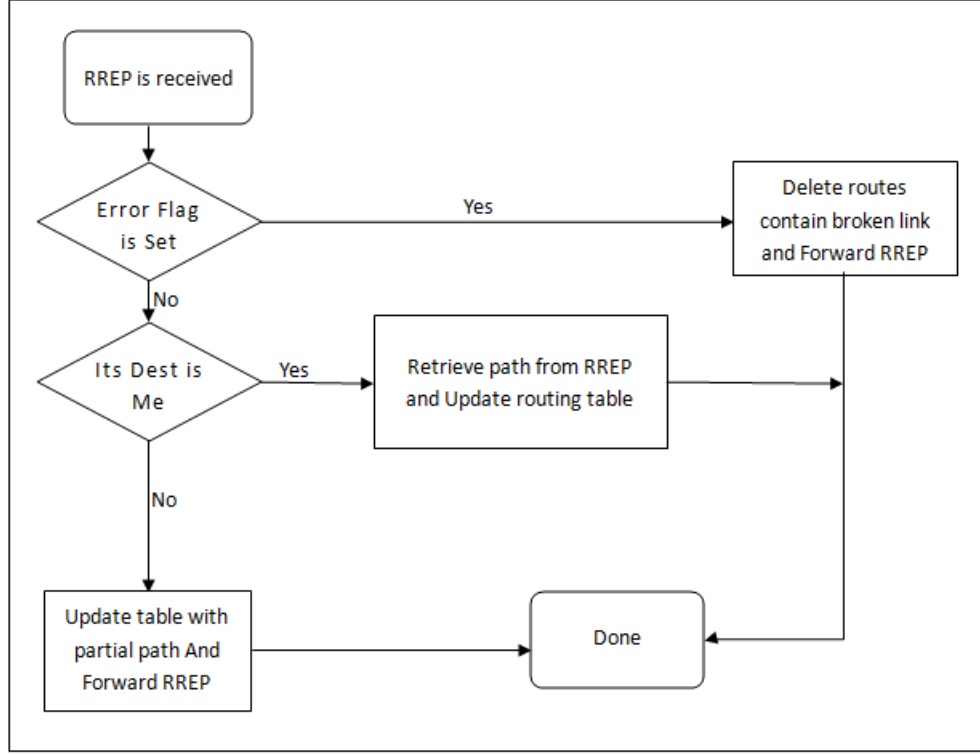


Figure 2: Flowchart for handling RREP

3.3 Traffic Distribution

We do not plan to study the effect of traffic distribution in our experiments, as a result, in our implementation, we distribute traffic randomly among paths kept in routing table, which is the simplest scheme for traffic distribution. Since routing table records detailed information of routes, we can also try different traffic distribution schemes in future. For example, another option is to split traffic inverse proportional to path cost. A thorough literature review on traffic distribution has been given in Section 2.

4 Performance Evaluation

We design a series of experiments to evaluate our multipath routing protocol on the testbed located in *PGPR*. To fully investigate the benefit of multi-channel strategy, we first verify the channel interference on a two nodes testbed. Based on the results of channel interference verification, two non-overlapping channels are chosen for our testbed in *PGPR*. After that, we study how path metric, path selection scheme, and other parameters affect the throughput of our implementation. Corresponding results are shown in this chapter.

4.1 Testbed Description

The testbed is located at *PGPR* (Prince George Park Resident), National University of Singapore and consists of twenty wireless nodes. These nodes spread around different blocks shown in Figure 3. Each node is equipped with two network cards (*MINIPCI* interface) developed based on *Atheros Chipset*. Network cards support IEEE 802.11a/b/g protocols. OpenWRT, an open source operating system for embedded devices, is running over these routers. Routing protocol is implemented with the help of *Click*, which is a software architecture for building routing protocols. Although software abstraction of network slows down packet transmission, it separates network module from operating system and greatly simplifies implementation of routing protocols. Auxiliary softwares such as *Jtg*, which works as network traffic generator, are also installed on mesh nodes.

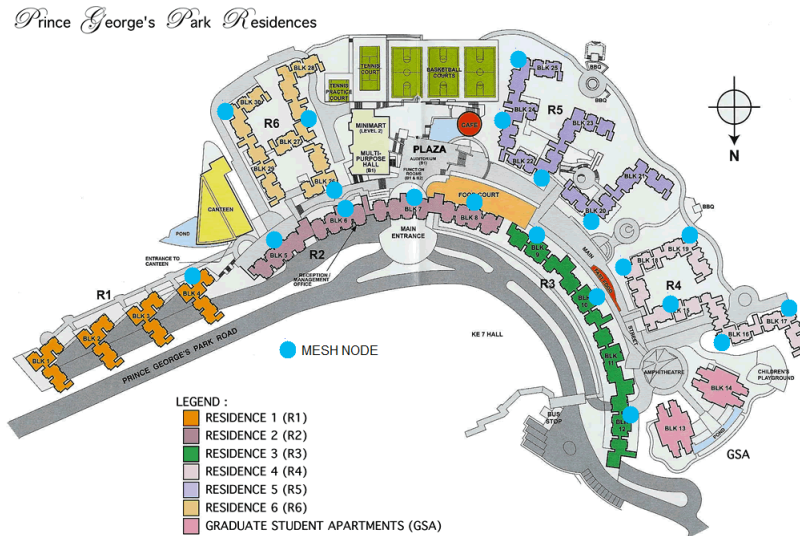


Figure 3: Deployment of wireless mesh network

4.2 Channel Interference

First, we design experiment to evaluate interference between channels supported by *IEEE 802.11* standard. In theory, *IEEE 802.11b* provides three orthogonal channels and *802.11a* has twelve non-overlapping channels. Channels supported by our testbed are listed in Table 3 together with corresponding frequency. In [SM10], Singh and Motani demonstrate *close interface effect* that packet loss rate is high on receiving interface due to interference from close interface in multi-interfaces networks. To fully investigate benefit of multipath routing, channels of network cards should be configured carefully to eliminate interference.

Channel Number	1	2	3	4	5	6	7	8
Frequency (MHz)	2412	2417	2422	2427	2432	2437	2442	2447
Channel Number	9	10	11	36	40	42	44	48
Frequency (MHz)	2452	2457	2462	5180	5200	5210	5220	5240
Channel Number	50	52	56	58	60	64	149	152
Frequency (MHz)	5250	5260	5280	5290	5300	5320	5745	5760
Channel Number	153	157	160	161	165	-	-	-
Frequency (MHz)	5765	5785	5800	5805	5825	-	-	-

Table 3: Channel number and corresponding frequency

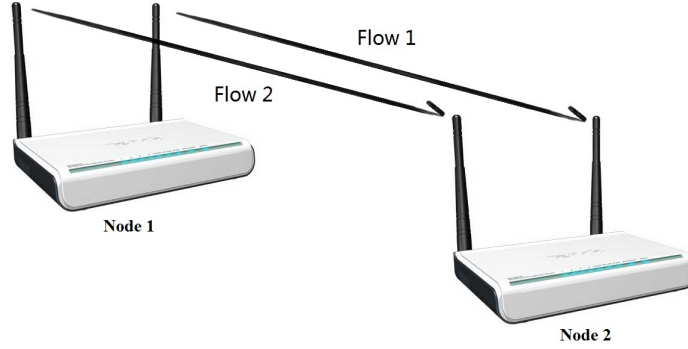


Figure 4: Testbed of channel interference evaluation

We set up two nodes to evaluate interference between different channels. Nodes are placed in laboratory far away from *PGPR*, but in the coverage of campus wireless network. One interface is set to be *channel 10* (*2457MHz*). The other interface randomly selects its channel from *channel 1* to *channel 165*. It can be seen from Figure 4 that two data flows exist in our experiment. First, we measure data throughput when only *flow*

1 is initialized on *channel 10*. Second, experiment is repeated on *flow 2* using varying channel while *flow 1* keeps quiet. Finally, two flows are initialized simultaneously with the same configuration and throughput are measured respectively.

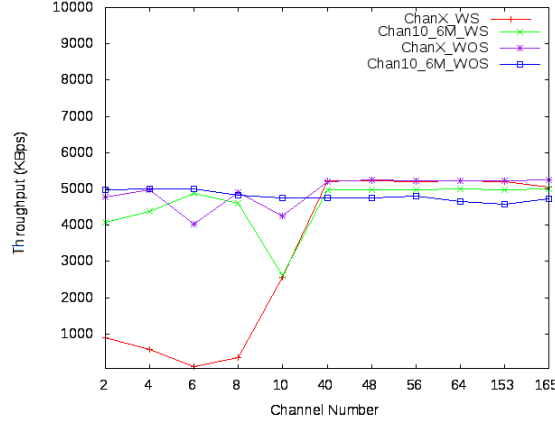


Figure 5: Throughput comparison (Single-channel VS. Multi-channel)

Figure 5 shows throughput comparison between single-channel and multi-channel. The x axis represents channel numbers used in *flow 2* and y axis represents the throughput of data flows. *ChanX_WS* and *Chan10_6M_WS* represent throughput on varying channels and fixed *channel 10* in simultaneous transmission. *ChanX_WOS* and *Chan10_6M_WOS* represent throughput on varying channels and fixed channel in single channel measurement. Data rate is set to be *6Mbps* as we can see from *Chan10_6M_WS* and *Chan10_6M_WOS*.

It can be seen that when single flow is initialized with regardless of fixed channel or varying channel, throughput is around *5Mbps*. When varying channel number is set to be *6*, throughput slightly decreases due to interference with campus wireless network. This phenomenon also can be observed in measurements with high data rates. Two flows in multi-channel experiment perform almost same as that in single channel experiment when the varying channel number is above *40*. In contrast, if the varying channel number is lower than *10*, two flows in multi-channel measurement compete for the fixed bandwidth. In summary, orthogonal channels of IEEE *802.11b* protocol interfere with each other; but channels from *2GHz* and *5GHz* bands can work simultaneously without

any interference.

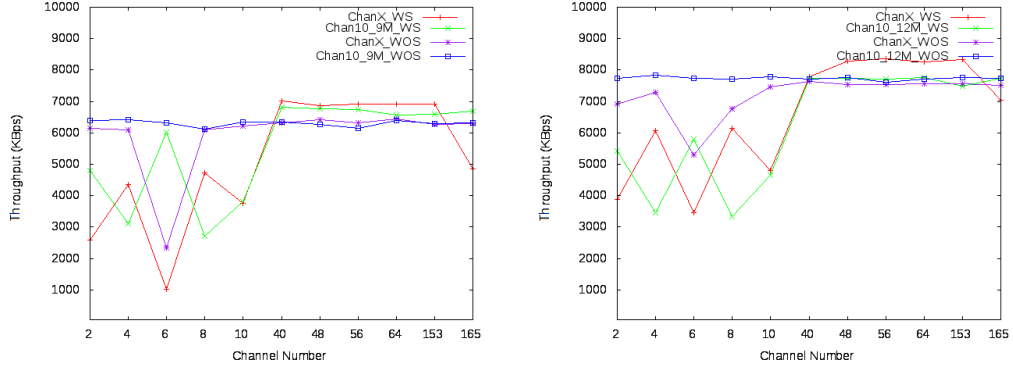


Figure 6: Throughput comparison (9Mbps and 12Mbps)

Similar experiments are conducted with different data rates such as 9Mbps and 12Mbps. Different rates are resilient to noise on different levels. Figure 6 shows throughput comparisons and similar conclusions can be drawn from 9Mbps and 12Mbps measurements.

4.3 Throughput Comparison

As the last mile of Internet, wireless networks become the bottleneck for relatively low bandwidth. Multipath routing is a promising technique to increase throughput and reduce delay. Up to now, tens of multipath routing protocols on wireless networks have been proposed for different purposes. To our best knowledge, most of researchers verify their arguments by analysis or simulation. Does multipath routing really increase throughput in reality? How much it can improve performance? To answer these kinds of questions, we extended *SRCR* into a multipath multi-radio protocol and thoroughly study performance of this new protocol on a real testbed.

The testbed is configured as follows. Each router sets one interface to be *channel 8* and the other one to be *channel 149*. According to aforementioned evaluation, these two channels can work simultaneously without any interference. Transmit power is set to be *23dBm* and data rate is *6Mbps*.

After the multi-radio multi-channel network is well configured, a series of experiments are conducted to collect data. First, we independently run two instances of *SRCR* on

two set of interfaces classified according to channel configuration. Each round, a pair of nodes is selected and each copy of *SRCR* initializes a data flow between this pair of nodes simultaneously. Then, the throughput of these two flows are separately measured. We repeat this procedure for all pair of nodes. Second, we install our multipath routing protocol, which works with two set of interfaces cooperatively. With same configuration, we start only one data flow for a pair of nodes and measure the throughput of all pairs for comparison. Finally, we tune some parameters to study how these changes affect final throughput. These results may assist in improving the design of multipath routing protocol in future.

I Throughput measurements of IEEE *802.11a* and *802.11bg*

We install *SRCR* on all the nodes and measure the performance as benchmark. *SRCR* periodically measures link quality in term of *ETT*. Each node maintains link table to record information of all known links, learnt from probes, *RREQ* and *R-REP*. Based on link table, *SRCR* runs *Dijkstra* algorithm to compute routes. If no path is found, node will initialize query procedure to learn more links from control packets. After that, one path is guaranteed to be found, if source and destination are connected.

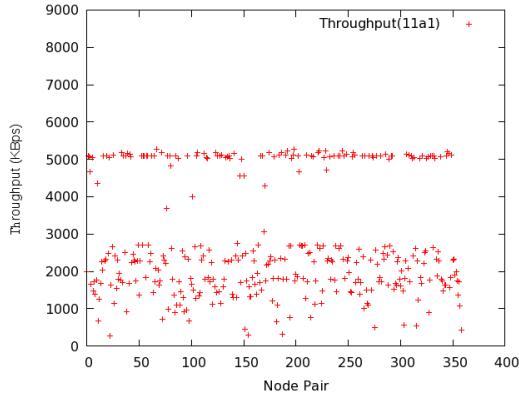


Figure 7: Throughput distribution (*11a*)

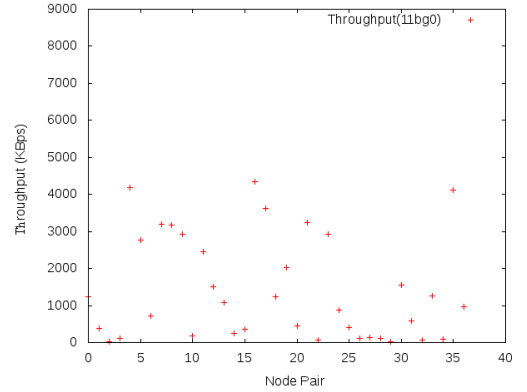


Figure 8: Throughput distribution (*11bg*)

As shown in Figure 7 and 8, IEEE *802.11a* performs much better than *802.11bg* due to the nature of channel. To be accurate, signal on *802.11bg* channels attenuates rapidly due to buildings or other obstacles. Besides, many other wireless devices work on similar frequency, which generate a large amount of interference. In our experiment, we will not initialize data transmission unless a reliable path

is found between source and destination. Consequently, only a few pair of nodes are connected for *802.11bg*. Interestingly, the throughput of *802.11a* shows a layer structure. The first layer is around *5Mbps* for one-hop path. The other two are around *3Mbps* and *2Mbps* for two-hop and three-hop routes respectively.

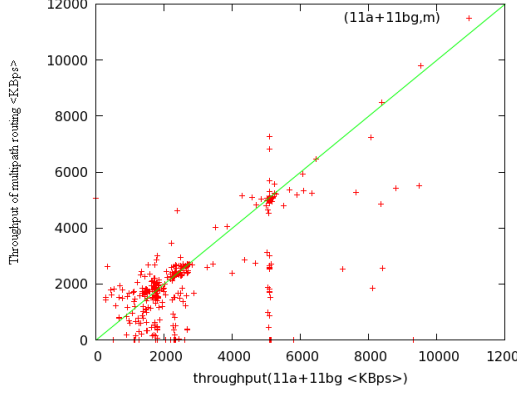


Figure 9: Throughput comparison

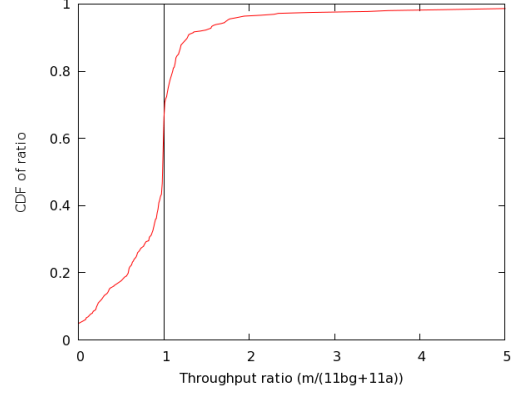


Figure 10: CDF of throughput ratio

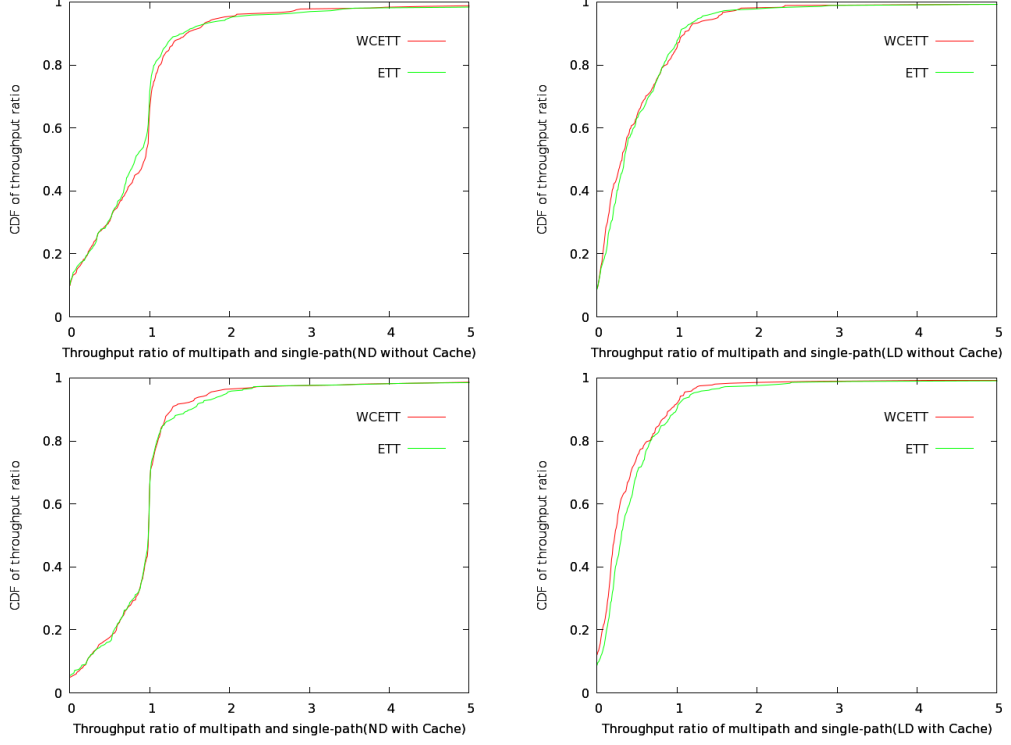
We sum up the throughput of *802.11a* and *802.11bg* and compare it with the throughput of multipath routing protocol in Figure 9. Cumulative distribution function of throughput ratio is shown in Figure 10. It can be seen that around 30 percent pairs benefit from multi-radio, multi-channel, and multipath routing protocol.

There are roughly three factors that may degrade multipath routing protocol performance. Firstly, IEEE *802.11bg* cannot provide enough links of high quality. Secondly, path selection scheme does not take interference between paths into consideration. Node disjoint or link disjoint schemes are not good enough to choose efficient multiple paths. Thirdly, every node has to broadcast query via all the interfaces in multi-radio networks, which potentially increases interference and degrades performance.

II Throughput comparison between *WCETT* and *ETT*

$$ETT = ETX \times \frac{S}{B} \quad \text{where } S \text{ is packet size and } B \text{ is bandwidth} \quad (1)$$

$$X_j = \sum_{\text{Hop } i \text{ is on channel } j} ETT_i \quad 1 \leq j \leq K \quad (2)$$

Figure 11: Throughput comparison between *WCETT* and *ETT*

$$WCETT = (1 - \beta) \sum_{i=1}^m ETT_i + \beta \max_{1 \leq j \leq K} X_j \quad (3)$$

In [DPZ04], Draves et al. claim *ETX* does not perform well in multi-channel and multi-rate environment. To overcome its limitations, *ETT* and *WCETT* are derived from *ETX*. It can be seen from Equation 1 that *ETT* considers bandwidth in computation of link cost, which works for multi-rate networks. *WCETT* is the weighted mean of channel cost (X_j) and *ETT* as shown in Equation 3. Therefore, paths with high channel diversity will be preferred if *WCETT* is adopted in routing protocol. Their measurements show that *WCETT* outperforms *ETT* and *ETX* in both one radio and two radio cases.

Since our testbed supports multi-channel design, *WCETT*, which takes channel diversity into consideration, is employed to measure qualities of paths traversed by query packets in our implementation. Route metric helps destination select best path and can reduce overhead as well. When a node receives duplicate query packet with higher path cost, it will drop this packet to save bandwidth. In our protocol,

β in Equation 3 is set to be 0.1.

We compare performances of *WCETT* and *ETT* under four different configurations, which are node disjoint path without cache, node disjoint path with cache, link disjoint path without cache, and link disjoint path with cache. Cache means sources do not choose routes among paths learnt from a single query procedure. In fact, sources record all the known routes and select paths for data among them.

It can be seen from Figure 11 that *WCETT* does not outperform *ETT*. The reasons are twofold. First, IEEE 802.11bg does not provide enough good links to explore channel diversity. Second, node disjoint or link disjoint schemes do not consider interference between multiple paths, which may degrade channel diversity gain.

We further evaluate the performance of *WCETT* with different values of β . It turns out that throughput does not change accordingly as shown in Figure 12. In our implementation, channel diversity is not the key factor limiting performance, which also explains why β is simply set to be 0.1 in other measurements.

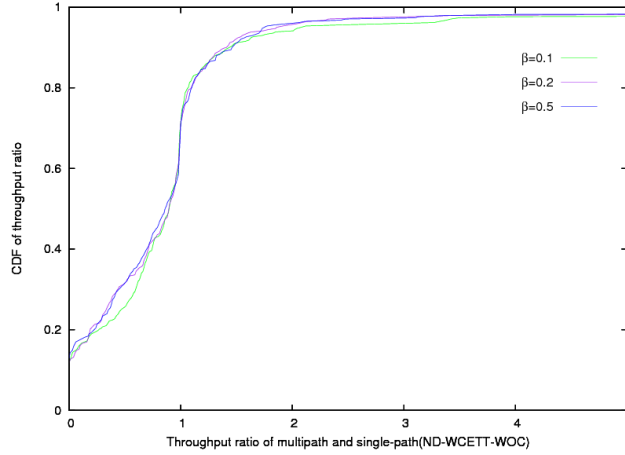


Figure 12: Measurement on different values of β in *WCETT*

III Throughput comparison between node disjoint and link disjoint

Path selection schemes decide on what kind of paths will be chosen as candidates for alternative paths. In our implementation, destination will wait two seconds for

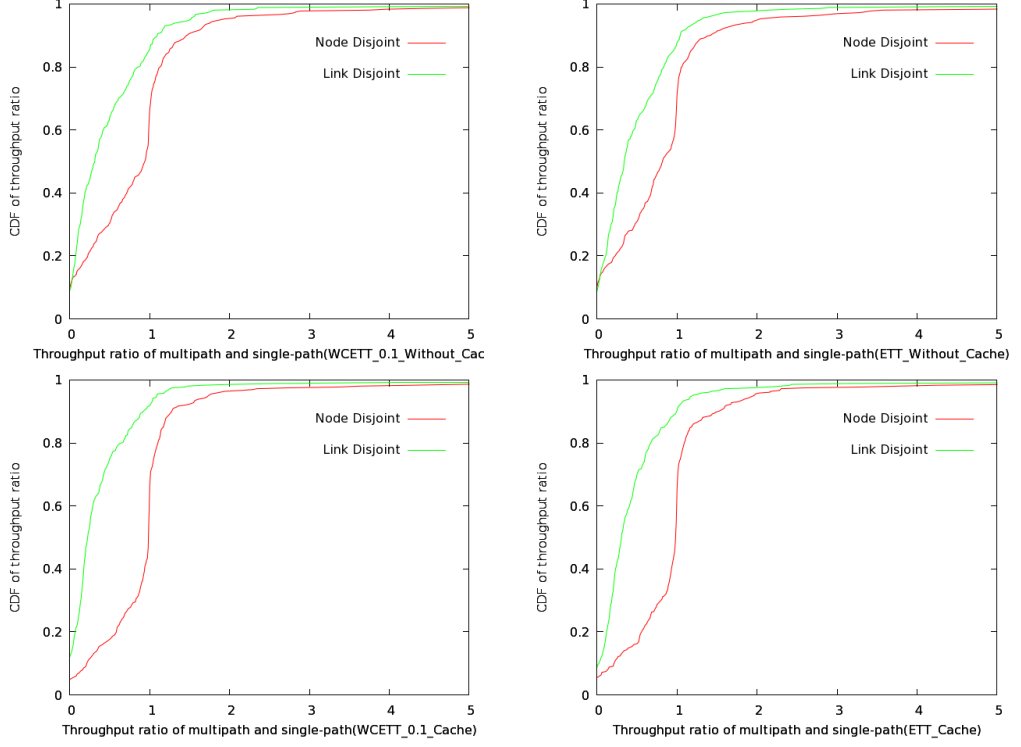


Figure 13: Throughput comparison between node disjoint and link disjoint schemes

more queries after the first query is received. Path with lowest cost will be selected as primary path. According to different schemes, destination will filter out paths that share interfaces or links with primary path. Among the left paths, the best one will be replied as alternative path.

Figure 13 shows node disjoint scheme outperforms link disjoint scheme in all four cases. According to our trace, link disjoint scheme generates a larger set of candidate paths for data transmission compared to node disjoint scheme. These selected paths, however, are highly correlated, which cannot increase throughput by simultaneous transmission. In contrast, multiple correlated paths produce more interference, which may degrade network performance. How to select multiple paths is not only the key issue, which bounds the performance of our implementation, but also a critical problem to be solved in multipath routing protocol design.

IV Throughput comparison between cache and without cache

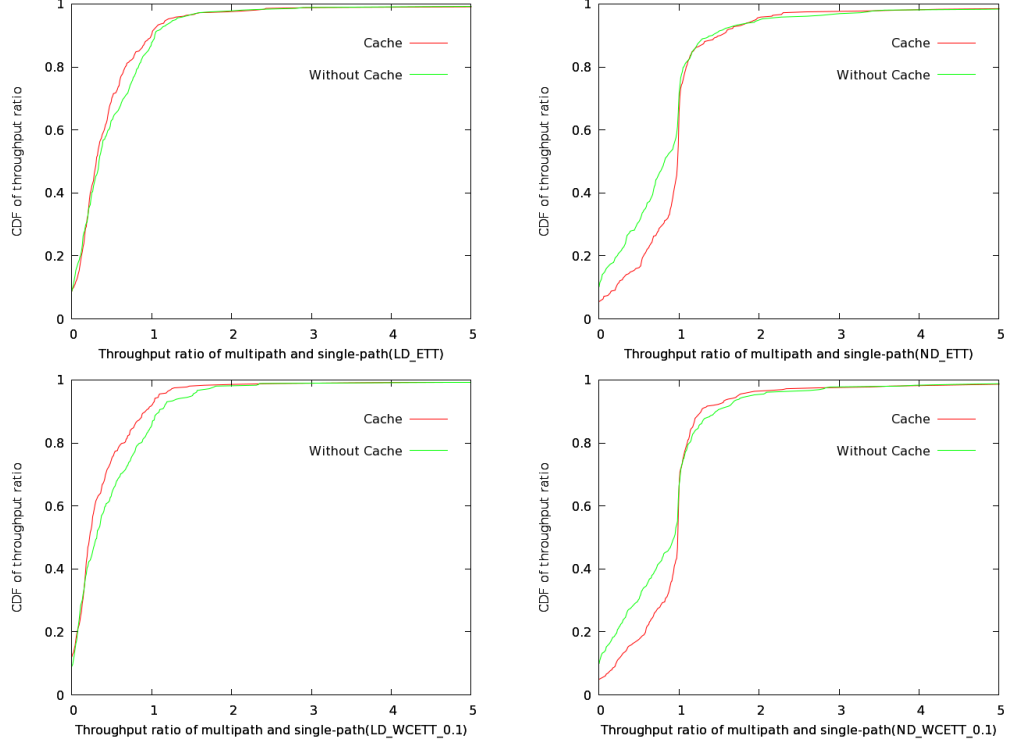


Figure 14: Throughput comparison between cache and without cache

Cache means sources do not choose routes among paths learnt from a single query procedure. In contrast, sources record all the known routes unless they are broken. If routes found by latest query already appear in the record, route metrics will be updated accordingly. Source can use latest metric to represent route quality or calculate a new metric based on historical and current metrics. We take the average value of historical and current metrics as new metric in cache scheme. If cache mechanism is not employed, source invalidates all routes to a particular destination when received *RREP* from the destination provides new sequence number.

Figure 14 shows cache can slightly increase throughput if node disjoint paths is computed and multipath routing protocol performs a bit worse than single path routing protocol. Cache makes path quality evaluation more stable but less sensitive to current network condition. Additionally, cache may combat query and response packet loss in some extent.

V Throughput comparison of different query frequencies

How to maintain routing table is critical to the performance of our implementation. Every entry of routing table will expire after a particular interval. Large interval

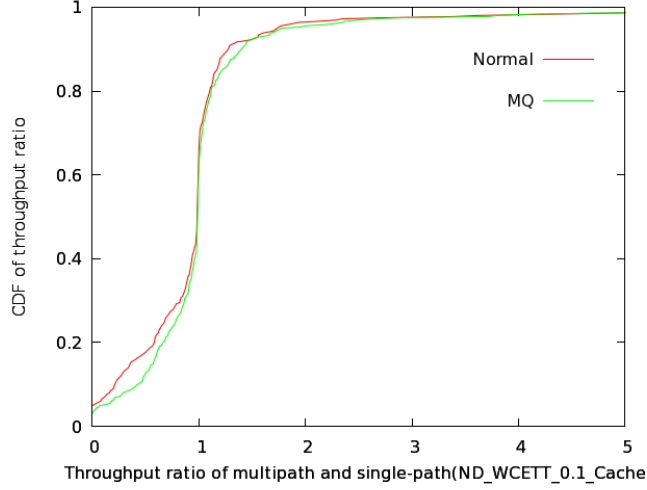


Figure 15: Throughput comparison on different query frequencies

generates lots of stale routes and small interval will produce heavy protocol overhead.

We roughly double query frequency by halving expire interval and measure throughput one more time to investigate the relationship between throughput and query frequency. The curve labeled with *MQ* in Figure 15 represents *CDF* of throughput ratio of multipath routing protocol with more queries. It can be seen that double query frequency only works when multipath routing scheme performs a bit worse than single path. Double query frequency definitely increases protocol overhead but can monitor current network environment more precisely. It is a tradeoff between overhead and accuracy.

5 Conclusions and Future Work

WMNs have been widely used for their easy deployments. Besides, the popularity of laptop, wireless devices, and mobile phones also stimulates the development of *WMNs*. As more and more network applications are running on wireless clients, bandwidth are required to increase correspondingly. Since then, many researchers focus on improving performance of *WMNs*.

Multipath routing is one of promising techniques to improve performance especially for multi-channel multi-radio networks. Until now, tens of multipath routing protocols have been proposed for different purposes. However, most of them are validated by analysis or simulation. We extend *SRCR* into a multipath routing protocol for a multi-radio network in *Click* and evaluate it on a real testbed consisting of twenty nodes. Measurements results are twofold.

First, we evaluate interference between different channels on a two nodes testbed. It turn out that all channels of IEEE *802.11b* are interfered with each other due to *close interface effect*. Luckily, channels from *2GHz* and *5GHz* bands can work simultaneously without any interference.

Second, a series of experiments are conducted to study how path metric, path selection scheme, and other parameters affect throughput of multipath routing protocol. Path selection scheme is the key factor determining throughput in our implementation. Throughput can be largely increased if node disjoint scheme is adopted instead of link disjoint scheme. Cache and query frequency can only slightly affect mesh network performance. These results are valuable to gradually improve multipath routing protocol in future. Some limitations exist in our implementation. For example, *Click*, as a software abstraction of network, slightly degrades protocol performance.

There are several directions for future work. First, our implementation of multipath routing protocol can be developed into a configurable framework that can dynamicaly adapt the protocol parameters without compiling the whole program. This design

can also simplify study on other path selection criteria or traffic distribution schemes. Similar to *OLSR* in [CJA⁺03], we can also exploit overhead reduction by leveraging relay nodes that can cover all two-hop neighbors. Multiple paths information can also be included in every *RREP* to increase resilience to random loss. As a joint problem, the most interesting direction is to study how to integrate existing techniques such as power control into routing protocol and propose an efficient protocol for wireless mesh networks.

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