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Cognitive Multipath Multi-Channel Routing Protocol for Mobile Ad-Hoc Networks

Suyang Ju and Joseph B. Evans

University of Kansas
Lawrence, Kansas, USA
{jusuyang,evans}@ittc.ku.edu

***Abstract*—This paper introduces a novel cognitive multipath multi-channel routing protocol (CMMRP) for mobile ad-hoc networks. It is designed for a multi-channel environment where nodes can simultaneously use multiple interfaces to transmit packets over different frequencies. It employs cognitive functions to make nodes intelligently select multiple node-disjoint, edge-disjoint and frequency-disjoint paths. Neural network machine learning is adopted to make nodes aware of history. CMMRP employs a modified path discovery protocol which can be divided into two parts, a space discovery and spectrum discovery. Simulation results show that CMMRP significantly improves network reliability and performance.**

***Index Terms*— multipath, multi-channel, cognitive, machine learning, mobile ad-hoc network, prediction**

I. Introduction

Multipath routing protocols have been proposed in many papers for both wired networks and wireless networks. In wired networks, the major consideration is how nodes utilize multiple paths such as back up redundant paths and load balancing among available paths. Currently, OSPF and BGP-4 are the dominant routing protocols for wired networks. They both include multipath capabilities. Based on desired metrics, nodes are able to balance load among paths or support redundant paths. On the other hand, mobile ad-hoc networks (MANETs) have two new characteristics, wireless communication and dynamic physical topologies. Nodes have to suffer interference from other nodes because of the broadcast nature of wireless communications. As a result, network performance degrades if neighboring nodes transmit packets over the same frequency. This problem becomes serious for multipath routing protocols when nodes simultaneously use multiple paths to transmit packets. Also, dynamic physical topology usually incurs considerable overhead to repair broken paths especially for multipath routing protocols. Nodes should select stable links to save routing overhead and maintain network reliability. On the other hand, it is hard to perform optimal load balancing in dynamic physical topologies because significant overhead has to be generated to inform nodes of updated conditions for each path. Considering the characteristics of MANETs, we argue that multipath routing protocols on MANETs should be focused on how nodes select multiple paths to improve network reliability and performance instead of how nodes optimally utilize multiple paths.

The problem we address in this paper is how nodes select multiple node-disjoint, edge-disjoint, and frequency-disjoint paths. Many multipath routing protocols have been proposed to allow nodes to select multiple node-disjoint and edge-disjoint paths. However, few of them provide solutions for how nodes can select multiple frequency-disjoint paths.

Our main contribution is the cognitive multipath multi-channel routing protocol (CMMRP). It falls into a novel category of routing protocols, cognitive routing protocols. Each node predicts future conditions of links and frequencies based on past experience. Multiple disjoint paths are discovered one by one by triggering RREQ packets multiple times from the source node, trading routing overhead for network reliability and performance.

This work is part of ongoing CogNet effort [1-4], which is focusing on applying cognitive techniques to improve network performance. The rest of paper is organized as follows. We describe related work in Section II, discuss the approach in depth in Section III, describe simulation results in Section IV, and conclude in Section V.

II. Related Work

In this section, we discuss work related to CMMRP.

A. Disjoint Multipath Routing Protocols

A multitude of disjoint multipath routing protocols have been proposed (e.g. [5-10]). The main idea is that a source node selects multiple non-overlapped paths to transmit packets to a destination node. In [5], the authors proposed a maximally disjoint multipath routing protocol, an on-demand routing protocol. Unlike traditional protocols where intermediate nodes discard duplicated RREQ packets, the proposed routing protocol lets intermediate nodes relay duplicated RREQ packets to make destination node know all possible paths. A destination node selects multiple disjoint paths according to recorded traversed paths of RREQ packets and sends RREP packets back to source node through the corresponding paths.

Disjoint multipath routing protocols improve network reliability because the possibility of multiple disjoint paths breaking simultaneously is much lower than possibility that one path breaks. However, the main drawback is the significant routing overhead incurred when intermediate nodes relay all duplicated RREQ packets.

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B. Meshed Multipath Routing Protocols

Many meshed multipath routing protocols have been proposed (e.g. [11-15]). The main idea is that a source node selects multiple overlapped paths to transmit packets to a destination node. Unlike disjoint multipath routing protocols, they let intermediate nodes have multiple paths between source node and destination node. As a result, there will be a large number of overlapping paths between source node and destination node constructed via links selected by intermediate nodes. In [11], the authors argue that meshed multipath routing protocols are more reliable than disjoint multipath routing protocols. However, the difference is small because the selected paths are overlapping but not independent.

Meshed multipath routing protocols improve network reliability considerably because of the large number of overlapping paths between source node and destination node. However, the main drawback is the excessive overhead incurred when intermediate nodes transmit replicated data packets over multiple links to the destination node.

C. Cognitive Routing Protocols

In recent years, several cognitive routing protocols have been proposed (e.g. [16-19]). The principle idea is that nodes are able to make wise decisions by predicting future network conditions based on past experience. Machine learning techniques are adopted to make nodes aware of history. Lower layer knowledge of wireless medium is shared with network layer. Currently, path selection and spectrum selection are common topics in cognitive routing protocols. Little prior work has focused on multipath routing. We argue that cognitive routing is a promising approach to make nodes intelligently perform multipath routing.

III. APPROACH

In this section, we discuss the details of our proposed routing protocol.

A. Overview of CMMRP

The cognitive multipath multi-channel routing protocol (CMMRP) is an on-demand disjoint multipath routing protocol.

CMMRP lets nodes trigger routing updates reactively when links break. Unlike the other on-demand multipath routing protocols where multiple paths are discovered at once by triggering one RREQ packet from source node, CMMRP allows multiple paths to be discovered one by one by triggering RREQ packets multiple times from the source node. The benefits of modification are:

- Nodes efficiently control the number of paths.
- CMMRP can downgrade to a single-path routing protocol.
- Nodes efficiently perform paths maintenance in dynamic networks.
- Nodes confidently discover frequency-disjoint paths.

CMMRP is designed for multi-channel environments where nodes can simultaneously use multiple interfaces to transmit packets over different frequencies. Unlike the other disjoint multipath routing protocols where nodes select multiple node-disjoint and edge-disjoint paths over one frequency, CMMRP employs cognitive functions to allow nodes to intelligently select multiple node-disjoint, edge-disjoint, and frequency-disjoint paths over multiple frequencies. Frequency-disjoint paths indicate that neighboring nodes on different paths transmit packets over different frequencies, which avoids interference from the other nodes. Neural network machine learning is adopted to make nodes aware of history, which makes CMMRP a cognitive routing protocol. Lower layer knowledge is shared with the network layer to help CMMRP work properly and efficiently.

The path discovery protocol of CMMRP can be divided into two parts, space discovery and spectrum discovery protocol, working in the two dimensions, space and spectrum.

B. Space Discovery Protocol

As the name implies, space discovery protocol is used to discover multiple node-disjoint and edge-disjoint paths in space dimension. It is further developed based on our own work [4]. In previous work, we developed a new metric, throughput increment, which is defined as predicted throughput after a new application joins minus current throughput. It is the throughput increment that determines future overall throughput. Predicted throughput increment is estimated based on predicted channel type and predicted channel capacity using neural network machine learning method. Simulation results show that throughput increment is an excellent metric for path selection.

In this work, space discovery protocol utilizes the developed metric to select paths after multiple disjoint paths are discovered. For ease of implementation, source node desires two disjoint paths to destination node.

Space discovery protocol works as follows. Source node floods RREQ packets reactively when number of paths to destination node is less than desired number. Unlike the other disjoint multipath routing protocols, intermediate nodes do not relay duplicated RREQ packets. Consequently, destination node knows a subset of possible paths to source node and selects the best path from them based on the developed metric. To discover two disjoint paths, source node has to flood RREQ packets again. Each intermediate node checks whether it already had a valid routing table entry to destination node. If so, it does not relay RREQ packets because it is already selected by destination node on one of the paths. Otherwise, it relays RREQ packets if they are not duplicated. Destination node selects the best path from updated known paths based on the developed metric. This approach guarantees source node to discover multiple node-disjoint and edge-disjoint paths.

Space discovery protocol makes multiple disjoint paths discovered one by one, which makes it possible for source nodes to independently determine the number of disjoint paths to destination nodes. This approach also enables CMMRP to downgrade to a single-path routing protocol, which makes it compatible with some other routing protocols. Compared to the other disjoint multipath routing protocols, CMMRP reduces routing overhead significantly by employing space discovery protocol. Traditional disjoint multipath routing protocols let intermediate nodes relay duplicated RREQ packets to make destination node know all possible paths. Routing overhead is mainly determined by the number of neighboring nodes because it determines the number of duplicated RREQ packets received by a node, which usually means a large amount of routing overhead especially for dense networks. Unlike them, CMMRP makes multiple paths discovered one by one by triggering RREQ packets multiple times from source node. Intermediate nodes discard duplicated RREQ packets. By applying space discovery protocol, routing overhead is mainly determined by the number of times that source node triggers RREQ packets. As a result, CMMRP does not generate significant overhead for dense networks.

C. Spectrum Discovery Protocol

As the name suggests, spectrum discovery protocol is used to discover multiple frequency-disjoint paths in spectrum dimension. It is further developed based on our own work [3]. In previous work, we developed a metric, delay of RREQ packets, for frequency selection. In wireless communication, packet delay is mainly determined by queuing delay which is affected by traffic load and channel capacity. Delay of RREQ packets is used to estimate queuing delay. The frequency over which delay of RREQ packets is small is predicted to have good channel conditions. Simulation results show that it is an excellent metric for frequency selection.

In this work, spectrum discovery protocol utilizes the developed metric to discover multiple frequency-disjoint paths. For ease of implementation, each node equips two interfaces which can be used simultaneously for packet transmission over different frequencies.

Spectrum discovery protocol works as follows. Nodes monitor as many frequencies as possible. Each node floods RREQ packets over all available frequencies to make neighboring nodes know conditions of each frequency. By applying the developed metric, when receiving a RREQ packet with a new sequence number or flooding ID, node records receiving frequency in the corresponding routing table entry and discards the rest duplicated RREQ packets. The recorded frequency is the most possible one which is different with the frequencies selected by neighboring nodes because allocated frequencies with interference from transmitting nodes tend to have large delay of RREQ packets. Each node on path selected by space discovery protocol transmits RREP packet back to source node over the recorded frequency to notify previous-hop node of the frequency selected by spectrum discovery protocol.

CMMRP is designed for multi-channel environment. It uses a novel approach, cognition, to discover multiple frequency-disjoint paths. Nodes estimate and predict future conditions of frequencies based on past experience. Spectrum discovery protocol utilizes the developed metric. Traditional multipath routing protocols only improve network reliability. However, by employing spectrum discovery protocol, CMMRP improves both network reliability and performance because spectrum diversity is maximized with frequency-disjoint paths, which avoids interference from neighboring nodes. Also, nodes are able to confidently discover frequency-disjoint paths because multiple paths are discovered one-by-one. Spectrum can be gradually allocated to each path according to updated environment. Otherwise, it is difficult to guarantee that neighboring nodes on different paths select different frequencies simultaneously in distributed manner.

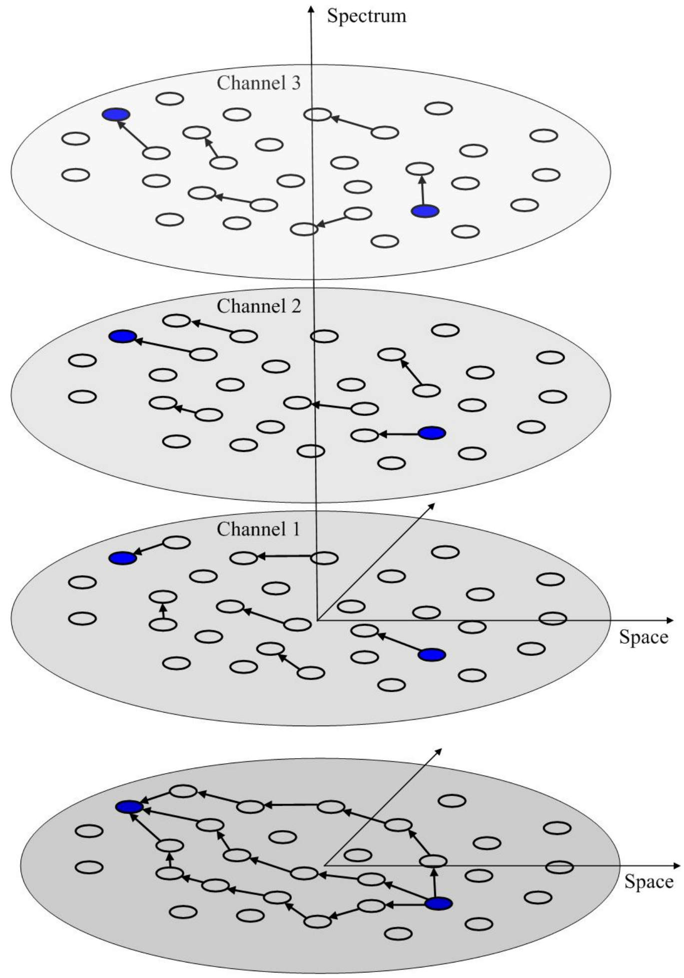

Figure 1: An example of constructed network topology by space discovery protocol and spectrum discovery protocol.

Figure 1 shows an example of constructed network topology by space discovery protocol and spectrum discovery protocol. It clearly shows the benefits of them. Blue nodes are indicated as source node and destination node. In spectrum view, nodes select frequency-disjoint paths for packet transmission. In space view, source node selects node-disjoint and edge-disjoint paths for packet transmission.

D. Paths Maintenance

In MANET, links tend to break because of dynamic physical topology. As a result, an efficient paths maintenance protocol is demanded to maintain network reliability.

Most traditional multipath routing protocols have to replace all valid paths between source node and destination node as long as one path breaks because source node initiates one RREQ packet to discover multiple paths at once. Otherwise, source node has to wait until number of valid paths is below a threshold to trigger RREQ packets. By applying traditional approaches, multipath routing protocols have to either generate significant routing overhead or degrade network performance. The problem becomes serious for MANET where network topology changes quickly. Unlike them, CMMRP provides an efficient paths maintenance protocol which is suitable for MANET. It makes multiple paths discovered one by one by triggering RREQ packets multiple times. Source node is able to efficiently control the number of valid paths by repairing one broken path each time, which usually incurs a small amount of routing overhead because of space discovery protocol.

E. Paths Usage

In wired networks, major consideration on multipath routing protocols is focused on paths usage because of the static network topology. However, in MANET, we argue that major consideration should be focused on path discovery.

CMMRP does not let nodes back up any redundant path because it shows little benefit in MANET. To balance load among multiple disjoint paths, source node should clearly know the conditions of each path. In [19], the authors proposed a routing protocol using WCETT as metric for path selection. In [4], we proposed a new metric, throughput increment, for path selection. CMMRP is able to balance load among multiple paths according to our developed metric. However, it shows little benefit in MANET because source node cannot continuously update conditions of each path. Otherwise, significant overhead has to be generated. Therefore, for ease of implementation, CMMRP equally balance load among multiple paths.

IV. SIMULATIONS

In this section, we provide simulation results of CMMRP using Qualnet 4.0 [20].

To show the benefits of CMMRP, it is compared with spectrum-aware routing protocol (SARP) [3] which is our own previous work and a simple multipath routing protocol (MRP).

MRP is an on-demand multipath single-channel routing protocol. SARP is described as follows. It is an on-demand cognitive single-path multi-channel routing protocol. Neural network machine learning method is used to make nodes aware of history. It employs two cognitive functions, intelligent multi-interface selection function (MISF) and intelligent multipath selection function (MPSF). The metric, throughput increment, is adopted by MPSF for path selection and the metric, delay of RREQ packets, is adopted by MISF for frequency selection. Simulation results show that SARP improves network performance.

We present following metrics with 95% confidence intervals of measured values to compare network reliability and performance of CMMRP with SARP and MRP.

- Overhead: Average number of RREQ packets received per frequency which dominates the number of route control packets.
- Throughput: Average rate of successful message delivery measured in Kbits per second which reflects network reliability and performance.

A. Impact of Network Size

In the first experiment, we show how network reliability and performance are affected when the number of nodes increases. We created a scenario which has 6 applications distributed in a 600m by 1500m region. We vary the number of nodes. There are ten available frequencies. Frequencies have different shadowing means such as 4, 6, 8, 10 or 12 and same Ricean K factor as 16. Automatic rate fallback is enabled. UDP is employed as transport layer protocol. IEEE 802.11 is employed as MAC protocol. We compare CMMRP with SARP and MRP.

Figure 2 and figure 3 show the comparison of overhead and throughput respectively as a function of number of nodes. As expected, overhead is increased as number of nodes increases because node density increases.

Compared to SARP and MRP, CMMRP increases overhead considerably. The reason is explained as follows. CMMRP is a disjoint multipath routing protocol and SARP is a single-path routing protocol. By employing CMMRP, multiple paths are discovered one by one by trigger RREQ packets multiple times, which incurs more overhead than SARP. On the other hand, CMMRP is a multi-channel routing protocol and MRP is a single-channel routing protocol. By

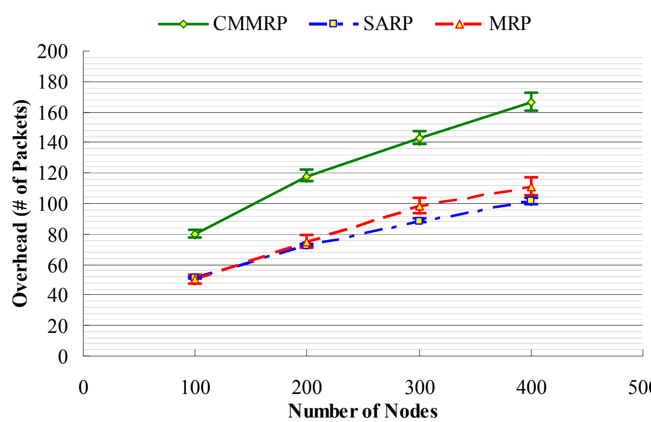

Figure 2: Comparison of overhead as a function of number of nodes.

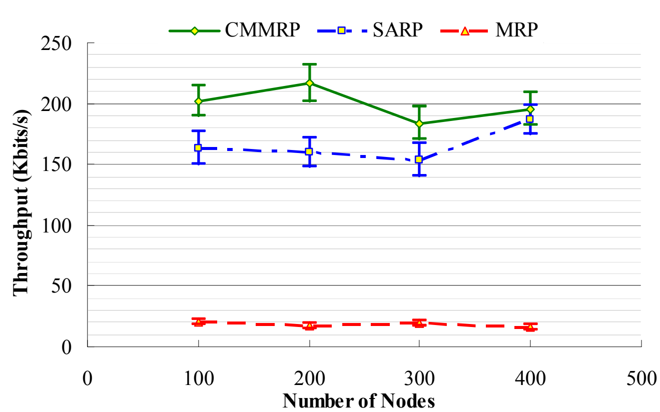

Figure 3: Comparison of throughput as a function of number of nodes.

employing CMMRP, each node equips two interfaces which monitor ten available frequencies and floods RREQ packets over all frequencies. CMMRP generates more average overhead per frequency than MRP because possibility that route control packets are transmitted over a long distance increases when number of frequencies increases.

Compared to SARP, CMMRP increases throughput considerably. The reason is explained as follows. CMMRP is a disjoint multipath routing protocol and SARP is a single-path routing protocol. By employing CMMRP, source node discovers multiple node-disjoint, edge-disjoint and frequency disjoint paths, which improves network reliability and performance. Compared to MRP, CMMRP increases throughput significantly. The reason is explained as follows. Like most multipath routing protocols, MRP can utilize only one frequency. As a result, interference between nodes is serious. On the other hand, CMMRP is a multi-channel routing protocol. Nodes discover multiple frequency-disjoint paths over ten frequencies. Consequently, interference between nodes decreases dramatically because frequency diversity is maximized by spectrum discovery protocol. These results show that CMMRP has better network reliability and performance than SARP and MRP for scenarios with a large number of nodes.

B. *Impact of Network Dynamics*

In the second experiment, we show how network reliability and performance are affected when node velocity increases. We created a scenario similar as the first experiment. 200 nodes are distributed in a 2500m by 2500m region. We vary node velocity. We compare CMMRP with SARP and MRP.

Figure 4 and figure 5 show the comparison of overhead and throughput respectively as a function of average velocity. As expected, overhead is increased and throughput is decreased as average velocity increases because links breakage happens frequently.

Compared to SARP, CMMRP increases overhead considerably. The reason is explained as follows. In MANET, nodes trigger routing updates frequently to repair broken paths. CMMRP generates considerable overhead especially for high node velocity to perform paths maintenance because nodes have to maintain multiple paths. Routing overhead of SARP increases slower than CMMRP as average velocity increases because it maintains fewer path than CMMRP. Routing overhead of CMMRP increases slower than MRP as average velocity increases because it makes multiple disjoint paths discovered one by one by triggering RREQ packets multiple times from source node, which is an efficient paths maintenance protocol.

Throughput is decreased as average velocity increases because of the dynamic network topology. Compared to SARP, CMMRP increases throughput considerably. Compared to MRP, CMMRP increases throughput significantly. The reasons are similar as the first experiment. These results show that CMMRP has better network reliability and performance than SARP and MRP for scenarios with high node velocity.

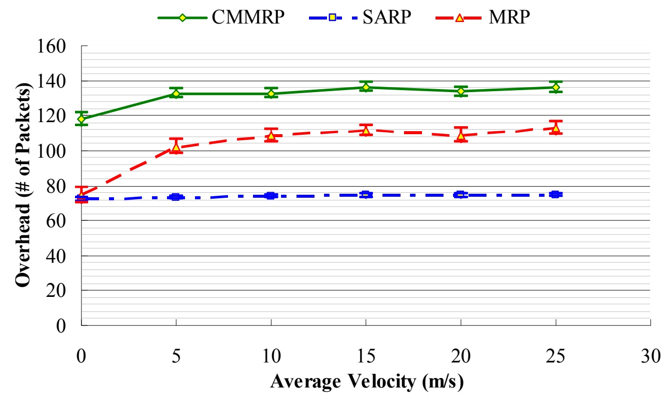

Figure 4: Comparison of overhead as a function of average velocity.

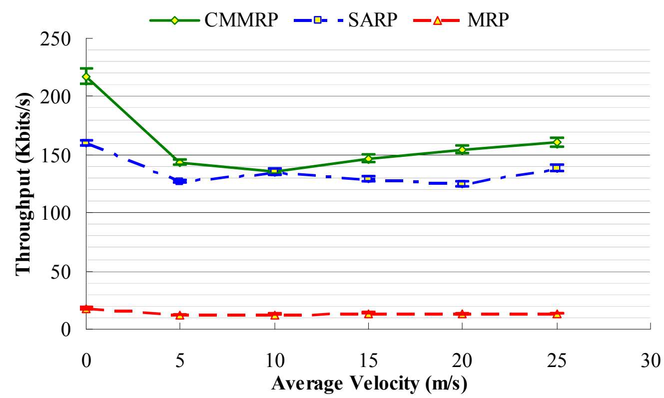

Figure 5: Comparison of throughput as a function of average velocity.

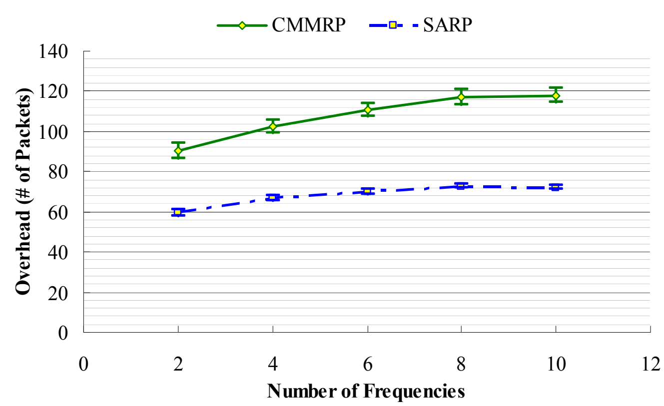

Figure 6: Comparison of overhead as a function of number of frequencies.

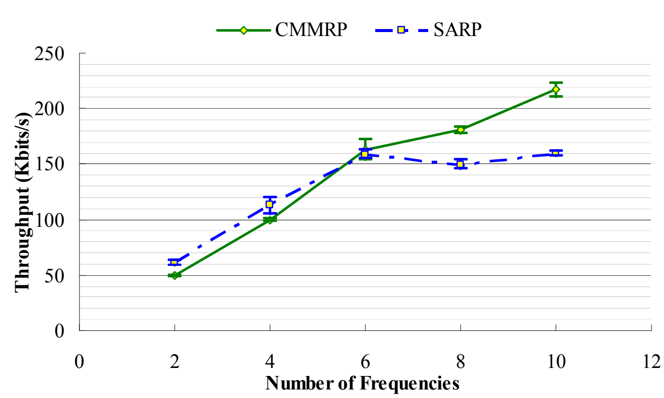

Figure 7: Comparison of throughput as a function of number of frequencies.

C. Impact of Network Spectrums

In the third experiment, we show how network reliability and performance are affected when the number of frequencies increases. We created a scenario similar as previous experiments. 200 nodes are distributed in a 600m by 1500m region. We vary the number of frequencies. We compare CMMRP with SARP.

Figure 6 and figure 7 show the comparison of overhead and throughput respectively as a function of number of frequencies. As expected, overhead and throughput are increased as number of frequencies increases.

Overhead is increased as number of frequencies increases because possibility that route control packets are transmitted over a long distance increases when number of frequencies increases. Compared to SARP, CMMRP increases overhead considerably. The reason is similar as previous experiments.

Throughput increases as number of frequencies increase because nodes are able to utilize more frequencies to increase frequency diversity. Compare to SARP, CMMRP has almost same throughput when the number of frequencies is smaller than 6 and it has more throughput when number of frequencies is bigger than 6. The reason is explained as follows. When the number of frequencies is small, nodes cannot effectively perform spectrum discovery protocol to discover multiple frequency-disjoint paths. On the other hand, when the number of frequencies is big, CMMRP makes nodes efficiently perform spectrum discovery protocol to maximize frequency diversity, which improves network performance. However, 6 frequencies are enough for SARP to allocate spectrum because it is a single-path routing protocol. These results show that CMMRP can improve network performance when number of frequencies is big enough.

V. Conclusions

We have investigated the problem of multipath routing in multi-channel mobile ad-hoc networks. We have proposed a novel cognitive multipath multi-channel routing protocol.

CMMRP lets nodes trigger routing updates reactively when links break. It is designed for multi-channel environment where nodes can simultaneously use multiple interfaces to transmit packets over different frequencies. It employs cognitive functions to make nodes intelligently select multiple node-disjoint, edge-disjoint and frequency-disjoint paths. Neural network machine learning method is adopted to make nodes aware of history. Lower layer knowledge is shared with network layer to help CMMRP work properly and efficiently. Path discovery protocol of CMMRP can be divided into two parts, space discovery protocol and spectrum discovery protocol. They work in two dimensions, space and spectrum. Simulation results show that CMMRP significantly improves network reliability and performance.

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