Multipath Selection in Multi-radio Mesh Networks

Irfan Sheriff   Elizabeth Belding-Royer
Department of Computer Science
University of California, Santa Barbara
{isheriff, ebelding}@cs.ucsb.edu

Abstract

Research has shown that multi-radio multi-channel mesh networks provide significant capacity gains over single-radio mesh networks [10, 20, 21]. Traditional single path routing can lead to poor utilization of the available channels in these networks. Opportunistic multipath routing can better exploit the available channel diversity in a multi-radio network. The goal of this paper is to select multiple paths that, when used concurrently, provide high end-to-end throughput. To this end, we present a metric for multipath selection in multi-radio networks. We evaluate the metric through simulations in Qualnet and show that intelligent multipath routing significantly outperforms single path routing in multi-radio mesh networks.

1. Introduction

Multihop wireless networks have emerged as an economical solution for providing last mile broadband access to the Internet. Community mesh networks, as they are popularly known, consist primarily of static wireless mesh routers that together form a multihop network. With the deployment of a few wired gateways, Internet access is provided throughout the network. However, due to the presence of a shared medium, the available bandwidth decreases considerably as the number of hops from the gateway increases. Multi-radio networks [10, 20, 21] that operate on multiple orthogonal frequency channels have been proposed as a solution to improve the capacity of mesh networks. We focus on these networks in this paper.

Additional capacity is gained in multi-radio networks through simultaneous data transmission on multiple orthogonal frequency channels. IEEE 802.11a supports 12 orthogonal channels and IEEE 802.11b/g supports 3 orthogonal channels. With the use of multiple radios tuned to different channels, a node can communicate with multiple neighbors simultaneously. Nodes within the interference range of each other can avoid interference through communication over different channels. The capacity of the network depends on the number of orthogonal channels supported by a radio and the number of radios per node. When the number of radios is smaller than the available orthogonal channels, the capacity depends on the channel assignment in the network. Multiple channel assignment techniques [10, 20, 21] have been proposed to achieve a capacity close to the optimal capacity of the network.

In order to utilize the bandwidth available on multiple channels in a multi-radio network, the WCETT [7] metric selects high throughput, channel diverse paths. However, a single path might not be able to utilize the bandwidth available on all the channels in the neighborhood. This can happen when the channel diversity on a single path does not ensure the utilization of all available channels or when the average path length is less than the number of available channels. Thus there is a need for the use of multiple paths to exploit the bandwidth available on the additional channels on a opportunistic basis. We use the term 'opportunistic' because the gain depends on the channel assignment and the availability of additional paths from the source node. Multiple paths have been shown to be useful in single-radio networks to provide error resilience and load distribution [15, 16]. The spatial diversity and data redundancy provided by multiple paths can be exploited for better end-to-end reliability and traffic distribution.

A number of multipath routing protocol solutions [9, 11, 12, 17, 22] have been proposed for ad hoc networks that discover multiple paths between a source and destination. In each of these protocols, the term *multipath* refers to the discovery of multiple paths that are actually used as *backup* paths. In a sense, then, these backup paths are actually *alternate* paths that are utilized only when the primary path fails. In this paper, the term *multipath* refers to the use of multiple *concurrent* paths between two nodes to increase the effective throughput. The goal of each previously proposed solution is to alleviate the problem of link breaks in the network by computing and caching alternate paths obtained during the route discovery process. In these protocols, link failure on the primary path, on which the data transmission is taking place, causes the source to switch to an alternate path instead of re-initiating the route discovery process. A new route discovery is initiated only when all the pre-computed paths break.

In this paper, we focus on exploiting channel diversity through multiple paths. Specifically, the contribution of this paper is a channel-aware routing metric for selection of multiple paths in multi-radio networks. We provide a comprehensive evaluation of the proposed metric through simulations in Qualnet and demonstrate that intelligent multipath selection can significantly outperform single path routing in multi-radio networks. To the best of our knowledge, this is the first work on multiple route selection for multi-radio networks.

The rest of the paper is organized as follows. First, we provide the background in Section 2. Section 3 summarizes the goals and objectives. We then present the design of the path selection metric in Section 4. Next, we evaluate the performance of the selection metric through simulations on Qualnet in Section 5. The related work is presented in Section 6. Finally, we summarize and conclude in Section 7.

2. Background

We first introduce a few terminologies used in the paper. We use 'multipath' to refer to a set of two or more paths, and use the terms 'multipath' and 'multipath combination' interchangeably. A 'Load ratio' of $(x : y)$ on a multipath combination of paths I and II means that for every x packets on path I, y packets are transmitted on path II. 'Load ratio' and 'load distribution ratio' are used interchangeably. 'Maximize' and 'minimize' do not mean finding the highest and lowest possible values, but refer to increasing as high as possible and decreasing as low as possible, respectively.

We next introduce the link metric followed by the single path routing metric proposed for multi-radio networks and then examine a simple network to motivate the need for multiple paths in multi-radio networks.

2.1. Expected Transmission Time

The ETT metric [7] represents the expected transmission time of a packet on a link. ETT takes both the link bandwidth and the loss rate into consideration. If S denotes the packet length, B denotes the bandwidth of the link, and ETX [6] represents the expected number of transmissions, then the ETT is computed as follows:

$$\text{ETT} = \text{ETX} * S/B \qquad (1)$$

The above calculation ignores the IEEE 802.11 backoff time. As shown in [7], the gain in accuracy taking the backoff into consideration is minimal. Hence we use Equation 1 to estimate the expected transmission time of a packet on a link. The ETT on a link closely represents the amount of time spent by a transmitted packet in the medium.

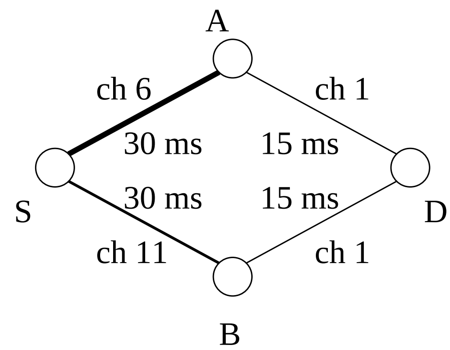


Figure 1. A two-radio IEEE 802.11g network.

2.2. Weighted Cumulative ETT

Draves et al. [7] proposed the Weighted Cumulative ETT (WCETT) metric for route selection in multi-radio mesh networks. A weighted average of the *bottleneck channel* transmission time and the aggregate delay of all the links reflects the goodness in terms of the achievable throughput on a path. The channel with the highest aggregate ETT is the *bottleneck channel* for a path. The WCETT for a path is given by:

$$\text{WCETT} = \eta * \text{BotETT} + (1 - \eta) * \text{AggrETT} \qquad (2)$$

where "BotETT" is the aggregate transmission time on the bottleneck channel and "AggrETT" is the aggregate transmission time on all the links. η is a value between 0 and 1, and reflects the extent to which channel diversity and end-to-end characteristics are considered for path selection.

2.3. A Motivating Example

Figure 1 shows a simple two-radio network where each node is equipped with two IEEE 802.11g radios. The numeric value on each link represents the ETT in milliseconds and the label "ch X" on a link denotes that channel X is used for communication. There are two paths available from S to D: path I with nodes S, A and D, and path II with nodes S, B and D. The ETTs of the links on path I are 15 ms on channel 1 and 30 ms on channel 6. Channel 6 is thus the bottleneck channel that limits the throughput. Similarly, channel 11, with an ETT of 30 ms, is the bottleneck channel on path II.

Suppose we use path I for routing packets from S to D. The maximum achievable throughput is limited by the bottleneck ETT of 30 ms on the channel 6. The achievable bottleneck throughput[1] is thus one packet every 30 ms. At this rate, channel 1, with an ETT of 15 ms, is only about 50% utilized while channel 6 is fully utilized. Further, channel 11 remains unused. On path II, the achievable bottleneck throughput is one packet every 30 ms on channel 11. In this case, channel 1 is 50% utilized at the bottleneck throughput rate, and channel 6 remains unutilized.

If the traffic is distributed equally on the two paths, the channel utilization is as follows: For every two packets transmitted by the sender, a total of 30 ms time is spent on channels 1, 6 and 11 since the packets can be transmitted concurrently on the paths. Thus the achievable bottleneck throughput is 2 packets every 30 ms or one packet every 15 ms. That is a 100% improvement in the achievable bottleneck channel throughput of the multipath combination over either of the individual paths. Hence we expect a significant gain in the end-to-end throughput as well. Of course, throughput gain can vary since the end-to-end throughput is affected by other factors such as the hop count and the end-to-end characteristics [7].

2.4. Traffic Partitioning

Multipath routing necessitates traffic partitioning. Traffic distribution can be accomplished in multiple ways. One technique is to distribute multiple concurrent flows from the source to the gateway node on multiple paths. The flows could belong to data or multimedia applications. A single multimedia application such as a video conference or streaming video is typically divided into multiple flows. If a layered scheme of multimedia streaming is used at the source [23], a single multimedia stream is divided into one base layer and several enhancement layers. Another technique, multiple description coding, splits a multimedia stream into multiple layers of equal importance.

Another method to partition traffic is to transmit packets from the same flow on different paths. The drawback of this scheme is that it leads to out of order packet reception at the destination and can thus negatively impact the performance of higher layer protocols such as TCP. Real time applications, however, have a resequencing buffer at the receiver and can tolerate packet reordering within certain end-to-end delay limits.

[1]The achievable bottleneck throughput is the maximum number of packets per unit time that can be sent over the bottleneck channel.

3. Objectives

The target network of this paper is a community mesh network that provides last mile Internet access. Since the mesh routers are typically static, we assume a stationary network that consists of nodes equipped with multiple IEEE 802.11a/b/g radios tuned to orthogonal frequency channels. The number of radios per node can be variable. The channel assignment is assumed to be static over short time scales. By ‘static’, we refer to a scheme that does not channel switch on a per packet basis. The channel switching happens across the network over longer periods of time.

The goals of our solution are the following. First, the selected set of multiple paths should maximize the end-to-end throughput. The selection metric should explicitly account for the intra-path and inter-path interference among the common channels on the paths. It should also take into account the degradation of throughput with longer paths. Extra hops on a path consume more resources and increase the contention in the medium. The additional packet delays affect the achieved throughput with protocols that use end-to-end acknowledgments (for example TCP).

Second, the multipath selection should be independent of the channel assignment scheme in the network. Recent research [10] has shown that the capacity of the network depends on the ratio of radios to channels. Channel assignment becomes critical when the number of radios per node is less than the orthogonal channels. Multiple channel assignment techniques have been proposed, including load aware [21], interference aware [20], and joint channel assignment and routing [2]. Our goal is to design a selection metric for the use of multiple paths in a network with any static channel assignment scheme.

4. Path Selection

4.1. The Selection Metric

We begin our discussion by asking the following question: Given paths P_a and P_b, what is the ‘goodness’ of the path combination?. Here, the goodness is measured in terms of the aggregate throughput achievable on the paths.

We propose a heuristic to quantify the goodness of a path combination (P_a, P_b). For ease of explanation, we consider two paths in our analysis. The analysis is, however, extensible to any number of paths. For our analysis, we assume that all the links on the paths interfere. We also assume that the traffic can be distributed in any ratio, $(x : y)$, over the two paths. Let the ETT of the i^{th} hop on a path P_k be represented as ETT_{ki} and let $SC(P)$ represent the set of channels on path P. We derive the goodness of the path combination (P_a, P_b) in two parts:

Inter-path interference index (λ): The inter-path interference index (λ) accounts for the interference among the common channel links on the two paths. Individually, the throughput on the paths is limited by the respective bottleneck channels. When used together, the interference between the links on the two paths can limit the joint throughput achievable. We show that the bottleneck channel depends on the load distribution over the multipath combination, and compute the load ratio at which the average per packet bottleneck channel transmission time is minimized. Consider a path P_k with m_k channels. Define X_{kj} as follows:

$$X_{kj} = \sum_{\text{Hop i is on channel j}} ETT_{ki} \quad j \in SC(P_k) \tag{3}$$

X_{kj} represents the total per packet transmission time on channel j and $\max_{1 \le i \le m_k} X_{ki}$ gives the transmission time on the bottleneck channel of the path. We now find the bottleneck channel transmission time for a multipath combination. Consider a traffic partition with a load ratio of $(x : y)$ on paths P_a and P_b. For a channel j, x packets on path P_a and y packets on path P_b consume a channel transmission time of $x * X_{aj} + y * Y_{bj}$. The average per packet consumption time on channel j in $SC(P_a) \cup SC(P_b)$ can thus be written as:

$$Y_j(x, y) = \frac{x * X_{aj} + y * X_{bj}}{x + y} \quad j \in SC(P_a) \cup SC(P_b) \tag{4}$$

Here, $X_{aj} = 0$ if the channel j is on path P_b alone and $X_{bj} = 0$ if it is on path P_a alone. Consider the case when a channel j is on path P_a alone. The packet transmission time on channel j is X_{aj}. The per packet channel consumption time, however, is $\frac{x * X_{aj}}{x+y}$ as given by Equation 4. This is because, for every $x + y$ packets, only x packets consume the bandwidth on channel j.

It is clear from Equation 4 that the traffic load ratio $(x : y)$ determines the packet consumption time on the channels. The channel with the highest packet consumption time acts as the bottleneck. Hence the bottleneck channel on a multipath can change with the load distribution ratio. If m_{ab} represents the total number of channels on the path combination (P_a, P_b), $\max_{1 \le i \le m_{ab}} Y_i(x, y)$ gives the bottleneck channel transmission time at the load distribution ratio $(x : y)$. We thus define $\lambda(x, y)$ as follows:

$$\lambda(x, y) = \max_{1 \le j \le m_{ab}} Y_j(x, y) \tag{5}$$

Independent path quality index (γ): The independent path quality index (γ) accounts for the end-to-end characteristics of the two paths. The WCETT metric gives the path quality of a single path in a multi-radio network. The WCETT for a path P_k with m_k channels and n hops is given by:

$$WCETT(P_k) = \eta * \max_{1 \le i \le m_k} X_{ki} + (1 - \eta) * \sum_{i=1}^{n} ETT_{ki} \tag{6}$$

The higher the WCETT is on a path, the lower is the expected throughput. To account for the end-to-end characteristics of both the paths, a weighted average of the WCETT on the paths is computed. We define $\gamma(x, y)$ as follows:

$$\gamma(x, y) = \frac{x * WCETT(P_a) + y * WCETT(P_b)}{x + y} \tag{7}$$

$\gamma(x, y)$ represents the independent path quality of the two paths taking the load distribution ratio into consideration.

Discussion: It is clear that both the inter-path interference index (λ) and the independent path quality index (γ) of a multipath depend on the load distribution ratio $(x : y)$. Ideally, the selection of the traffic partition should be such that it maximizes the end-to-end throughput of the multipath. It is, however, difficult to estimate the extent to which λ and γ impact the end-to-end throughput, and hence taking both the factors into consideration for estimation of the load ratio is difficult.

$\lambda(x, y)$ does not account for the end-to-end characteristics of the paths. For example, consider a multipath combination (I, II) with IEEE 802.11a orthogonal channels 34 and 42 on path I, and orthogonal channels 42 and 44 on path II. If an additional hop operating on channel 48 with an ETT lower than the bottleneck ETT sum is added on path I, $\lambda(x, y)$ remains the same.

$\gamma(x, y)$ does not account for the interference between the paths. For example, consider a multipath combination with channels 34 and 42 on path I, and channels 46 and 48 on path II. If we replace channel 48 with channel 42 on all the links on path II, the channel interference between the paths increases while $\gamma(x, y)$ remains the same.

Consider an example multipath combination of paths I and II. Let path I consist of a single hop on channel 34 at an ETT of 10 ms. Let path II consist of three hops that operate on channels 44, 46 and 48, all at an ETT of 10 ms. If we were to minimize $\lambda(x, y)$, the traffic would be equally distributed so that all the channels share the load equally and the bottleneck is minimized. However, path

I, with fewer hops, has lower WCETT and is expected to provide higher throughput. With no interference between the paths, path I should share a higher proportion of the traffic load for good end-to-end performance of the multipath combination.

It might seem that the individual path characteristics could be used to decide the load ratio on the paths. However, this could be undesirable when there is channel interference between the paths. Consider the same topology in the above paragraph with modifications. Let path I consist of a single hop on channel 34 at an ETT of 15 ms and let path II consist of three hops that operate on channels 44 and 46 at an ETT of 10 ms, and channel 34 at an ETT of 5 ms. The two paths interfere on the common channel 34. The WCETT of path II is higher than path I. However, the ETT on channel 34 on path I is higher than any other channel. If WCETT is used to decide on the traffic distribution, the slowest link of the multipath is loaded with more traffic, potentially resulting in under-utilization of the other channels on the multipath.

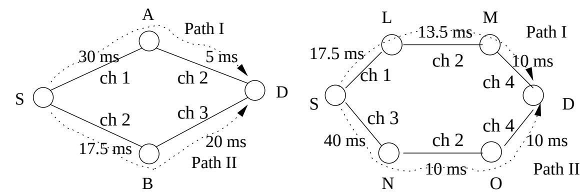
When there is no channel interference between the paths, we expect $\lambda(x, y)$ to have little impact on the end-to-end throughput of a multipath. Hence we select the load ratio in the inverse ratio of the WCETT of the paths when there is no common channel between the paths. When there is channel interference between the paths, we partition the traffic so as to minimize the inter-path interference index (λ).

CAM: We define the Channel Aware Multipath (CAM) metric for selection of multiple paths as a combination of λ and γ:

$$\text{CAM} = \beta * \lambda + (1 - \beta) * \gamma \tag{8}$$

CAM accounts for both channel diversity between the paths and the end-to-end characteristics of the individual paths. A low value of CAM corresponds to high throughput and vice versa. If β is chosen to be one, the metric only takes channel diversity between the paths into consideration. If β is zero, only the end-to-end characteristics of the paths determine the multipath selection. A value between zero and one for β accounts for both.

As an example, consider a 3-radio network with four orthogonal channels. We construct multipaths 1 and 2 from node S to node D as shown in Figure 2. The channel and the ETT on the links are shown. Since there is a common channel between the paths on both the multipaths, the load ratio is selected to minimize the inter-path interference index (λ) on the multipaths. We plot the variation of the per packet consumption on each channel with the load distribution ratio. As given by Equation 4, the per packet channel consumption time $Y_i(x, y)$ on channel i for a load ratio $(x : y)$ can be written as:



(a) Multipath 1. (b) Multipath 2.

Figure 2. Two possible sets of multiple paths available from node S to node D.

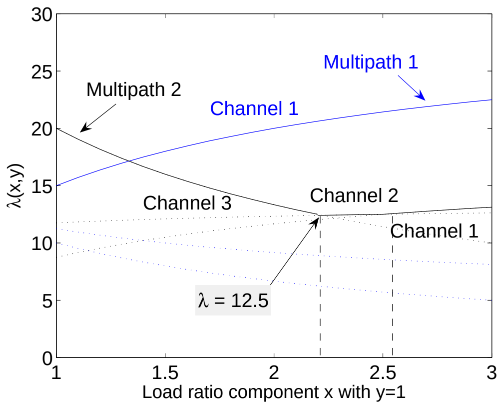
$Y_1(x, y) = \frac{30x}{x+y}$, $Y_2(x, y) = \frac{5x+17.5y}{x+y}$ and $Y_3(x, y) = \frac{20y}{x+y}$, for Multipath 1.

$Y_1(x, y) = \frac{17.5x}{x+y}$, $Y_2(x, y) = \frac{13.5x+10y}{x+y}$, $Y_3(x, y) = \frac{40y}{x+y}$ and $Y_4 = \frac{10x+10y}{x+y}$, for Multipath 2.

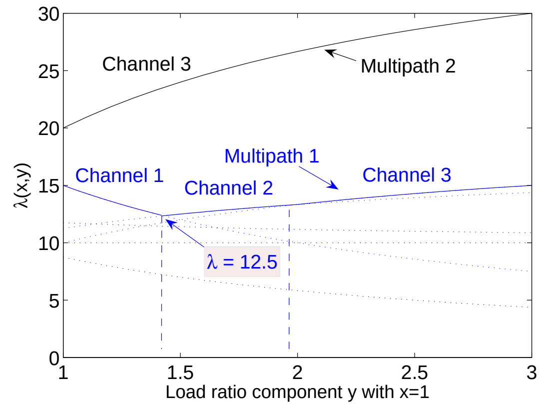
A plot of $Y_i(x, y)$ for channel i on multipaths 1 and 2 is shown in Figure 3. Figure 3(a) represents the traffic variation on path I with the load on path II fixed and Figure 3(b) represents the traffic variation on path II with the load on path I fixed. The dotted lines on the graph represent $Y_i(x, y)$ for all the channels and the solid lines represent the highest $Y_i(x, y)$ for a given $(x : y)$. Hence the solid lines represent the variation of inter-path interference index (λ) on the multipaths. The channel numbers on the solid lines denote the bottleneck channel in a given load distribution range with vertical demarcators. For example, in the load ratio range $(1 : 1)$ to $(2.2 : 1)$, channel 3 is the bottleneck on multipath 2, while channel 1 is the bottleneck in the load distribution range $(1 : 1)$ to $(3 : 1)$ on multipath 1. The load ratio $(x : y)$ at which $\lambda(x, y)$ is minimized is the chosen load distribution ratio. The minimum inter-path interference index (λ) is the same on multipaths 1 and 2. It occurs at a load ratio of $(1 : 1.4)$ on multipath 1, and $(2.2 : 1)$ on multipath 2. The load distribution ratio only serves as an indicator to the traffic allocator. The traffic allocator should strive to partition traffic so as to achieve a distribution close to this ratio.

We now compute γ for the two multipaths. For any η,[2] γ on multipath I $> \gamma$ on multipath II. This is due to the longer paths and consequently higher end-to-end packet transmission time on multipath II. CAM thus selects multipath I over multipath II for any β value < 1. $\beta = 1$ does not differentiate between the two multipaths.

[2] η controls the degree of importance of channel diversity over path length on a single path.



(a) Load fixed on path II.



(b) Load fixed on path I.

Figure 3. The variation of the inter-path interference index with the load distribution ratio.

4.2. Interface Disjoint Paths

IEEE 802.11 uses exponential backoff upon packet failure before a retransmission takes place. Hence the channel utilization of a single interface reduces with an increase in the packet error rate. Multiple instances of 802.11 could thus operate on the same channel and potentially provide better channel utilization, and thereby provide a gain in throughput. The analogy is similar to the gain obtained with multiple TCP connections [18]. If the throughput with multiple interfaces on a common channel is significantly higher than the single interface throughput, the path selection metric should explicitly account for the degree of interface disjoint-ness between paths.

We show in the Appendix that the additional complexity to evaluate the gain obtained with interface disjoint paths does not justify the gain in throughput. Hence, CAM does not differentiate paths with a common interface from interface disjoint paths. However, interface disjoint paths could provide better spatial diversity than common interface paths. Quantifying the trade-off between the spatial and channel diversity gain is not clear and we plan to explore this in future.

4.3. Revisiting Link Interference

In our analysis, we have assumed that all the links on a multipath interfere. This is a pessimistic assumption and does not hold true for longer spatially diverse paths. This assumption can be relaxed by building the interference graph for the mesh network. The interference graph $G = (V, E)$ consists of a set of vertices connected by edges. The vertices represent the links in the network and an edge between two vertices indicates that the two links representing the vertices interfere with each other. Padhye et al. [19] proposed an $0(n^2)$ algorithm for measuring the all-pair link interference in a n node network. We define X_{kj}^p as follows:

$$X_{kj}^p = \sum_{\text{Hop i on channel j interferes p}} ETT_{ki} \qquad (9)$$

where the link p operates on channel j and X_{kj}^p represents the aggregate ETT of links interfering with link p. X_{kj}^p represents the total transmission time on all the links interfering with link p. The interfering links can be obtained from the interference graph G. The maximum of X_{kj}^p on all the links operating on channel j represents the channel consumption time X_{kj} on a channel j. X_{kj} can thus be given by:

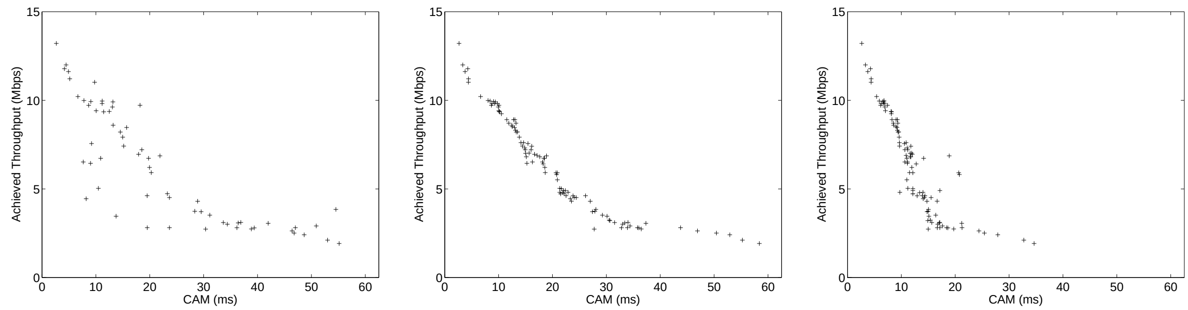
$$X_{kj} = \max_{link\, p\, on\, channel\, j} X_{kj}^p \qquad (10)$$

We can compute the inter-path interference index (λ) by taking the per link interference into consideration and computing the maximum $Y_j(x, y)$ over all links. In this paper, we compute λ and γ by assuming all the links to be in the interfering range of each other.

5. Implementation and Evaluation

In this section, we evaluate the effectiveness of CAM in selecting high throughput multiple paths and we quantify the gain in throughput with multiple paths in multi-channel networks.

The Qualnet simulator is used for the performance evaluation. The Optimized Link State Routing (OLSR) [5] protocol is modified to support multiple radios. OLSR propagates link information in the network. Since multiple paths have to be used simultaneously and path selection happens on a packet by packet basis,



(a) $\beta = 0.0$ (b) $\beta = 0.5$ (c) $\beta = 1.0$

Figure 4. Achieved throughput versus CAM for 100 randomly selected pairs of paths.

source routing is used to forward the packets. The measurement of ETT is done using the ETX and packet pair technique described in [7]. The nodes in the network are homogeneous in that they support the same number of radios. Each node periodically exchanges ETT information with each of its neighbors. The periodic exchange of ETT information is infrequent, about every 20 minutes, because there is no mobility in the network. Neighbor link information is propagated throughout the network every 30 minutes.

Multipath discovery is through a simple exponential exhaustive search. Using a breadth first search, we build all possible routes from a source to a destination and limit the maximum path length to six. λ and γ are computed[3] for all possible multipath combinations between the two nodes; the multipath with the lowest CAM is selected. Even though the exhaustive search is inefficient, it serves our purpose to evaluate the metric. Because the neighbor link information is only updated in the network once every 30 minutes, we limit the re-computation of paths to once every 15 minutes. The load ratio of each set of selected paths is rounded to the closest integer value and packets are split on the paths in this ratio.

The simulations consist of 100 nodes equipped with IEEE 802.11a radios in a 2000m X 2000m area. Unless otherwise mentioned, we use three 802.11a radios per node tuned to orthogonal channels 34, 42 and 46. The channel assignment is thus a redundant scheme as in [1, 7]. For computing WCETT, we assign equal weight to channel diversity and path length. Hence, we select η in Equation 6 to be 0.5.

The traffic consists of a single UDP stream split over the multiple paths in the chosen load distribution ratio. The maximum achievable throughput is obtained through multiple simulations, where each simulation incrementally increases the bandwidth of the stream.

[3] The computation of λ involves finding points of intersection between $Y_i(x, y)$ on all channels i.

5.1. Throughput Prediction

We first evaluate the effectiveness of CAM as a metric to select high throughput multipaths. 100 pairs of nodes are randomly selected and the best multipath combination as predicted by CAM is chosen for each node pair. The achievable throughput on the multipaths is measured. Figure 4 shows a scatter plot of the achieved throughput versus CAM. The plots show the throughput values for $\beta = 0.0$, $\beta = 0.5$, and $\beta = 1.0$. When $\beta = 0.0$, only the WCETT average over the paths, γ, contributes to CAM. In this case, CAM accounts only for the end-to-end characteristics of the paths without considering the channel diversity between the paths. The scattered throughput values show that $\beta = 0.0$ is a poor indicator of the achievable throughput and channel diversity between the paths needs to be taken into account.

When $\beta = 1.0$, CAM only considers the channel diversity between the paths. It is interesting to observe that the prediction works well for higher throughput paths. In this region (CAM < 10), the graph is less scattered and hence the throughput corresponds well to the predicted CAM. The region of high throughput corresponds to smaller path lengths. With smaller path lengths, the end-to-end characteristics of the paths (γ) have limited impact on the throughput. Hence, λ predicts the throughput well for smaller paths where channel diversity alone is a good indicator of the achievable throughput.

The plot with $\beta = 0.5$ is less dispersed over all the values of CAM. In this case, there is a good correspondence between CAM and the achievable throughput on a multipath combination. The result illustrates that the path selection metric performs well when both channel diversity and end-to-end characteristics are taken into account.

5.2. Impact of Traffic Partitioning

We now examine the impact of variable traffic partitioning on paths. The load ratio on 100 random multi-

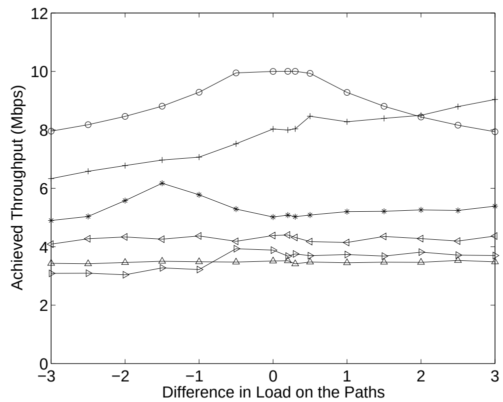


Figure 5. Impact of load variation on throughput.

paths is varied from $(1:4)$ to $(4:1)$. We found that for more than 50% of the paths, the achieved throughput varied by at least 25% over the entire load distribution range. Figure 5 shows the throughput variation over a chosen set of six paths. The x-axis represents the difference in the load over the paths. For example, a load distribution ratio of $(1:2)$ is shown as -1 on the the graph. The load variation affects some paths more than the others. The predicted ratio as discussed in Section 4 was found to lie within 10% of the peak value for about 78% of the multipaths.

The results show that traffic distribution plays a role in determining the achieved throughput on a multipath combination. Hence it is crucial to distribute the flows in the right proportion.

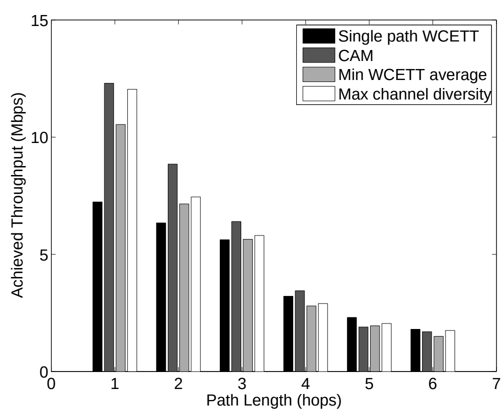


Figure 6. Throughput gain with CAM.

5.3. Throughput Gain

We next perform a throughput comparison of multipath routing with single path routing. Single paths are selected using the WCETT metric. Figure 6 illustrates the achieved throughput comparison between multipath routing and single path routing. The results represent the average throughput obtained between 100 randomly selected node pairs in the network. The x-axis represents the path length of the single path selected with WCETT. We refer to CAM with $\beta = 0.5$ as "CAM". When $\beta = 1.0$, only the channel diversity between paths (λ) is taken into consideration during the selection of paths and when $\beta = 0.0$, only the end-to-end characteristics of paths (γ) is taken into account. Thus we refer to the former case as the "Maximum channel diversity" metric and the latter as the "Minimum WCETT average" metric. The results show that the use of multiple paths provides a significant throughput gain primarily with extremely short path lengths.

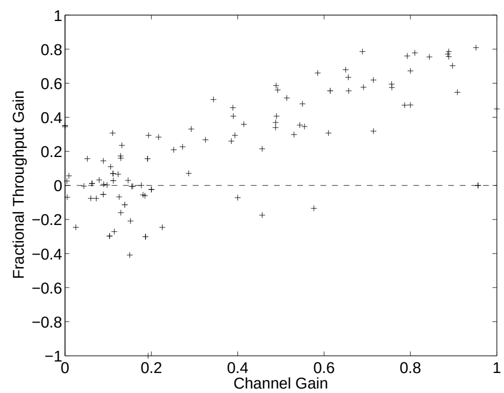


Figure 7. Channel utilization versus throughput.

To investigate further, we evaluate the correlation between the gain in throughput and the reduction in the per packet bottleneck channel consumption time with the use of multiple paths. λ denotes the bottleneck on multipath. Let λ_s denote the single path bottleneck channel consumption time. If m denotes the number of channels on the single path, λ_s can be given by:

$$\lambda_s = \max_{1 \le i \le m} X_i \tag{11}$$

We define the channel gain as follows:

$$\text{Channel Gain} = \frac{\lambda_s - \lambda}{\lambda_s} \tag{12}$$

A plot of throughput gain with multipath over single path versus the channel gain given by Equation 12 is shown in Figure 7. The y-axis represents the fractional gain in throughput with the use of multiple paths over single path routing. It can be seen that up to a channel gain of 0.25, the throughput gain is unpredictable.

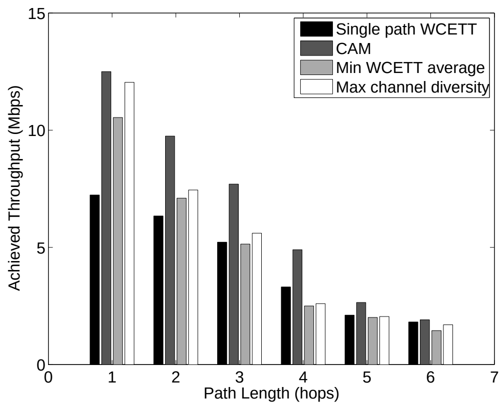


Figure 8. Throughput gain with CAM.

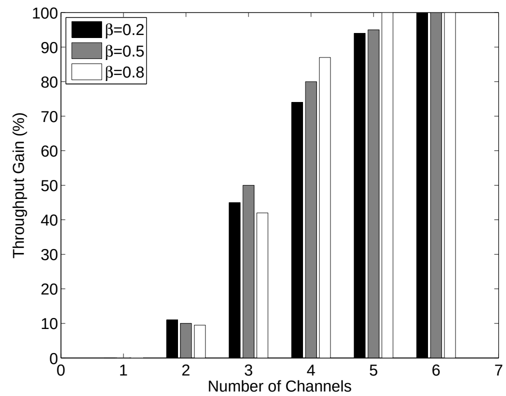


Figure 9. Throughput versus number of orthogonal channels.

Beyond 0.25, the throughput gain with multipaths is significant. One explanation for this behavior is that when the gain in channel bandwidth due to the additional path is low, the extra contention introduced compensates for the gain in throughput and can reduce the end-to-end throughput. Hence it is better to use single path routing when the gain in channel bandwidth is low.

We now plot the throughput gain comparison with the restriction that multiple paths are used only when the channel gain is more than 0.25. Figure 8 shows the results only for the subset of the paths for which multipath routing is used with CAM. In this scenario, CAM ($\beta = 0.5$) significantly outperforms both single path routing and the other β values. The average gain is about 50%.

5.4. Impact of Orthogonal Channels

We next evaluate the impact of the number of orthogonal channels on the achieved throughput. We use a redundant channel assignment scheme with one interface per channel. The number of channels is varied by changing the number of radio interfaces per node. The average throughput gain with two-path routing over single path routing is shown in Figure 9. Beyond six channels, more than two paths are required to exploit the bandwidth in the network. We observe that $\beta = 0.8$ provides higher gain than $\beta = 0.2$ when the number of channels is more than three. When the available channel diversity is low, the end-to-end characteristics of the paths (γ) play a greater role in limiting the achievable throughput. With more channels available, the channel diversity (λ) between the paths has to be maximized to achieve larger gains in throughput.

Typically, nodes are equipped with only two or three interfaces. A more optimal channel assignment scheme [20, 21] needs to be in place to exploit all the available orthogonal channels with the radio. The multipath gain with such a channel assignment scheme depends on the connectivity in the network and the number of paths available between the nodes. We plan to investigate the gain of multiple paths with such channel assignments in the future.

6. Related Work

Multipath routing has been an active research area in ad hoc networks for years. Techniques have been proposed to achieve load balancing, failure recovery, error resilience and increased end-to-end throughput in multihop wireless networks [8, 13, 15, 16]. These techniques use multiple paths to alleviate the issues that arise out of dynamicity in ad hoc networks. The issues could be link failures on the primary path, packet loss due to congestion or interference, path breaks and route changes due to node mobility and failures. All of these techniques achieve the benefits of error resilience and load balancing through spatial diversity provided by multiple paths. Video encoding [3, 14] and multipath partitioning techniques have been proposed to improve the end-to-end video quality in multihop networks. A number of multipath routing protocol solutions [9, 11, 12, 17, 22] have been proposed for ad hoc networks that discover and route packets on multiple paths between the source and destination.

Our work assumes the presence of a static multi-hop mesh network with little dynamicity in the network. Node failures and link breaks are infrequent. We focus on increasing the end-to-end throughput with efficient utilization of the available frequency channels in the neighborhood of the nodes. The notion of ETT as the link metric captures packet errors and bandwidth on a link. Unlike earlier work, the emphasis is on better utilization of the channel diversity rather than spatial diversity.

Multi-radio wireless networks [2, 10, 20, 21] have gained wide interest due to their ability to enhance the capacity of a multihop network. Draves et al. [7] proposed the Weighted Cumulative Expected Transmission Time (WCETT) metric for single path route selection in multi-radio networks. We believe that single path routing does not utilize the full benefits of a multi-channel network. An opportunistic multipath scheme can better exploit the bandwidth available in the neighborhood of the nodes.

7. Conclusion

Multi-radio multi-channel mesh networks provide significant capacity gains over single-radio mesh networks. Single path routing is unlikely to utilize the bandwidth available on all the channels in the neighborhood. This occurs when the channel diversity on a single path does not ensure the utilization of all available channels or when the average path length is less than the number of available channels.

To better utilize the available bandwidth, we have proposed CAM, a channel aware multiple path selection metric for multi-channel networks. We showed that by using multiple paths on an opportunistic basis, a significant gain in throughput can be achieved in a multi-channel network. The benefit with short paths to the destination is higher than long paths. This is because the end-to-end characteristics of long paths limit the gain obtained with additional channel diversity.

Acknowledgments

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A. Appendix

IEEE 802.11 uses exponential backoff upon packet failure before a retransmission takes place. Hence the channel utilization of a single interface decreases with an increase in the packet error rate. The use of multiple instances of IEEE 802.11 on a common channel can result in the reduction of the "idle" period since one instance of 802.11 can transmit packets while the other backs off. If the gain provided by multiple instances of 802.11 is significant, the multipath selection metric should take into account the degree of interface disjointness between multiple paths. We now show that when the packet error rate is less than 60%, there is little gain obtained with multiple instances of 802.11 on a common channel.

We use a simplified model of 802.11 and our analysis follows Bianchi's model [4]. We assume that the total transmission duration of a packet is dominated by the duration of the backoff and the packet transmission time. If there is only one transmitter in the medium, the medium utilization can be given by:

$$\text{Utilization} = \frac{T_{xmit}}{T_{xmit} + T_{backoff}} \tag{13}$$

where T_{xmit} is the expected packet transmission time and $T_{backoff}$ is the expected time spent during backoff. T_{xmit} can be written as:

$$T_{xmit} = \sum_{k=1}^{\text{inf}} (k * s(k) * S/B) \tag{14}$$

where $s(k)$ represents the probability that a packet is successfully delivered after k attempts and S is the size of the packet and B is the data rate. $s(k)$ can be expressed as a function of the packet error rate p as follows:

$$s(k) = p^{k-1} * (1-p) \tag{15}$$

We can express the expected time spent during backoff as follows:

$$T_{backoff} = \sum_{k=1}^{\text{inf}} (s(k) * \sum_{i=1}^{i=k} CW_k) \tag{16}$$

where CW_k represents the duration time of the k^{th} contention window. As in [7], we make the following assumptions. First, when the backoff window is chosen from $(0, CW)$, the average contention window size is $CW/2$. After 7 packet retransmissions, the contention window size remains $64 * CW_{min}$, but packet retransmissions occur infinitely. With the above assumptions, substituting Equation 15 in Equations 14 and 16

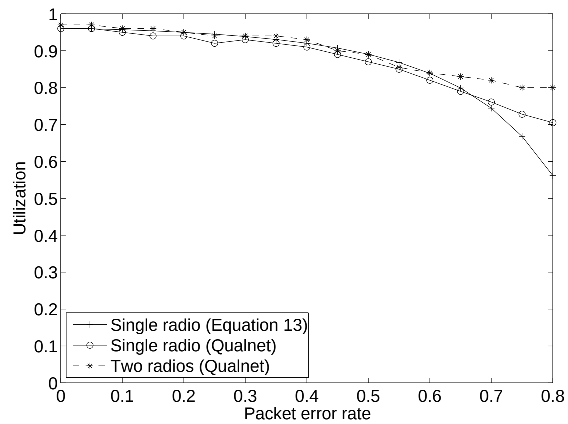

Figure 10. Channel utilization with IEEE 802.11.

and simplifying, we obtain the following for T_{xmit} and $T_{backoff}$:

$$T_{xmit} = \frac{S}{B} * (1-p) * (1 + 2p + 3p^2 + 4p^3) \tag{17}$$

$$T_{backoff} = \frac{CW_{min}}{2} * \frac{1 + p + 2p^2 + 4p^3}{1-p} \tag{18}$$

Since $0 < p < 1$, the higher order terms with p are very small and have been ignored in the above equations. The medium utilization can thus be obtained using Equation 13 as a function of the packet error rate p in the medium.

We evaluate the medium utilization through simulations in Qualnet. 1000 byte packet are transmitted between two nodes on a single interface operating at 1Mbps. The same experiment is then repeated with the nodes communicating simultaneously on two interfaces operating on a common channel. A plot of the channel utilization is shown in Figure 10. Channel utilization represents the fraction of the total time during which the medium is utilized for packet transmissions.

The graph shows that a single instance of 802.11 provides good utilization of the medium when the loss rate is low. Also, the additional gain obtained with the use of multiple interfaces is low when the packet error rate is less than 60%. Typically, link rate adaptation techniques keep the packet error rate low, and poor links with high error rates are avoided during path selection. Due to the complexity involved in quantifying this small gain with disjoint interfaces, we ignore it in the design of the multipath selection metric.