Design of a Channel Characteristics-Aware Routing Protocol

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***Abstract*—Radio channel quality of real-world wireless networks tends to exhibit both short-term and long-term temporal variations that are in general difficult to model. To maximize the utilization efficiency of radio resources, it is critical that these temporal fluctuations in radio signal quality be incorporated into wireless routing decisions. In this paper, we explore the design considerations in leveraging accurate real-time radio channel quality information when making routing decisions. Specifically, we propose a *Channel Characteristics-Aware Routing Protocol* (CARP) that (1) uses per-packet transmission time to estimate the effective residual capacity of a wireless link, (2) employs a bandwidth probability distribution model to better approximate a wireless path's capacity profile, and (3) applies multi-path routing to exploit diversity among alternative paths and deliver more robust throughputs despite temporal fluctuations in wireless link quality. We evaluated the performance gains of incorporating each of these mechanisms on a miniaturized multi-hop wireless network testbed– MiNT-m.**

I. INTRODUCTION

The channel quality of wireless networks is affected by many factors such as attenuation caused by physical objects, signal strength, interference from other radio signal sources etc. As a result of these complex radio signal propagation dynamics, a wireless link's signal quality and capacity tends to fluctuate significantly over time. It has been shown in [8], [6] that efforts to model [14] these temporal quality fluctuations have been largely unsatisfactory for real-world networks. This is because they cannot accurately account for the effects of all external interference, physical obstacles, and low-level radio propagation dynamics. The main goal of this research is to examine the alternative of leveraging real-time channel quality measurements in the design of routing algorithms for wireless mesh networks.

In this paper we focus on the design of a routing protocol for Wireless Mesh Networks (WMN). WMNs are multi-hop wireless networks serving as an last-mile access alternative besides DSL and cable modem. Nodes in WMNs are mostly stationary, with a small number of them connected to the wired network serving as gateways. Most existing routing protocols for WMNs do not account for temporal fluctuations of wireless link quality, and therefore leave room for further optimizations. In particular we address the following design considerations:

- Accurate estimation of the effective available capacity of a wireless link.
- Combining per-link metrics into an end-to-end path metric for route selection.
- Properly accounting for temporal variations in wireless link quality to ensure robust application-level performance.

In this paper we present a WMN routing protocol called *Channel Characteristics-Aware Routing Protocol* (CARP), which exploits real-time wireless link quality measurements to maximize the sustained throughput of a WMN. In particular, CARP (i) uses per-packet transmission time to estimate the effective residual capacity of a wireless link, (ii) employs a bandwidth probability distribution model to better approximate a wireless path's capacity profile, and (iii) applies multi-path routing to exploit diversity among alternative paths and deliver more robust throughputs despite temporal fluctuations in wireless link quality. We evaluate the effectiveness of CARP using a multi-hop wireless network testbed called Mint-m [7], which is designed to be reconfigurable while providing the same fidelity as a real-world testbed.

The rest of the paper is organized as follows. Section 2 describes the CARP protocol. Section 3 presents the performance analysis of CARP on the Mint-m testbed. Section 4 reviews previous work on wireless routing protocols and Section 5 concludes this paper with a summary of the main research contributions of this work.

II. CHANNEL CHARACTERISTICS-AWARE ROUTING PROTOCOL (CARP)

CARP is a WMN routing protocol that leverages real-time radio channel quality information to maximize the sustained throughput of a wireless mesh network. It is similar in spirit to several recent WMN routing protocols, such as Srcr [3] and MCL [9]. Nodes gather link state information about the WMN and use it to compute the "best" path to the gateway. Although the topology of a wireless mesh network is static, the quality of a WMN's link could vary significantly over time. These temporal fluctuations in wireless link quality have been observed in several previous works [1], [5]. In subsequent sections we discuss different design issues for WMN routing protocols and show how they are addressed in CARP.

A. Wireless Link Capacity Metric

Intuitively, an ideal wireless link capacity metric should accurately capture the residual capacity of a wireless link by incorporating all related factors, such as (i) the physical transmission rate (e.g., 1, 2, 6 and 11 Mbps for IEEE 802.11b links), (ii) the contention among wireless nodes sharing the same radio channel, and (iii) the bit error rate. Previous works on wireless link capacity metrics [6], [10], [16], [17] captured most of these factors except the effects of contention. Since interference affects both contention and bit error rate, including both these factors in the metric implicitly accounts for interference.

CARP approximates the ideal wireless link capacity metric using *end-to-end per-packet transmission time measurements*. The end-to-end transmission time (TT) of a packet can be modeled as

$$TT = T_{access} + N_{retransmit} * \frac{S}{B} \tag{1}$$

where T_{access} represents the time a packet spends in exponential back-off or channel access, $N_{retransmit}$ is the number of times a packet is transmitted before receiving an ACK successfully, S represents the packet's size, and B represents the wireless link's physical transmission rate.

Instead of computing TT, CARP uses the Measured Transmission Time (MTT) to approximate TT as follows. If there are already packets in the wireless interface, then the end-to-end transmission time of the i^{th} packet, TT_i is

$$TT_i = Ack_i - Ack_{i-1} \tag{2}$$

where, Ack_i is the time at which the ACK of the i^{th} packet arrives at the sender. If no packet is currently in the wireless interface, then the end-to-end transmission time of the i^{th} packet, TT_i, is

$$TT_i = Ack_i - Pkt_i \tag{3}$$

where Pkt_i is the time at which the ith packet is moved to the wireless interface. MTT_i is the normalized end-to-end per-packet transmission time, and is equal to $\frac{TT_i}{S_i}$, where S_i is the size of the ith packet in bytes. Finally, a wireless link's MTT is a smoothed average of the normalized end-to-end per-packet transmission times for all packets traversing a wireless link.

$$MTT = MTT_i * \beta + MTT_{old} * (1 - \beta) \tag{4}$$

where β is a smoothing constant that represents a tradeoff between responsiveness and stability.

To measure MTT we modified the Madfwifi driver for Atheros-based wireless LAN interfaces so that it generates an interrupt when a MAC-layer ACK packet is received. In addition, we leveraged the 64-bit timestamp counter in these WLAN interfaces to take high-resolution timing measurements.

B. Path Capacity Metric

There are two possible ways to convert a link capacity metric into a path metric – one can sum up the per-link metrics of the path, or take the maximum of the inverse of the per-link metrics of the path. The former approximates end-to-end delay as seen by a packet (sum of per-link transmission times), while the latter approximates the available bandwidth of the path's bottleneck link. Because longer paths consume more network resources, most routing metrics take the summing approach to favor paths with a fewer number of hops. Conceptually, summing the per-link transmission times is designed to minimize a flow's end-to-end delay, which is not the same as maximizing a flow's throughput. Hence, we propose the following two path capacity metrics based on per-link MTT estimates:

$$MTTDelay_p = \sum_{l \in p} MTT_l * I_l^p \tag{5}$$

$$MTTBW_p = \frac{1}{MAX_{l \in p}(MTT_l * I_l^p)} \tag{6}$$

where $MTTDelay_p$ approximates the expected end-to-end delay of packets traversing the path p, whereas $MTTBW_p$ approximates the bandwidth available to a new flow. I_l^p represents the impact on the MTT of link l due to the flow's packets crossing l's neighboring links on path p. Thus representing the degree of self interference experienced by a flow going along link l on path p. Typically the value of I_l^p is set to 2, i.e., each link interferes with its immediate neighbouring links. Neither of the above path capacity metrics account for temporal fluctuations in wireless channel quality.

C. Accommodating Temporal Variation

Temporal fluctuations in wireless channel quality, could have a significant performance impact. Since path bandwidths vary significantly over time the best routing decision made at time T may no longer be optimal at time $T + \delta$. In this subsection we present techniques to incorporate radio channel quality fluctuations into routing decisions.

1) Modeling Path Capacity as A Probability Distribution: To accurately account for channel quality fluctuations, CARP models the capacity of a wireless path p as a probability density function F_p. For many transport protocols that are TCP-like, the variance of a wireless path's capacity is as important as its mean because these protocols react very poorly to sudden increase in packet loss. Therefore, in many cases, a wireless path with a smaller mean and variance may be a better choice from the standpoint of transport-layer performance.

To account for path capacity fluctuations in routing we first compute the Cumulative Distribution Function (CDF) of each path's capacity. The CDF ($F_p(B)$) of a path p is

$$F_p(B) = Pr(x \leq B) \tag{7}$$

$$G_p(B) = 1 - F_p(B) = Pr(x > B) \tag{8}$$

$G_p(B)$ is the complimentary CDF of a path and is more convenient to use because it provides a lower bound on a path's capacity. The CCDF of a path's capacity can be derived from the CCDFs of its constituent links. Assume a N-hop path p consisting of the following set of links, $l_1, l_2 ..., l_N$, each of whose capacity CCDF is denoted as G_{l_i}. The CCDF of p's capacity can be expressed as

$$G_p(B) = G_{l_1}(B) * G_{l_2}(B) * ..G_{l_N}(B) \tag{9}$$

In practice, each individual wireless link's capacity CCDF is derived from histograms of measurements.

Once the CCDFs of the candidate paths are computed, CARP computes the maximal capacity that each path is able to guarantee with a probability threshold T, and chooses the path with the highest such guarantee. T is an empirical constant that is set to 0.8 (20th percentile) in our experiments. Hence the value B_T is calculated for the ith path such that $G_i(B_T) = 0.8$, and path with the highest B_T is chosen. Hence, the best path p_{best} is the one satisfying:

$$p_{best} = arg\,max_{p_i}(G_{p_i}^{-1}(0.8)) \tag{10}$$

Intuitively, with $T = 0.8$, CARP is looking for the path with the best 20th percentile bandwidth, which is close to a path's mean capacity if its path capacity is stable, but may deviate significantly from its mean if the quality fluctuations of the path's links are substantial.

CARP is designed for WMNs and assumes a gateway-based architecture. Each WMN node sends the mean bandwidth of each of its outgoing links during the previous N seconds to the gateway. The gateway uses the past H samples to compute the capacity CDF of the links in the network. Therefore the current CARP prototype can only account for fluctuations of the granularity of N seconds, and uses path quality history in the last H seconds for routing decisions. Given a pair of source and destination nodes, the gateway computes the top K paths using $MTTBW$ as the path metric and their corresponding path distributions, and then chooses the best path among them according to Equation 10. In the rest of this paper we will refer to this CDF-based routing algorithm as $MTTProb$.

2) Exploiting Diversity through Multi-path Routing: In the real world, there are many cases in which there is no clear winner among the candidate paths and all the paths experience substantial channel quality fluctuations. In this case, the best course of action is to use multiple paths to route a flow in the hope that they can compensate for each other. There are two key decisions in multi-path routing design: (i) which subset of paths to use, and (ii) how to distribute a flow's traffic among the paths. The following algorithm is used in the CARP to address these two issues:

1) Given a sender and a receiver, use the $MTTBW$ metric to compute a set of atmost K disjoint paths D_p starting with the best path and adding disjoint paths to the set.
2) Compute the capacity CCDF of each of the K paths found in Step 1. Let the capacity CCDF of the ith path be $G_i()$, and its input load assignment be a_i, the load that successfully goes through the ith path be b_i, and the cumulative distribution function for b_i be $T_i()$. Then
$$T_i(X) = \begin{cases} G_i(X) = 1 - F_i(X) & \text{if } X \leq a_i, \\ 0 & X > a_i \end{cases} \tag{11}$$
3) The total throughput of using all K paths, B, is equal to $\sum b_i$, and is a convolution of the $T_i()$ associated with these paths. We incorporate the effect of inter-path interference by modifying the value of I_l^p in Equations 5 and 6 to include both intra-path and inter-path interference.
4) To search for the best a_i's, maximizing $T^{-1}(0.8)$, we start by partitioning the bandwidth requirement of the user flow among the K candidate paths in a weighted fashion, where the weight assigned to the ith path is proportional to $T_i^{-1}(0.8)$. Because the search space is large, we randomly vary the initial weights, and find the weight assignment that maximizes $T^{-1}(0.8)$. For each candidate weight assignment, repeat Steps 2 and 3.
5) Compare the 20th percentile bandwidth of the best multi-path routing choice with that of $MTTProb$ routing choice, and choose the better of the two. This way CARP uses multi-path routing only when it is advantageous to do so.

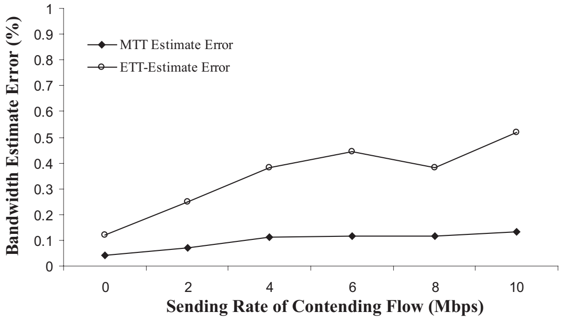

Fig. 1. The percentage estimation errors of MTT and ETT for a UDP connection running over a one-hop wireless link with a sending rate of 6Mbps when there is a contending UDP connection that varies its sending rate from 0Mbps to 10Mbps. ETT's estimation error increases with the background load, while MTTs estimation error remains almost constant.

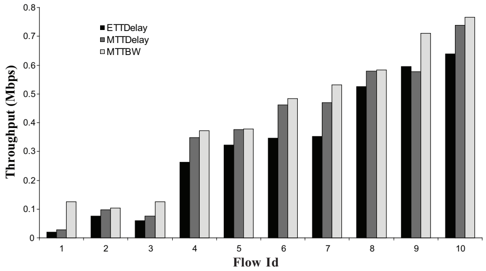

Fig. 2. End-to-end throughput measurements of 10 best flows on the MiNT-m testbed for ETTDelay, MTTDelay and MTTBW schemes in the presence of a background flow with a sending rate of 2Mbps. MTTDelay and MTTBW always outperform ETTDelay. MTTBW performs the same or better than MTTDelay in all cases.

III. PERFORMANCE EVALUATION

We evaluated the performance of CARP on the MiNT-m testbed [7], [8], which is a 12-node multi-hop wireless network testbed developed at Stony Brook University. We used a 3x4 grid topology, and set the WLAN cards to operate in the 802.11a mode. In this section we present our evaluation.

A. Results and Analysis

The goal of this performance evaluation study is to empirically quantify the throughput gain of CARP over known wireless routing algorithms. The main performance metric used is connection throughput expressed in bits/sec. We compare MTT schemes against the ETT metric [10] given by.
$$ETT = ETX * (S/B_l). \tag{12}$$
where the ETX is the number of retransmissions, S is the packet size and B is the link bandwidth. ETT of a path is the sum of link ETTs, hence we refer to it as $ETTDelay$. In [10], the authors use a packet pair based technique to determine B_l, which requires explicit probing of each link with a packet pair. This can be expensive and does not accurately reflect short term channel variations or auto-rate. Hence, for our evaluation we have set the value of B_l to the link rate reported by the driver.

1) Effectiveness of MTT: To evaluate the effectiveness of MTT as a wireless link capacity metric, we compare the application-level throughput of a UDP connection under different background loads with the predictions from MTT and ETT metrics. The UDP connection sends at 6Mbps over an IEEE

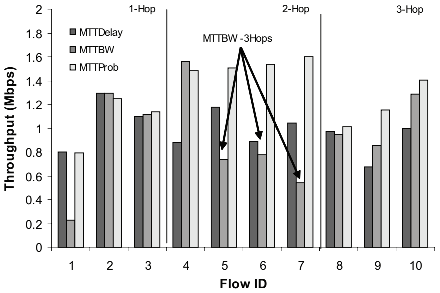

Fig. 3. Throughput of 10 TCP Flows on the MiNT-m testbed for MTTProb (T=0.8), MTTDelay and MTTBW. Flows are classified by the number of hops in the path chosen by MTTProb. MTTDelay outperforms MTTBW for Flow 1,5,6,7 because MTTBW chooses a longer path for those flows.

802.11a link that is configured to physically transmit at 6Mbps. The background load is in the form of another UDP connection over a neighboring IEEE 802.11a link that operates in the same channel but at the physical transmission rate of 24Mbps. Figure 1 shows the estimation errors of MTT and ETT as the background UDP connection's sending rate varies from 0 to 10 Mbps. As the background load of the radio channel increases, the throughput estimation error of ETT increases since it does not consider contention and interference from the background source. In contrast, MTT's throughput estimate error remains largely the same However, even MTT does not account for all performance overheads and therefore still exhibits a 5-15% estimation error.

2) Comparison among ETTDelay, MTTDelay and MTTBW: We next investigate if taking the inverse of the MTT of a path's bottleneck link (MTTBW) is a better path capacity metric than taking the sum of link ETTs or MTTs of a path (ETTDelay, MTTDelay). We randomly selected 20 pairs of nodes, ran a UDP connection between each node pair and measured their throughputs. The reported throughput of each connection is the average of three runs' measurements. A one-hop UDP connection with the sending rate of 2 Mbps that could interfere with a number of wireless links in the testbed is used as the background traffic. The average throughputs of the 10 best flows under the three routing metrics are shown in Figure 2. In almost all cases, MTTDelay and MTTBW metrics outperform ETTDelay, thus further validating that MTT is a better capacity metric than ETT. In addition, MTTBW performs equally well or better than MTTDelay.

3) Probability Based Metric: A probability distribution-based path capacity estimate is particularly useful for transport protocols such as TCP that are sensitive to fluctuations in path quality. To demonstrate this, we ran 20 TCP flows over 20 randomly selected node pairs on the MiNT-m testbed. The background traffic consisted of 3 UDP flows sending traffic at the rate of 200Kbps. The measured throughputs of 10 of these 20 TCP flows under MTTProb (T=0.8), MTTDelay, MTTBW are shown in Figure 3. Except two flows (2 and 4), MTTProb performs better than the other two, because it prefers stable paths with lower variance. Also, the average throughput for MTTBW is lower than that of MTTDelay, as MTTBW sometimes chooses longer paths with higher mean capacity. A larger number of hops tends to increase the packet loss probability affecting TCP because it backs off unnecessarily whenever it detects consecutive packet losses.

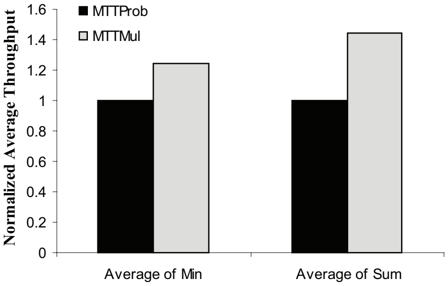

Fig. 4. Normalized averages of the minimum and sum of each flow pair's throughputs for 20 flow pairs running on the MiNT-m testbed under MTTMul and MTTProb. MTTMul improves minimum by 24% and the sum by 44%

4) Multi-path Metric: MTTMul further improves the robustness of a wireless routing decision by leveraging diversity in multiple paths. In its current design, MTTMul only chooses a multi-path route if and only if such a route's estimated capacity is higher than that of the best path found by MTTProb.

To compare MTTMul with MTTProb, we randomly chose 20 pairs of UDP flows (40 flows in total). In each run, a pair of flows are routed simultaneously both using MTTMul or both using MTTProb, and we measured the minimum (MIN) and the sum (SUM) of their throughputs for each scheme. The average results for the measurements for 20 flow pairs are shown in Figure 4. MTTMul outperforms MTTProb in both MIN and SUM measurements. MTTMul does better in MIN throughput because using multiple paths provides an effective hedge against sudden decrease in link quality especially for poorly connected node pairs. MTTMul also improves the aggregate throughput of the two test flows as it utilizes more network resources simultaneously.

IV. RELATED WORK

There is a large body of literature on exploiting channel quality feedback in the design of wireless routing protocols. Due to limitations in space, we restrict ourselves to those that are most relevant to protocol mechanisms in CARP.

A. Wireless Routing Metrics

One of the earliest works on channel aware routing metric is the Expected Transmission Count metric (ETX) [6], where the weight of a link is the expected number of times a packet is retransmitted over it. To overcome the limitations of the ETX metric authors in [10] propose the WCETT metric. WCETT of a n hop path is given by

$$WCETT = (1-\beta) * \sum_{i=1}^{n} ETT_i + \beta * max_{1 \leq j \leq k} X_j. \quad (13)$$

Here the X_j component represents channel diversity. If the system has a total of k channels

$$X_j = \sum_{Hop\ i\ is\ on\ channel\ j} ETT_i \quad 1 \leq j \leq k \quad (14)$$

and β is a parameter that controls the weight of each term. For a single channel network (β = 0) WCETT metric reduces to *ETTDelay*. One main limitation of WCETT is that it does not accurately account for contention from other flows in the neighbourhood. The authors suggest a packet-pair technique to estimate link bandwidth, which requires the use of explicit probe packets. Our technique not only estimates the effective path bandwidth more accurately but also uses on-going transmissions to measure at a fine time scale.

Several recent works [2], [17], [16] incorporate contention in the routing metric. The goal of all these works is to find the path with highest end-to-end throughput, but they do so indirectly by approximating the effective path capacity. The MTT metric is a practical metric that accurately estimates the effective link capacity instead of using indirect measurements or approximations. Recent papers such as [5], [11] have studied the effects of measurement techniques on the accuracy of link metrics. The measurement technique used in CARP avoids the limitations addressed in these works.

B. Diversity and Multipath Routing

Multi-path routing has been used in several mobile wireless network protocols [12], [13] to increase reliability of data transfer in mobile ad-hoc networks. Multi-path routing can also be used in wireless networks to exploit channel diversity. ExOR is an opportunistic routing mechanism that leverages the broadcast nature of the wireless medium to make delayed forwarding decisions at the Routing layer[4]. Each relay node forwards packets only if it fails to overhear a higher priority node forwarding the same. However, it may not always be possible for neighbours of a node to overhear each other, and hence multiple copies of the same packet could be propagated in the network. ROMER [15], another routing protocol based on this framework leverages transient variations to select the highest throughput path using a credit based forwarding scheme. Both ExOR and ROMER exploit the redundancy due to the broadcast nature of the medium, but do not explicitly leverage the multirate option at the physical layer.

V. CONCLUSION

The fundamental motivation behind the development of CARP is the recognition that temporal fluctuation of wireless channel quality is a fact of life that is difficult to model, and hence must be explicitly incorporated in the design of wireless routing protocols. To accurately estimate the residual capacity of a wireless link, CARP uses per-packet transmission time measurements, which successfully account for back-off delay, physical transmission rate, and retransmission time. For path capacity metrics, CARP advocates focusing more on a path's bottleneck link's capacity rather than a path's end-to-end delay. To explicitly accommodate wireless link quality fluctuations, CARP pioneers the use of a probability distribution-based path capacity model in route selection, and is able to identify paths that are more likely to produce better application-level throughputs for TCP-like transport protocols. Finally, to improve the robustness of the throughput between a pair of nodes, CARP exploits diversity among multiple paths by extending the probability distribution-based path capacity model to compute traffic load assignment for multiple candidate paths.

Preliminary results show that these design decisions indeed yield better performance. Specifically we conclude that (1) MTT is more accurate than existing wireless link capacity metrics. (2) Taking the bottleneck capacities of a path is more effective than summing the delays of constituent links. (3) Using probability distribution to model wireless path capacity produces better paths than using mean value. and (4) Multi-path routing can further improve the throughput robustness of wireless flows by leveraging path diversity.

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