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An Optimization Framework for Opportunistic Multipath Routing in Wireless Mesh Networks

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ABSTRACT

we consider wireless mesh networks, and exploit the inherent broadcast nature of wireless by making use of mnltipath ronting. We present an optimization framework that enables us to derive optimal flow control, routing, scheduling, and rate adaptation schemes, where we nse network coding to ease the routing problem. We prove optimality and derive a primal-dual algorithm that lays the basis for a practical protocol. Wireless mesh networks have emerged as a promising solution to providing cost effective last-mile connectivity. Employing multiple channels is shown to be an effective approach to overcoming the problem of capacity degradation in multihop wireless networks. However, existing routing schemes that are designed for single channel multihop wireless networks may lead to inefficient routing paths in multi channel WMNs.

Keywords : wireless mesh networks, network coding. opportunistic routing, Wireless multi-hop networks, multi-radio, routing. performance

1. INTRODUCTION

One of the main challenges in building wireless mesh networks ([2], [3j, [4j) is to guarantee high performance. The difficulty is mainly caused by the unpredictable and highly-variable nature of the wireless channel. However, the use of wireless channels presents some unique opportunities that can be used to improve the performance. For example, the broadcast nature of the medium can be used to provide opportunistic transmissions as suggested in [51. Also, in wireless mesh networks, there are typically multiple paths connecting each source destination pair; using some of these paths in parallel can improve performance [61, [7]. The optimal use of multiple paths and of opportunistic transmissions is the main focus of this work. We use network coding [81 to simplify the problem of scheduling packet transmissions across multiple paths, similarly to [6],[7], [9]. We propose a network optimization framework that optimizes the rate of packet transmissions between source and destination pairs wireless mesh networks (WMNs) are considered a promising solution to last mile broad band access thanks to their desirable features, such as low upfront cost, easy network maintenance, robustness, and reliable service coverage [1]. Tn WMNs each node plays the roles of both a host and a router, and packets are forwarded in a multi hop fashion to and from the gateway to the Internet The major challenge in WMNs is to conquer the degradation of capacity due to the interference problem. Recent research results [2, 3] show that employing multiple channels is an effective approach to increasing network capacity. This improvement comes from concurrent transmissions on non overlapping channels, which are available in IEEE 802 11

WLAN standards. The emerging IEEE 802.1 Is standard for WMNs thither introduces the concept of a Common Channel Framework (CCF) [4], which defines the operation of single radio devices in a multichannel environment. While employing multiple channels improves the network capacity, the multichannel environment introduces new research challenges including routing, scheduling, and allocating wireless channels In this article we focus on the routing problem in multichannel WMNs. This problem is to detennine which nodes to include on the routing path and which channel to use on each link of the path. II. MODEL In this section we introduce the notation used in the paper. We extend the model of wireless erasure network developed in [14] to include multiple flows. Vectors are denoted in bold. A. PRY and MAC Characteristics We consider a network comprising of a set of nodes N, N N Whenever a node transmits a packet, several nodes may receive it. We model packet transmission from node ito a 2set of nodes J N with a hyper arc (i, J). We define an activat on— profile S = Sl} to be a set of hyper arcs active at the same

time. There may be several constraints on feasible activation profiles. For example, a node may be limited to receive from but one node, or transmit to only one node at a time. The only condition we shall impose is that a node can be the source of only one hyper arc in one activation profile. We denote by S the set of feasible activation profiles and let SRC(S) = **{i** 2 N 9J N, (i, J) 2 S be the set of transmitters in activation profile

S. Each transmission has two associated parameters, power P 2

P and rate R 2 R, where P is the set of allowed transmission powers (e.g. P 2 [0, PMj, where PM is given by regulations) and R is sets of available PHY transmission rates, defined by supported spreading, coding, and modulations. Consider an activation profile S in which node i transmits to set of nodes J and suppose node i is transmitting with power Pi and rate Ri We can associate power vector P = (Pi) i2Nrate vector R

(Ri)i2N to these transmissions. Let Tij I if a packet is successftully transmitted from i to j 2 J. We define pij(P,Ri, 5) of the nodes in K

N. We have CiK (P,Ri, 5) — Ri —

or more 802.11 radios. These can be a mix of 802.lla, b or g

LTHE MR-LQSR PROTOCOL

MR-LQSR is a combination of the LQSR protocol [16j with a new metric that we call WCETT (Weighted Cumulative Expected Transmission Time). LQSR is a source-routed link-state protocol derived from DSR [26]. A link-state protocol consists of four components:

1 A component that discovers the neighbors of a node
2 A component that assigns weights to the links a node has with its neighbors
3 A component to propagate this information to other nodes in the network
4 A component that uses the link weights to find a good path tor a given destination. In other words, the link weights are combined to form a path metric. The first and the third components of MR-LQSR are similar to the corresponding components in DSR. We will not discuss them further except to briefly point out some implementation- related issues later in the paper. The second and the fourth components of MR LQSR are very different from DSR. DSR assigns equal weight to all links in the network. The path metric is simply the sum of link weights along the path. Thus, DSR implements shortest path routing. Instead of shortest-path, MR-LQSR uses the WCETT metric. Before we go into the details of how WCETT assigns link weights and combines them into a path metric, it is useful to discuss certain assumptions that we made while designing MR-LQSR, as well as the overall design goals

II. AssuMPTIoNs AND GOALS

We begin by listing the assumptions we made about the Networks in which MR-LQSR is supposed to operate. These assumptions are not necessary for the correct operation of MR-LQSR. We will discuss them later in the paper. All nodes in the network are stationary. Each node is equipped with one for **1** 6 1 or j 6 k, which is justified by measurements (cf. [151) By convention, we assume pij (P, Ri, 5) — 0 ifj 62 J, for **(1** J) 2 S. We can now calculate CiK (P, Ri, 5) the average number of packets per unit time conveyed from node i to any will successfully receive the packet from i, given the above conditions. We also assume that Tij and TIk are independent radios. The number of radios on each node need not be the same. We assume that if a node has multiple radios, they are tuned to different, non-interfering channels. The channel assignment is determined by some outside agency [44, 12] and changes relatively infrequently. We have three main design goals for MR-LQSR. First, the MR-LQSR protocol should take both the loss rate and the bandwidth of a link into account while considering it for inclusion in a path. Since the 802.11 MAC incorporates an ARQ (retransmit) mechanism the transmission time of a packet on a wireless link depends on both the bandwidth of the link and the PHY-layer loss rate Second, the path metric, which combines the weight of individual links, should be increasing. That is, if we add a hop to an existing path, the cost of the path must never decrease and our preference is that it should increase. This is due to three reasons. First, by traversing an extra hop, the flow is consuming more resources. By ensuring that paths with fewer hops are favored over paths with more hops, we are attempting to minimize the impact this flow has on other flows in the networks. Second, by adding a hop, we are increasing the total delay along the path. For a TCP connection, this would mean increased round trip time, and hence reduced throughput. Third, the non-decreasing property lets us use Dijkstra's algorithm to find paths. Third, The path metric should explicitly account for the reduction in throughput due to interference among links that operate on the same channel Similarly, it should also account for the fact that links along a path that do not operate on the same channel do not interfere with one another. Hence, a path that is made up of hops on different channels is better than a path where all the hops are on the same channel. However, this does not mean that we should add links to a path merely to get channel diversity

III.IMPLEMENTATION

Virtual network adapter, so that to the rest of the system the ad-hoc network appears as an additional (virtual) network link Under the covers, MCL routes packets using the LQSR protocol. We have implemented a variety of link-quality metrics for LQSR, including WCETT and ETX, and basic shortest-path routing. In this section, we briefly review our architecture and implementation to provide background for understanding the performance results. More architectural and implementation details are available in [16].The MCL driver implements an interposition layer between layer 2 (the link layer) and layer 3 (the network layer). To higher-layer software, MCL appears to be just another ether net link, albeit a virtual link. To lower-layer software, MCL appears to be just another protocol running over the physical link. See Figure 2 for a diagram. This design has several significant advantages. First, higher- layer software runs unmodified over the ad-hoc network. In our testbed, we run both IPv4 and IPv6 over the adhoc network. No modifications to either network stack were required. Network layer ftmnctionality, for example ARP, DHCP, and Neighbor Discovery, just works. Second, the ad- hoc routing runs over heterogeneous link layers. Our current implementation supports Ethernet-like physical link layers (eg 802.11 and 802.3) but the architecture accommodates link layers with arbitrary addressing and framing conventions. The virtual MCL network adapter can multiplex several physical network adapters, so the ad-hoc network can extend across heterogeneous physical links. Third, while we have currently implemented only the LQSR protocol in the MCL framework, the design, in principle, can support any ad-hoc routing protocol, such as DSR [261 or AODV [331. Since the virtual MCL network adapter appears to higher layer software as an ether net link, the MCL adapter has its own 48-bit virtual ether net address, distinct from the layer-2 addresses of the underlying physical adapters. This address is first assigned using a random number generator and then stored persistently in the Windows registry. The MCL network ftinctions just like an ethernet, except that it has a smaller MTU. To allow room for the LQSR headers, it exposes a 1280-byte MTU instead of the normal 1 500-byte ethernet MTU. The impact of the smaller MTU and other per-packet overheads incurred by MCL is discussed in detail in [1 7j. The MCL adapter routes packets using LQSR. The LQSR implementation in MCL is derived from DSR. It includes all the basic DSR ftinctionality, including Route Discovery (Route Request and Route Reply messages) and Route Maintenance (Route Error messages). LQSR uses a link cache instead of a route cache, so ftindamentally it is a link state routing protocol. The primary changes in LQSR versus DSR relate to its implementation at layer 2.5 instead of layer 3 and its support for link-quality metrics, including WCETT and ETX. LQSR uses the 48-bit virtual ethernet address of the MCL network adapter for routing. All LQSR headers, including Source Route, Route Request, Route Reply, and Route Error, use 48-bit virtual addresses instead of 32-bit IP addresses. Using the approach of [9] the 48-bit addresses are augmented with 8-bit interface indices to support multiple physical network interfaces per node Each node locally assigns interface indices to its physical network adapters. Two nodes may be connected by multiple links, for example if the nodes have multiple radios. To umquely specify a link, LQSR uses the source virtual address, the outgoing interface index, the incoming interface index, and the destination virtual address. We have modified DSR in several ways to support routing according to link-quality metrics. These include modifications, to Route Discovery and Route Maintenance plus new mechanisms for Metric Maintenance. In brief, the DSR messages include a 32-bit lmk quality metric value for each hop in Source Routes, Route Requests, Route Replies, *etc.* We do not include a longer description due to space limitations. Our design does not assume that the link-quality metric is symmetric. To implement WCETT, we had to convey a channel number as well as the loss-rate and bandwidth or the ETT of each link We considered several different ways of implementing this including encoding a channel number in the locally-assigned interface indices. Finally, we decided to use lower 8 bits of the metric value to encode an abstract channel number.

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