Ad Hoc Networks 9 (2011) 95–107

Contents lists available at ScienceDirect

Ad Hoc Networks

journal homepage: www.elsevier.com/locate/adhoc

Lattice routing: A 4D routing scheme for multiradio multichannel ad hoc networks

Sandeep Kakumanu [a,*], Stephan Eidenbenz [b], Raghupathy Sivakumar [a]

[a] Georgia Institute of Technology, 5174 Centergy One, Atlanta, GA 30308, United States
[b] Information Sciences (CCS-3), Los Alamos National Laboratory, Los Alamos, NM-87545, United States

ARTICLE INFO

Article history:
Received 23 March 2009
Received in revised form 17 March 2010
Accepted 22 June 2010
Available online 1 July 2010

Keywords:
Ad hoc network
Multiradio multichannel wireless network
Routing protocol

ABSTRACT

An efficient channel assignment strategy ensures capacity maximization in a multiradio, multichannel ad hoc network. Existing mechanisms either use a static channel assignment or a centralized process intensive system that assigns channels to individual nodes. These are not effective in a dynamic environment with multiple flows that are active at different time instants. The protocol proposed in this work (Lattice routing) manages channels of the radios for the different nodes in the network using information about current channel conditions and adapts itself to varying traffic patterns in order to efficiently use the multiple channels. Further the protocol uses multipathing, a key mechanism that is found to alleviate bottlenecks present in single path routes in such an environment. Results indicate that Lattice routing consistently outperforms it closest competitor ((MCR) Kyasanur and Vaidya (2006) [1]) across a large number of experiments.

1. Introduction

Multichannel wireless data networks have garnered increasing attention over the last few years because of the great promise they hold in terms of the achievable spectral efficiencies. This work focuses on a sub-topic of the above general area: ad hoc networks with individual nodes equipped with multiple radios or interfaces that can switch between the available multiple orthogonal channels. In such networks a good channel assignment strategy is required to utilize the capacity of all channels efficiently. The problem has been answered at various levels by related works [2–4]. However, the protocols proposed in some of these works are based on direct extensions of a single radio, single channel ad hoc network architecture [3,4] where a flow between a single source and destination node uses a single path to route all the traffic while others [2,5,6] are based on complex centralized linear programming algorithms that are not practical to implement. This work introduces a new protocol known as Lattice routing that is shown to effectively combat capacity related issues in such multiradio, multichannel environments. It is a completely distributed protocol and uses local information from neighboring nodes to adapt the paths.

A bottleneck, identified in this work as the *interface insufficiency bottleneck*, arises in such networks. The bottleneck, as the name suggests, is the result of insufficient number of interfaces at the intermediate nodes in a single path for a flow between a source and destination node. This bottleneck reduces the throughput capacity of the network. One way to alleviate this bottleneck is to use multiple paths (or routes) for each flow. Multipath routing is not new in ad hoc network literature [7–10]. However these works focus on multipath routing for reasons of reliability, QoS requirements, or load balancing. The current work, on the other hand, focuses on improving aggregate end-to-end throughput in multiradio multichannel networks. We call the routing in such networks as 4D routing because multipathing is a two-dimensional problem in space, and the multiple radios and channels provide two additional dimensions for routing.

* Corresponding author. Tel.: +1 404 229 8294.
E-mail address: ksandeep@ece.gatech.edu (S. Kakumanu).

1570-8705/$ - see front matter © 2010 Elsevier B.V. All rights reserved.
doi:10.1016/j.adhoc.2010.06.007

In single channel environments paths are assigned at the start of every flow and this is sufficient because the underlying MAC layer takes care of scheduling the transmissions belonging to the different flows in the network. Given the requirement to form multiple paths for every flow, a fundamental question arises, "*is it sufficient to assign multiple paths at the start of the flow?*" The answer to this question turns out to be *no*. This is because routing and scheduling of packets cannot be decoupled in multiradio multichannel environments. The formation of paths must be an informed decision based on existing traffic conditions at various stages of the flow.

Based on the above observations a new protocol called Lattice routing is proposed in this work that uses multiple paths for every flow (when possible) and is also dynamic in adjusting the various paths based on changing traffic conditions. The protocol works as a cross layer solution for rate control, and routing. It uses a back-pressure based algorithm [11] for rate control. The architecture can be realized as a completely distributed protocol, with the individual nodes taking purely local decisions about forwarding data. Each node uses the following principle to route traffic to a destination node: "*serve as much as possible*". Nodes can forward traffic through any or all of the possible paths to a destination to serve the traffic they receive from a previous node.

Extensive ns-2 based simulations show the benefits of the proposed architecture as opposed to related work on multiradio, multichannel ad hoc networks. Results indicate that Lattice routing can adapt to a wide variety of network conditions such as density of nodes and number of flows. Since Lattice routing is proposed as a cross layer solution between routing and rate control, it can be used with existing off-the-shelf components such as 802.11 a/b/g cards using pure software modifications. Further the architecture has an added benefit of security against eavesdropping attacks because of its inherent multipath characteristics.

2. Motivation

In this section, the proposed Lattice routing architecture will be motivated using three important requirements in multiradio multichannel ad hoc networks. These requirements are used to design the protocol that realizes the proposed architecture.

2.1. 4D routing

In a multihop flow from a source node to a destination node, the source and destination nodes have only one function of either transmitting packets or receiving packets, while the forwarding nodes in between have two functions of both transmission and reception. If the forwarding node has a single radio, it cannot transmit and receive data at the same time because of the half-duplex nature of the radios.

If each node in the flow has two radios, then in a single path (assuming only the top path in Fig. 2) the intermediate nodes can utilize one radio each for transmission and reception. But the source and destination node will have an additional radio that cannot be utilized. Thus the intermediate nodes experience an "*interface insufficiency bottleneck*". If W is the capacity of a channel, then assuming each link on a different channel, it can be shown that such a single path can achieve a flow throughput of W. The additional radios at the source and destination can be utilized if an additional path can be formed as shown in the figure. In this case the flow using two paths can result in a throughput of $2W$. Thus, for every radio that a source and a destination node provide for a path, every intermediate node should be able to provide two radios for each path to fully utilize the capacity. We refer to a path as a set of nodes from source to destination, irrespective of the number of radios each node provides for the path. So, if all the nodes in the network have the same number of radios (say r), then a single path between source and destination will have a capacity of rW. However, this will leave $r/2$ radios free at both source and destination node. A second path will achieve the maximum capacity of $2rW$ for the path. We call such a multipath routing in multiradio multichannel networks as 4D routing because multipathing is a two-dimensional problem in space, and the multiple radios and channels provide two additional dimensions for routing.

The above discussion was for a single source destination pair. An ad hoc network will likely have a number of such source destination pairs. From the above discussion, it is clear that every source destination needs only two paths to achieve maximum capacity. This requires every intermediate node in every path to provide all its radios exclusively for one path between some source destination pair. However, in the presence of multiple source destination pairs, paths can intersect each other. When paths intersect each other, the nodes at the intersections will not be able to provide all their radios exclusively to a single path as required. In such a scenario, additional paths can be added for the source destination pairs to add capacity. Thus, multiple paths may be required for every source destination pair to get maximum capacity out of the network.

On similar lines, one might argue that multipathing should benefit single radio, single channel environments as well. There are several related works [7–10] that deal with multipathing in single channel ad hoc networks. However, in single channel environments, hops belonging to the flow using multiple paths that are close to the source node (or the destination node) contend with each other and only one such hop can operate at any given time. If the nodes in Fig. 2 are operating on a single channel, then hops 1, 2, 4 and 5 contend with each other and only one of them can operate at a time. This reduces the benefit of multipathing in single channel environments. In fact multpathing does not help in the presence of multiple flows either. Fig. 1a shows ns-2 based results of aggregate throughput in a single channel ad hoc network using both single path and multipath routing. The results are for a network of size 1000 m $\times$ 1000 m with 150 nodes in the network and the channel datarate of 2 Mbps. The results show little improvement in aggregate throughput by using multiple paths. All the related works focus on multipathing for reasons other than increasing aggregate throughput.

To study the impact of multiple flows, ns-2 simulations are used. Fig. 1b and c show the performance benefits of 4D