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On-demand routing and channel assignment in multi-channel mobile ad hoc networks ☆

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Abstract

The capacity of mobile ad hoc networks is constrained by the *intra-flow* interference introduced by adjacent nodes on the same path, and *inter-flow* interference generated by nodes from neighboring paths. By assigning orthogonal channels to neighboring nodes, one can minimize both types of interferences and allow concurrent transmissions within the neighborhood, thus improving the throughput and delay performance of the ad hoc network. In this paper, we present three novel distributed channel assignment protocols for multi-channel mobile ad hoc networks. The proposed protocols combine channel assignment with distributed on-demand routing, and only assign channels to active nodes. They are shown to require fewer channels and exhibit lower communication, computation, and storage complexity, compared with existing approaches. Through simulation studies, we show that the proposed protocols can effectively increase throughput and reduce delay, as compared to several existing schemes, thus providing an effective solution to the low capacity problem in multi-hop wireless networks.
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1. Introduction

Despite recent advances in wireless technologies, today's wireless links still cannot offer the comparable data rates as their wired counterparts. The low throughput problem is further aggravated in multi-hop wireless environments due to the *intra-flow interference* introduced by adjacent transmitting nodes on the same path and *inter-flow interference* generated by transmitting nodes from neighboring paths. Two transmitting nodes within the interference range will interfere with each other. In addition, cumulative interference from a large number of transmitters outside a node's interference range will also cause low signal-to-interference-plus-noise-ratio (SINR) at the node. For instance, it has

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been shown in [2] that the maximum capacity that the IEEE 802.11 MAC can achieve for a chain network could be as low as just one seventh of the nominal link bandwidth.

We observe that all current IEEE 802.11 physical (PHY) standards divide the available frequency into several orthogonal channels, which can be used simultaneously within a neighborhood. Therefore, increasing capacity by exploiting multiple channels becomes particularly appealing. In fact, such bandwidth aggregation has been widely used in infrastructure-based WLANs, where high-end access points are equipped with multiple interfaces that operate on different channels simultaneously [3]. In such networks, non-overlapping channels are distributed among different access points at the network planning stage [4]. However, IEEE 802.11 WLANs that operate in ad hoc mode rarely use multiple channels simultaneously. This is partly because that the IEEE 802.11 MAC is not designed to operate with multiple channels, resulting in a waste of precious network resources. As an example, an ad hoc network based on the IEEE 802.11a technology utilizes only one out of 12 available orthogonal channels, wasting more than 90% of the potentially available spectrum.

Consequently, there has been substantial interest in multi-channel MAC schemes that can achieve higher throughput by exploiting multiple available channels [3,5,6]. Some of the early works, e.g. [7,8], assume that every node has its own unique channel. Therefore, no channel assignment or selection is needed. However, in reality, the number of channels is limited and has to be carefully assigned to each node, in order to avoid contention and collisions and to enable optimal spatial reuse of available channels. Many channel assignment problems have been proven to be *NP*-complete and, thus, computationally intractable [4,9,10]. There exist only a few heuristic solutions, which have good performance under certain environments, for instance, in a static wireless network. However, these heuristic schemes suffer from inefficiency when employed in the mobile ad hoc environment [9,11].

In this paper, we present three principles for designing efficient distributed channel assignment schemes. *First*, to reduce the complexity of the channel assignment algorithm, channel assignment and routing should be jointly designed. This "cross-layer" design approach is motivated by the fact that both the channel assignment algorithm and the ad hoc routing algorithm are invoked when there is a change in the network topology. Exploring this design principle can potentially reduce the complexity of channel assignment algorithms. *Second*, channels should be assigned only to active nodes. This "on-demand" channel assignment principle is motivated by the fact that only nodes on active routes need valid channels. Some existing channel assignment schemes assign channels to *all* nodes in the network, regardless of whether they are active or not, thus requiring a large number of orthogonal channels. If this on-demand assignment principle is implemented, fewer channels (i.e. fewer resources) may be required in the network to achieve a comparable performance.

Third, the capacity of mobile ad hoc networks can be adversely affected by both "hidden terminals" and "exposed terminals." The *hidden terminal* problem occurs when transmitters outside of radio range of each other transmit at the same time, causing a collision at the receivers [10]. The *exposed terminal* problem occurs when a node is prevented from sending packets to other nodes due to a neighboring transmitter, even though this transmission will not cause interference. In addition, cumulative interference generated by nodes two or more hops away may also adversely affect channel utilization and network capacity. Thus, to improve network performance, distinct channels should be assigned such that hidden terminals, exposed terminals, and cumulative interference can be avoided as much as possible.

We present a new channel assignment protocol, named Channel Assignment Ad hoc On-demand Distance Vector routing (CA-AODV), that implements these design principles. In CA-AODV, channel assignment is combined with the AODV routing protocol and is performed in a cross-layer and on-demand fashion. Specifically, channel assignment is performed during the route discovery phase and channel information is piggybacked in the routing control messages. CA-AODV assigns different channels for neighboring nodes within a k-hop region along the same path, thus allowing concurrent transmission on neighboring links along the path and effectively reducing the intra-flow interference. We also present two extensions to the CA-AODV protocol, namely, the Enhanced 2-hop CA-AODV (E2-CA-AODV) protocol and the Enhanced k-hop CA-AODV (Ek-CA-AODV) protocol. In addition to intra-flow interference, these two extensions also aim to minimize inter-flow interference by assigning orthogonal channels to active nodes within a k-hop neighborhood, where $k \geqslant 2$. With such channel

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