An efficient multi-channel MAC protocol for wireless ad hoc networks

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A B S T R A C T

IEEE 802.11 MAC is designed for single channel and based on Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA). The throughput of network is limited by the bandwidth of the single channel and the CSMA-based MAC protocol with omnidirectional antennas can cause the serious unfairness or flow starvation. By exploiting the multiple channels and using the directional antennas, nodes located in each other's vicinity may communicate simultaneously. This helps to increase the spatial reuse of the wireless channel and thus increase the network performance. In this paper, we propose a Multi-channel MAC protocol with Directional Antennas (MMAC-DA) that adopts IEEE 802.11 Power Saving Mechanism (PSM) and exploits multiple channel resources and directional antennas. Nodes have to exchange control packets during the Announcement Traffic Indication Message (ATIM) window to select data channels and determine the beam directions which are used to exchange data packets during the data window. The simulation results show that MMAC-DA can improve the network performance in terms of aggregate throughput, packet delivery ratio, energy efficiency and fairness index.

1. Introduction

In a dense network, nodes may suffer from intensive contention from their neighbor nodes. As a result, some flows may be starved and refrained from their transmissions for a long time. There are three well-known sources of starvation [1,2] such as hidden node starvation, asymmetric sense starvation and carrier sense starvation. IEEE 802.11 [3] provides multiple channels at Physical layer (three non-overlapping channels in IEEE 802.11b and g, and twelve non-overlapping channels in IEEE 802.11a) but the

MAC layer is designed for single channel. By exploiting multiple channel resources, applying appropriate power control mechanisms or using directional antennas, more concurrent transmissions are supported and the starvation can be mitigated.

The multi-channel MAC protocols can be classified into 4 categories: Dedicated Control Channel [4], Split Phase [5–7], Common Hopping and Parallel Rendezvous. Each node has two transceivers in Dynamic Channel Assignment (DCA) [4]. One transceiver is tuned to control channel for exchanging control packets while another can switch to any data channel for data transmissions. This scheme does not require synchronization, however, it may suffer the bottle-neck on the control channel. Both Multi-channel MAC (MMAC) [5] and Hybrid Multi-channel MAC (H-MMAC) [6,7] protocols adopt IEEE 802.11 PSM in which

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the ATIM window is used for exchanging control packets for channel negotiation. They require time synchronization. MMAC does not allow nodes to exchange data packets during the ATIM window while H-MMAC allows nodes to use the ATIM window for data transmissions to utilize the channel resources more efficiently.

In Power Control MAC (PCM) [8], nodes increase the transmission power periodically during the data transmission in order to warn nodes in the carrier sensing range. PCM helps mobile nodes to save energy, it does not improve the spatial reuse of wireless channel through the power control algorithm. The SINR-based transmission power control (STPC-MAC) [9] guarantees the SINR at the receiver. Nodes exchange the transmission power information during the ATIM window. Based on overheard transmission power information, neighbor nodes estimate the transmission power which they can use to transmit simultaneously. STPC-MAC does not only improve the spatial reuse of wireless channel, but also save the energy of wireless nodes. The power control algorithm can be combined with multi-channel MAC protocols to mitigate the starvation in wireless ad hoc network in [2,10].

In addition to two above approaches, using directional antennas can improve the spatial reuse. Dai et al. [11] present an overview of using directional antennas in wireless network. The Directional Virtual Carrier Sensing (DVCS) [12] employs a steerable antenna system which can point to any specified direction. Each node maintains a list of neighbor nodes and their directions based on Angle of Arrival (AoA) of the overheard signals. The Directional Network Allocation Vector (DNAV) is used instead of the traditional Network Allocation Vector (NAV) for channel reservation to increase the network capacity 3 to 4 times. Circular Directional RTS (CDR-MAC) [13] uses the circular directional RTS in which the RTS is transmitted directional consecutively in circular way. This helps the intended receiver to identify the location of the sender. The receiver replies with the directional CTS at the direction of the sender. CDR-MAC cannot avoid the deafness problem as the receiver only transmits the directional CTS and it suffers from the overhead of the circular directional RTS when the number of beams increases. All RTS/CTS packets are transmitted in directional mode in Multi-hop Directional RTS MAC (MMAC) [14]. The sender uses the multi-hop RTSs to establish link to the intended receiver, then they transmit CTS, DATA and ACK in directional mode over single hop. An additional busy tone is used in Dual Sensing Directional MAC (DSDMAC) [15] with two patterns: continuous and ON/OFF patterns. MMAC-DA [16] employs the directional antenna to multi-channel MAC MMAC protocol [5] to exploit multiple channels as well as improve spatial reuse of wireless channel. However, it does not utilize channel resources during the ATIM window.

In this paper, we propose a multi-channel MAC protocol with directional antennas (MMAC-DA). Similar to MMAC [5] and H-MMAC [7], MMAC-DA uses the ATIM window to exchange control packets to select data channels. Moreover, nodes use data structures to maintain the status of the neighbor nodes and the channel availability. Compared to the previous MMAC-DA [16], the current proposal allows nodes to exchange data packets during the
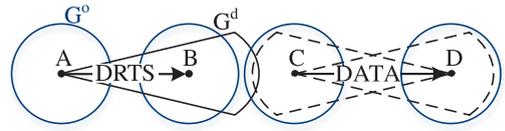

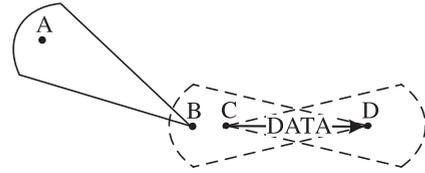**Fig. 1.** Hidden terminal due to the asymmetric antenna gains.

Fig. 2. Hidden terminal due to the unheard RTS/CTS.

ATIM window in order to utilize the channel resource more efficiently.

The rest of this paper is organized as follows. In Section 2, we discuss some MAC issues related to multi-channel environment and directional antennas. We describe briefly the operation of IEEE 802.11 PSM in Section 3. The antenna model is presented in Section 4. Section 5 explains the proposed MMAC-DA protocol in details. The performance evaluation is given in Section 7. Finally, we conclude our paper in Section 8.

2. MAC issues with multi-channel and directional antennas

2.1. Neighbor discovery

Neighbor discovery is one of critical issues in wireless network with directional antennas. A node needs to determine the intended receiver in order to beamform to it. It is very difficult when two nodes do not beamform to each other in directional mode. A node can obtain the location information of other neighbor nodes through the overheard RTS/CTS. Based on the overheard control packets RTS and CTS, a node knows the Angle of Arrival (AoA) as well as the power of the received signals, it can estimate the direction and the distance to its neighbors.

2.2. Hidden terminal problem

A hidden node is not aware of another on-going transmission and its transmitted packets may cause the collision with the on-going transmission. The hidden terminal problem can be caused by the asymmetric antenna gains (Fig. 1) or the unheard RTS/CTS (Figs. 2 and 3). The hidden terminal problem in multi-channel environment is also known as multi-channel hidden terminal problem (Fig. 3). In Fig. 1, since node A is listening in omnidirectional mode with gain G^o, it may not overhear the directional CTS (DCTS) from node D. While node C is transmitting data packets to node D in directional mode with gain G^d, node A has data packets to node B. Node A senses channel in direction toward node B, and channel is idle because node D is in the receiving state. Node A starts transmitting the