Chapter XIX
Mobile Ad Hoc Networks Exploiting Multi-Beam Antennas

Yimin Zhang
Villanova University, USA

Xin Li
Villanova University, USA

Moeness G. Amin
Villanova University, USA

ABSTRACT

This chapter introduces the concept of multi-beam antenna (MBA) in mobile ad hoc networks and the recent advances in the research relevant to this topic. MBAs have been proposed to achieve concurrent communications with multiple neighboring nodes while they inherit the advantages of directional antennas, such as the high directivity and antenna gain. MBAs can be implemented in the forms of multiple fixed-beam directional antennas (MFBAs) and multi-channel smart antennas (MCSAs). The former either uses multiple predefined beams or selects multiple directional antennas and thus is relatively simple; the latter uses smart antenna techniques to dynamically form multiple adaptive beams and thereby provides more robust communication links to the neighboring nodes. The emphases of this chapter lie in the offerings and implementation techniques of MBAs, random-access scheduling for the contention resolution, effect of multipath propagation, and node throughput evaluation.

I. INTRODUCTION

Traditional wireless networks require single-hop wireless connectivity to the wired network. Recently, mobile ad hoc networks have yielded considerable advances to support communications among a group of mobile hosts where no wired backbone infrastructure is available (Lal, 2004; Choudhury, 2006; Ramanathan, 2005). User nodes in ad hoc networks traditionally employ omnidirectional antennas, where a transmission on a given channel requires all other nodes in range keep silent or use alternative channels with a different time slot, frequency, or spreading code. As such, the use of omnidirectional antennas does not provide effective channel use and, subsequently, wastes a large portion of the network capacity (Huang, 2002a; Bandyopadhyay, 2006). Incorporation of directional antennas has been proposed to achieve improved network capacity and quality of service. Compared to omnidirectional antennas, directional antennas have higher directivity and antenna gain. Therefore, directional antennas not only significantly reduce the power necessary for the service coverage and packet transmission, but also mitigate the interference in the directions away from that of the desired users. As a result, the use of directional antennas provides a platform to serve increased number of nodes and network throughput. The antenna gain due to directional transmission and reception enables extended communication range of each hop, thereby reducing the number of hops between distant source and sink nodes, and increasing the efficiency and reliability of the network (Ko, 2000; Nasipuri, 2000; Wang, 2002; Zhang, 2005).

A directional antenna with a single beam, however, does not fully utilize the offering of multi-sensor systems. In addition, the deployment of directional antennas may result in new problems. For example, the deafness problem appears when a node is tuned to a specific direction and thus cannot hear a node in another direction, even they are closely located. The deafness problem not only impedes dynamic resource allocation, but also increases the possibility of network outage for certain services (Choudhury, 2004; Jain, 2006a). To mitigate the deafness problem and enhance the network capacity, multi-beam antennas (MBAs) have been proposed to achieve concurrent communications with multiple neighboring nodes while inheriting the advantages of directional antennas, such as the high directivity and antenna gain. MBAs can be implemented in the forms of multiple fixed-beam directional antennas (MFBAs) and multi-channel smart antennas (MCSAs). To form multiple fixed-beams, MFBAs and multiple radios (MRs) with a directional antenna equipped in each radio can be exploited (Bahl, 2004; Draves, 2004). As a result, high network throughput can be achieved. In a stationary environment, the antenna patterns can be optimized to further improve network performance. However, the performance of MFBAs and MRs degrades in a time-varying multipath propagation environment, which is typically experienced in indoor and low-altitude outdoor wireless networks (Winters, 2006).

Another approach to implement MBAs is to use MCSAs (Singh, 2005; Zhang, 2006; Li, 2007). By using smart antenna techniques, multiple beams can be adaptively and dynamically formed by a node so as to provide robust communication links with multiple users. At the expense of higher complexity, an MCSA-based approach takes the same advantages as the MFBA implementation, but its performance does not degrade in time-varying multipath environment (Zhang, 2006; Li, 2007).

The purpose of this chapter is to discuss the recent advances of MBA approaches for wireless ad hoc network applications. To bridge the gap between omnidirectional antennas and MBAs, the concept and offerings of ad hoc networks with directional antennas are first reviewed and a brief introduction of the medium access control (MAC) protocols and routing approaches developed for directional antennas is provided. Beamforming techniques and random-access scheduling (RAS) schemes in the contention resolution are then introduced. The respective node throughput performance and probability of concurrent communications are examined using a simplified ideal sector-based model as well as a precise output signal-to-interference-plus-noise ratio (SINR) based model.

This chapter is organized as follows. Section II reviews the concept of directional antennas as well as the associated MAC protocols and routing schemes for ad hoc networks. Section III discusses multi-channel beamforming techniques in detail, including adaptive multi-channel beamforming, fixed-beam antennas, and the analysis of output SINR performance. Section IV provides RAS schemes respectively based on the prioritized packet delivery and throughput maximization criteria, where two different models, respectively based on idealized sectors and the output SINR, are considered. The analysis and numerical evaluation of node throughput performance of the two RAS schemes in single-path and multipath environments are presented in Sections V and VI, respectively. Relevant issues to the MBAs are addressed in Section VII to broaden understanding of this topic. Finally, the conclusion of this chapter and some important remarks are provided in Section VIII.

II. AD HOC NETWORKS WITH DIRECTIONAL ANTENNAS

Concept and Offerings

A directional antenna is typically implemented using the switch beam scheme, where a set of predefined beams are formed and the one that best receives the signal from a particular desired user is selected. It is relatively simple in terms of hardware implementation and processing complexity. As such, it has become a conveniently accessible and adoptable technology for use in wireless LANs and ad hoc networks (Bandyopadhyay, 2006).

In an ad hoc network, co-channel interference is one of the key factors that limit the overall network capacity and quality. Refer to Fig. 1(a). When nodes S and D communicate using omnidirectional antennas, all other nodes depicted in this figure are within the respective ranges of S and D and, therefore, should remain silent to avoid co-channel inter-

Related Content