Chapter XIX
Mobile Ad Hoc Networks Exploiting Multi-Beam Antennas

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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 multichannel 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 interference. When the network is multihop, another key limiting factor is the forwarding burden of the intermediate nodes which increases with the number of hops.

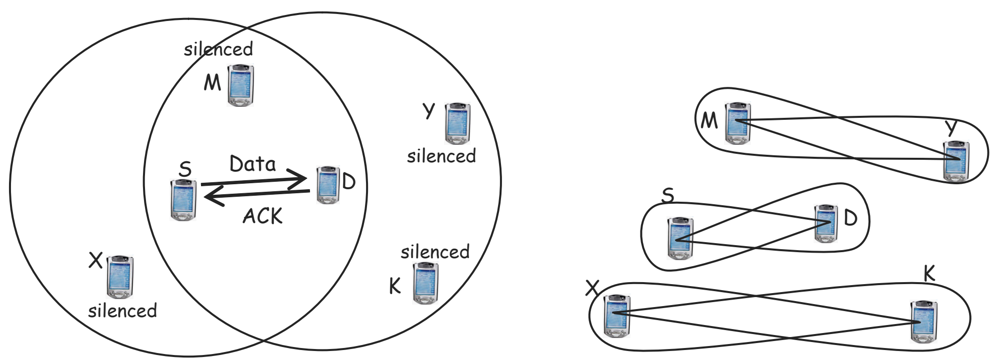
Directional antennas can enhance the network capacity by reducing the above two limiting factors. As shown in Fig. 1(b), when directional antennas are used, multiple parallel links can be constructed without interfering to each other. Yi (2003) has shown that, due to the reduction of the interference area, the capacity gain can be increased with an improvement factor inversely proportional to the beamwidth of the transmit and receive antennas. Furthermore, due to the beamforming gain, the use of directional antennas yields a longer communication range and a higher receive signal level, leading to improved power efficiency, increased signal quality, and reduced number of hops. For example, nodes X and K may not have direct link when they are separated beyond the communication range corresponding to omnidirectional antennas, whereas they can be directly linked when the antennas are directional. Thus, the use of directional antennas provides improved routing performance as well as enhanced capacity (Choudhury, 2003; Ramanathan, 2005; Das, 2006).

MAC Protocols Using Directional Antennas

The node capability enhancement using directional antennas can be effectively leveraged only through appropriate changes to higher layer network protocols. Below, we summarize MAC protocol schemes that take directional antennas into account.

So far, a variety of directional antenna-based MAC protocols have been developed (e.g., Dai, 2006; Korakis, 2003; Jurdak, 2004). These MAC protocols can be classified into two major categories: random access and scheduling access. Random access based protocols can be further classified into different collision avoidance approaches: 1) pure-RTS/CTS protocols; 2) tone-based protocols; and 3) other protocols using additional control packets (Dai, 2006). Refer to Fig. 1(a), RTS/CTS (Request-to-Send/Clear-to-Send) based protocols using an omnidirectional antenna reserve the wireless media over a large area. Thus, effective network capacity is not achieved. Several directional MAC (DMAC) schemes have been proposed to take the advantages of the directivity of antennas. The DMAC proposed in (Nasipuri, 2000) is based on omnidirectional RTS and omnidirectional CTS (oRTS/oCTS). As such, the neighboring nodes sense the communication links to avoid collision in a fashion similar to omnidirectional MAC algorithms. This protocol does not assume the *a prior* knowledge of each node's location information, and the respective direction of the senders can be estimated from the beam position corresponding to the strongest signal power of the oRTS and oCTS packets. The co-channel interference is reduced by directionally transmitting and receiving data packets. When there are ongoing communication links around the sender, however, collision may occur if the sender initiates an oRTS. In this situation, sending directional RTS (DRTS) enables the establishment of transmission links in the unblocked directions (Ko, 2000). Directional transmission can be used in both RTS and CTS between a pair of nodes (Bandyopadhyay, 2001). In this case, neighboring nodes may not be aware of the communication link between the pair, and thus the deafness problem

Figure 1. Ad hoc networks using omnidirectional and directional antennas



(a) Omnidirectional antennas (b) Directional antennas may occur. In the directional virtual carrier sensing (DVCS) protocol (Takai, 2002), each node caches the estimated directions-of-arrival (DOAs) of all its neighboring nodes when it hears any signal from them. The RTS is transmitted directionally if the location information of a neighboring node is available. The directional network allocation vector (DNAV) is used to indicate the directions reserved by neighboring nodes. The multihop MAC (MMAC) proposed by Choudhury *et al* (2006) incorporates the DMAC and DVCS protocols, exploits the extended transmission range provided by directional antennas and, depending on the channel status, establishes directional-omni (DO) or directional-directional (DD) wireless links. In the circular-DMAC protocol (Korakis, 2003), a DRTS is transmitted consecutively at each switch beam and the location information of the neighboring nodes is recorded. Such information can be used to solve the hidden terminal and deafness problems.

The dual busy tone multiple access protocol with directional antennas (DBTMA/DA) (Huang, 2002b) is a tone-based directional MAC protocol that uses transmission and reception busy tones to notify neighboring nodes of the channel use. A node defers to transmit/receive when a busy tone is sensed. The toneDMAC (Choudhury, 2004) uses a time slot to transmit the tone signal. As such, it simplifies the system as transmission is needed only at a single frequency band. For the DOA-MAC protocol (Singh, 2004), each time frame contains three miniframes, respectively for tone transmission, packet transmission, and acknowledgement (ACK) transmission. In the tone transmission period, each transmitter sends a tone to its intended receivers. The receivers, with the help of DOA estimation algorithms, then point their respective beams towards the sender.

Practically, it is often not feasible for a node to receive signals from neighboring nodes when it makes transmission to other nodes. As such, for an MBA, synchronization across the active beams connecting to neighboring users is required, in addition to the use of directional transmission and reception. The explicit synchronization via intelligent feedback (ESIF) protocol (Jain, 2006a/b) is a random access based DMAC protocol for MBAs to achieve node synchronization with the use of embedded feedback information. By using a control packet (SCH), it is desirable to mitigate the deafness problem.

Another category of directional antenna based MAC protocols exploits scheduling. For example, the receiver-oriented multiple access (ROMA) protocol can simultaneously form multiple beams for the transmission or reception through proper scheduling (Bao, 2002). In each time slot, the active nodes are equally divided into transmitters and receivers, and they couple together in pairs to maximize the throughput. Either end of the transmission can use a directional mode. In the directional transmission and reception algorithm (DTRA) (Zhang, 2005), each time frame is divided into three subframes: neighbor discovery and handshaking period, connection confirmation and data reservation period, and data transmission period. The location information among neighboring nodes is exchanged via directional scanning.

Routing

In an ad hoc network, each node has a limited transmission range. Two nodes cannot communicate directly when they are separated beyond their node transmission range. In this case, multihop communication becomes necessary with some intermediate nodes acting as routers (Rajaraman, 2002). In addition, an ad hoc network may experience rapid and unpredictable topology change, as the nodes move with an arbitrarily pattern. Consequently, proper network routing, i.e., the determination of the path of data delivery from one node to another, becomes an important issue in ad hoc networks. Routing protocols have to fulfill two major tasks: route discovery and route maintenance. While routing protocols in ad hoc networks resemble those developed for wired networks, they should consider the special limitations of ad hoc networks, such as limited bandwidth, highly dynamic topology, and limited range of links. Routing protocols available for ad hoc networks are either of reactive, proactive, or fixed nature (Bandyopadhyay, 2006). Traditional network routing protocols like the destination sequenced distance vector (DSDV) are proactive, where they maintain a route to all nodes within the network, including those to which no packets are to be sent. They also react to dynamic topology changes, even if these changes have no effect on the traffic. Reactive routing protocols, like the dynamic source routing (DSR) and the ad hoc on-demand distance vector (AODV), on the other hand, only react when a route is needed between the source and destination nodes. They do not maintain the routes to the nodes that they are not communicating with. Lang (2003) provides a comprehensive overview of the ad hoc network routing protocols when the nodes are equipped with omnidirectional antennas.

When directional antennas are used, directional routing algorithms have been developed to improve the spatial reuse. Most existing directional routing schemes either assume a complete network topology beforehand or use omnidirectional routing schemes to forward packets in a directional environment. For example, the directional routing protocol (DRP) (Gossain, 2006) is an on-demand directional routing protocol for single switch beam antennas. This protocol assumes a cross-layer interaction between the routing and MAC layer, and includes an efficient route discovery mechanism, establishment and maintenance of the directional routing table (DRT) and directional neighbor table (DNT), and novel directional route recovery mechanisms. Simulation results show that the DRP considerably improves the packet delivery ratio and decreases the end-to-end packet latency. When MBAs are employed, it is desirable that the directional routing protocols support concurrent data links at a node. Development of routing protocols for MBAs still remains an open issue.

Security

With lack of infrastructural support, security in ad hoc networks becomes inherently vulnerable to susceptible wireless link attacks. Achieving security within an ad hoc network is a challenging problem due to several reasons (Zhou, 1999). 1) Dynamic topologies and membership, in which the network topology of ad hoc network may be dynamic because the mobility and the membership of nodes can be random and time-varying. 2) Vulnerable wireless link, in which passive/active link attacks like eavesdropping, spoofing, denial of service, masquerading, impersonation are possible. 3) Roaming in dangerous environments, characterized by any malicious node or misbehaving node that might create hostile attacks or deprive all other nodes from providing any service.

Secure communication among nodes requires secure communication links. Before establishing a secure communication link, a node should have the capability of identifying another node by virtue of the identity and the associated credential information, which needs to be authenticated and protected so that the authenticity and integrity cannot be questioned. Thus, it is essential to provide security architecture and a seamless privacy protection to harness the use of ad hoc networks. The deployment of directional antennas and MBAs provides another degree-of-freedom, i.e., spatial dimension, to strengthen the security of ad hoc networks (Hu, 2004; Caballero, 2006; Wu, 2007).

III. MULTI-CHANNEL BEAMFORMING TECHNIQUES

In this section, we introduce multi-channel transmit and receive beamforming techniques. MBA implementations with MFBAs and MCSAs are provided. The performance of MCSAs and MFBAs, in terms of throughput gain and output SINR, is respectively examined.

Multiple Fixed-Beam Antennas and Multi-Channel Smart Antennas

In MFBAs, multiple active beams can be selected from the predefined beams, whereas in MRs, each radio is equipped with its own predefined directional antenna (Bahl, 2004). Both directional structures achieve concurrent communications with multiple users in addition to inheriting the advantage of the switch beam antennas. When the propagation environment is stationary, beam design and allocation can be optimized to provide high network throughput. Beam optimization, however, becomes impractical in a mobile wireless network where the channels are time-varying. More importantly, in a multipath propagation environment, which is typically the case in indoor and low-altitude outdoor wireless networks (Winters, 2006), the paths originated from the same neighboring node are likely to occupy multiple beams, increasing the probability of collisions (see Fig. 2(a)) (Zhang, 2006). Neither MFBA nor MR is effective in accommodating a multipath propagation environment, even with sophisticated MAC and higher-layer controls.

MCSAs, on the other hand, are flexible in beam steering and thus support concurrent communications with multiple nodes with a substantially reduced probability of collision (see Fig. 2(b)). In contrast to MFBAs, MCSAs can be designed to provide multi-fold advantages (Zhang, 2006): (1) They can adaptively form nulls in the directions of interfering signals (co-channel interferers or jammers). (2) When a signal arrives with multiple paths, they achieve spatial diversity without exhausting additional degree-of-freedom. (3) They can tradeoff array gain, spatial multiplexing gain, and interference mitigation gain so as to obtain the optimum transmission performance. (4) They allow coexistence of dedicated channels to specified users as well as shared standby channels for other active and potential users, thus eliminating the deafness problem at no additional cost of overload/resource and dynamically optimizing the resource allocation among different data streams.

Adaptive Multi-Channel Beamforming

A node equipped with an MCSA in the network can form M_a beams to separate up to M_S spatially independent signal streams through electronic steering of an array consisting of *M* omnidirectinal antennas or the use of *M* antennas with different directivities, where $M_s \leq M_a \leq M$. In the following, we consider multi-channel transmit beamforming and multi-channel receive beamforming using M omnidirectional antennas with appropriate array weights.

Multi-Channel Transmit Beamforming

Assume that a node has M_S signal streams to be simultaneously sent to different neighboring nodes, and the signal vector corresponding to these streams at time t is denoted as $\mathbf{d}(t) = [d_1(t) \cdots, d_{M_S}(t)]^T$, where $(\cdot)^T$ denotes transpose. The streams may have different modulations to provide appropriate data rates according to the required data size, priority class, and channel quality. We only consider flat-fading environment and, therefore, the time index t is omitted from all subsequent expressions for notational simplicity. The transmitted signal vector can be expressed as

$$\mathbf{x}_s = \mathbf{A}\mathbf{Q}^{\frac{1}{2}}\mathbf{d}, \tag{1}$$

where $\mathbf{A} \in \mathbb{C}^{M \times M_S}$ is the beamformer matrix (to be determined later), $\mathbf{Q} = \text{diag}(q_1, \cdots, q_{M_S})$ is the power loading matrix subject to the total power constraint $\text{tr}(\mathbf{Q}) = \sum_{i=1}^{M_S} q_i = P$, with P denoting the total transmit power.

The multi-channel transmit beamforming problem can be solved by either linear or nonlinear techniques (Costa, 1993; Peel, 2005). Assume that the transmit node has the channel state information (CSI), denoted as $\mathbf{H}_T \in \mathbb{C}^{M_S \times M}$. If a linear zero-forcing technique is used, the beamforming matrix can be obtained as (Peel, 2005)

$$\mathbf{A} = \frac{1}{\sqrt{\lambda}} \mathbf{H}_T^H \left(\mathbf{H}_T \mathbf{H}_T^H\right)^{-1}, \tag{2}$$

where $\lambda = \text{tr}\left[\left(\mathbf{H}_T \mathbf{H}_T^H\right)^{-1}\right]$, $(\cdot)^H$ denotes conjugate transpose, and tr$(\cdot)$ denotes matrix trace.

Multi-Channel Receive Beamforming

Consider a target node (TN) with receivers designed to simultaneously receive up to $S_R \leq M$ signals. Assume that there are $n \leq S_R$ neighboring users communicating with the TN. Denote s_i and $\mathbf{u}_i \in \mathbb{C}^{M \times 1}$ as, respectively, the signal stream transmitted from the ith source node and the corresponding equivalent channel vector, where i=1, ..., n. Then, the M×1 received signal vector at the TN is given by

$$\mathbf{x} = \sum_{i=1}^{n} \mathbf{u}_i s_i + \mathbf{n} = \mathbf{U}_R \mathbf{s} + \mathbf{n}, \tag{3}$$

where $\mathbf{U}_R = [\mathbf{u}_1, \cdots, \mathbf{u}_n] \in \mathbb{C}^{M \times n}$, $\mathbf{s} = [s_1, \cdots, s_n]^T \in \mathbb{C}^{n \times 1}$, and $\mathbf{n}$ is the noise vector.

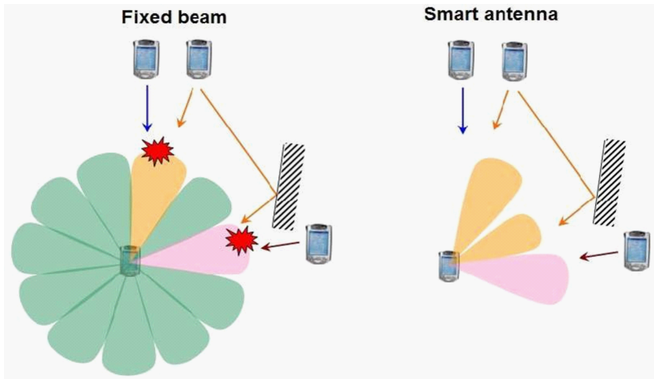
We can design a set of weights for the TN to simultaneously receive and separate the n signals. The well-known optimum weights in the minimum mean square error (MMSE) sense, assuming that the CSI can be estimated at the TN, is given by (Monzingo, 1980; Winters, 1984)

$$\mathbf{W}_0 = \left(\sigma^2 \mathbf{I} + \mathbf{R}_\mathbf{x}\right)^{-1} \mathbf{U}_R \in \mathbb{C}^{M \times n}, \tag{4}$$

where σ^2 is the noise variance in each receive channel, $\mathbf{I}$ is the identity matrix with an appropriate dimension, and $\mathbf{R}_\mathbf{x} = E(\mathbf{x}\mathbf{x}^H) \in \mathbb{C}^{M \times M}$ is the covariance matrix of the received data. It is noted that an improved detection performance can be achieved using optimum or suboptimum multi-user detection methods (Verdu, 1998).

To avoid the deafness problem, a standby channel can be secured using a dedicated or shared spatial channel so that the TN can hear new communication requests (Zhang, 2006). The standby channel can either be omnidirectional or perform directional scanning.

Figure 2. MFBA and MCSA in a multipath environment



(a) MFBA (b) MCSA

Fixed-Beam Antennas

MFBAs form multiple fixed beams in different directions. When there is no *a priori* information of the neighboring users to be communicated, as in a typical wireless ad hoc network, the beams are designed to cover the entire azimuth plane. Some wireless networks, such as fixed mesh networks, are designed to serve certain sectors or users located in specific directions and, thus, the beams are designed only to cover these directions.

In this chapter, we consider that wireless nodes are mobile and their connections are dynamic. Therefore, the beams should be equipped with the capability of serving all the azimuth directions. Such beams can be implemented using multiple directional antennas, which collectively serve the entire azimuth plane, or an array of omnidirectional antennas with multiple sets of array weights. We use the array model, where each set of array weights corresponds to a directional array pattern (Li, 2007). For example, an array of M beams can be designed to have a half-power beamwidth (HPBW) of $2\pi/M$. Adjusting the array configurations may alter the array pattern and, as such, changes the tradeoff between the signal transmission/reception quality and the interference mitigation capability in different spatial locations.

Output SINR Analysis

The output SINR of MFBAs and MCSAs is first analyzed in a single-path environment, and the results are then generalized to the case of multipath propagation.

Single-Path Propagation Environment

A single or multiple active neighboring nodes (ANNs) make transmission to a TN equipped with multiple beams. In the absence of a proper contention resolution scheme, e.g., without the use of substantial data coding or spectrum spreading, it is practical to consider that, at each TN beam, only one ANN signal can achieve sufficiently high output SINR for successful data decoding. For a specific TN beam, therefore, one signal is considered as the signal-of-interest (SOI), and others become signals-not-of-interest (SNOIs). Generally, we assume that, at a certain time, there are n ANNs, i.e., one SOI and n–1 SNOIs with respect to a node. Denote s_d and s_j as the SOI and the jth SNOI, respectively, with $E[|s_d|^2]=E[|s_j|^2]=1$, $j=1,\ldots, n-1$. Then, the received signal vector $\mathbf{x}$ in (3) can be rewritten as

$$\mathbf{x} = \mathbf{x}_\mathrm{d} + \mathbf{x}_\mathrm{I} + \mathbf{n} = \mathbf{u}_\mathrm{d} s_\mathrm{d} + \sum_{j=1}^{n-1} \mathbf{u}_j s_j + \mathbf{n}, \quad (5)$$

where $\mathbf{x}_d$, $\mathbf{x}_I$, and $\mathbf{n}$ are respectively the SOI, SNOI, and noise vectors, and $\mathbf{u}_d$ and $\mathbf{u}_j$ are the propagation vectors of the SOI and *j*th SNOI.

Assume that the SOI, the SNOIs, and the noise are statistically independent. In addition, the elements of the noise vector $\mathbf{n}$ are assumed to be independent and identically distributed (i.i.d.) complex Gaussian processes. Furthermore, the channels are assumed to be quasi-stationary, i.e., they do not change over the time interval of an array processing operation but impose random variation over a long time period. Then, for each SOI, we can properly define the covariance matrix of the received data as $\mathbf{R_x}=E[\mathbf{xx}^H]$, and the covariance matrix of the interference-plus-noise as $\mathbf{R_{IN}}=E[(\mathbf{x}_I+\mathbf{n})(\mathbf{x}_I+\mathbf{n})^H] = \mathbf{R}_I + \sigma^2\mathbf{I}$, where $\mathbf{R_I}=E[\mathbf{x}_I\mathbf{x}_I^H]$ is the covariance matrix of the SNOIs.

For an MCSA, the beam for the SOI can be formed with the optimum weight vector in the MMSE sense, given by (Monzingo, 1980; Winters, 1984)

$$\mathbf{w}_o = \mathbf{R}_{IN}^{-1}\mathbf{u}_d, \tag{6}$$

and the corresponding output SINR is

$$\gamma = \mathbf{u}_d^H \mathbf{R}_{IN}^{-1}\mathbf{u}_d. \tag{7}$$

For an MFBA, its beams are predefined and a free beam can be selected to receive the SOI. Denote $\mathbf{w}_b$ as the corresponding weight vector of the beams corresponding to the SOI. Then, the output SINR can be written as

$$\gamma^{FBMA} = \frac{\mathbf{w}_b^H\mathbf{u}_d\mathbf{u}_d^H\mathbf{w}_b}{\mathbf{w}_b^H\mathbf{R}_{IN}\mathbf{w}_b}, \tag{8}$$

which, in general, is not optimum. Therefore, an MFBA may suffer from an SINR loss, as opposite to an MCSA which maximizes the output SINR.

As an example of an MFBA (Li, 2007), a simple coverage scheme is shown in Fig. 3(a), where four fixed beams are formed using a uniform circular array (UCA) consisting of four omnidirectional antennas with an array radius of 0.235 λ, where λ is the carrier wavelength. This array pattern covers the entire azimuth plane, where each beam has a HPBW of 90° and a maximum sidelobe gain of –15.5 dB. The beam that receives the highest signal level from a desired ANN is selected as the receive beam. For example, the beam with direction of maximum gain toward 90° is selected if the incident wave falls into the angular range over [45°, 135°].

On the other hand, an MCSA consists of an array followed by *M*-channel adaptive processing circuitries to form up to *M* dynamic beams adapted to the incident waves. Hence, the angular width and position of each beam is reconfigured real-time. For a fair comparison, we consider an MCSA consisting of an identical UCA with M=4 omnidirectional antennas and an array radius of 0.235 λ.

Consider the case of two ANNs. The SOI arrives with a DOA of 30°, whereas that of the SNOI is 40°. Assume that the received power at the TN corresponding to each ANN is the same and the resulting input SNR is 20 dB. For the MFBA, the beam with the maximum gain towards 0° is selected to receive the SOI, shown as the solid line in Fig. 3(a). The output SINR is obtained as merely 1 dB. Obviously, a collision between the SOI and SNOI occurs in this beam. On the contrary, when the MCSA is used, a dynamic beam is formed as shown in Fig. 3(b). Although the two signals are closely spaced, a null is formed and directed toward the direction of the SNOI, resulting in an output SINR of 11.5 dB. As such, the advantage of an MCSA over an MFBA is evidently demonstrated.

For MFBA, the output SINR is 1 dB. (b) For MCSA, the output SINR is 11.5 dB.

Multipath Propagation Environment

A wireless channel often experiences multipath propagation, i.e., the TN receives not only the direct path of the transmitted signal, but also its reflected signals that propagate over other paths. Multipath propagation is a typical problem in many wireless systems. Specifically, the multipath propagation phenomenon may become even richer (with a higher angular spread) in ad hoc networks, since the nodes are typically located in indoor or low-altitude outdoor environments (Winters, 2006; Babich, 2006).

It is well known that, in a frequency-nonselective multipath environment, the paths arriving from the same ANN form an equivalent path with a generalized steering vector, often referred to as the spatial signature (Lin, 1982). For example, consider one signal, whose waveform is represented as $s_1(t)$. When this signal arrives through K>1 paths, the received signal vector is expressed as $\sum_{i=1}^{K}\mathbf{u}_{1,i}s_1=\tilde{\mathbf{u}}_1 s_1$, where $\mathbf{u}_{1,i}$ is the channel vector corresponding to its ith path. Therefore, it becomes obvious that the contribution of the K paths is equivalently represented by a single spatial signature $\tilde{\mathbf{u}}_1$ which, in general, does not have an angular bearing.

Using the above equivalent model, the received signal vector in a multipath environment can be expressed as

$$\tilde{\mathbf{x}}=\tilde{\mathbf{u}}_{d}s_{d}+\sum_{j=1}^{n-1}\tilde{\mathbf{u}}_{j}s_{j}+\mathbf{n}\,, \tag{9}$$

where $\tilde{\mathbf{u}}_d=\sum_{i=1}^{N_d}\mathbf{u}_{di}$ and $\tilde{\mathbf{u}}_j=\sum_{k=1}^{N_{Ij}}\mathbf{u}_{j,k}$ are the spatial signatures of the desired and the jth SNOI propagation vectors, respectively, N_d is the number of paths of SOI, and N_{Ij} is the number of paths of the jth SNOI. Similar to the single-path case, we can properly define $\mathbf{R}_{\tilde{\mathrm{X}}}=E\left[\tilde{\mathbf{x}}\tilde{\mathbf{x}}^H\right]$ as the covariance matrix of the received signal samples, and $\mathbf{R}_{\tilde{\mathrm{I}}}=E\left[\tilde{\mathbf{x}}_I\tilde{\mathbf{x}}_I^H\right]$ and $\mathbf{R}_{\widetilde{\mathrm{IN}}}=E\left[\left(\tilde{\mathbf{x}}_I+\mathbf{n}\right)\left(\tilde{\mathbf{x}}_I+\mathbf{n}\right)^H\right]=\mathbf{R}_{\tilde{\mathrm{I}}}+\sigma^2\mathbf{I}$ as that of the SNOIs and interference-plus-noise, respectively. For the MCSA, the optimum beam in the MMSE sense can be formed as

$$\tilde{\mathbf{w}}_o=\mathbf{R}_{\widetilde{\mathrm{IN}}}^{-1}\tilde{\mathbf{u}}_d\,, \tag{10}$$

and the corresponding output SINR can be expressed as

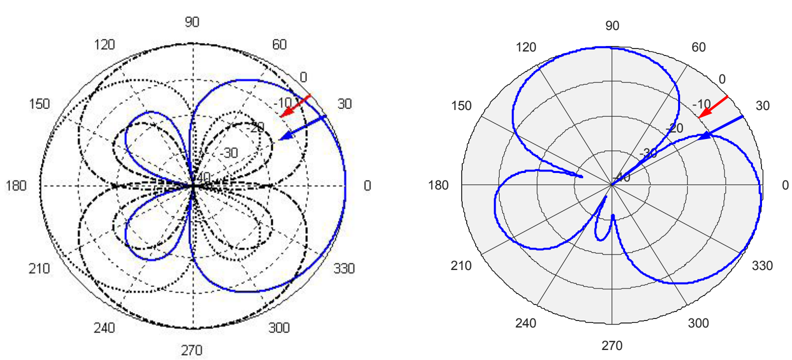
$$\tilde{\gamma}=\frac{\tilde{\mathbf{w}}_o^H\tilde{\mathbf{u}}_d\tilde{\mathbf{u}}_d^H\tilde{\mathbf{w}}_o}{\tilde{\mathbf{w}}_o^H\mathbf{R}_{\widetilde{\mathrm{IN}}}\tilde{\mathbf{w}}_o}=\tilde{\mathbf{u}}_d^H\mathbf{R}_{\widetilde{\mathrm{IN}}}^{-1}\tilde{\mathbf{u}}_d \tag{11}$$

In contrast, for the MFBA, a free beam is selected to receive the SOI. Due to the fixed-beam nature, the weights $\mathbf{w}_{b'}$ used in a multipath environment are the same as that used in a single-path propagation environment. Consequently, the output SINR of the MFBA is given by (Li, 2007)

$$\tilde{\gamma}^{\mathrm{FBMA}}=\frac{\mathbf{w}_{b'}^H\tilde{\mathbf{u}}_d\tilde{\mathbf{u}}_d^H\mathbf{w}_{b'}}{\mathbf{w}_{b'}^H\mathbf{R}_{\widetilde{\mathrm{IN}}}\mathbf{w}_{b'}}. \tag{12}$$

Again, the solution of an MFBA is not optimal and is expected to provide inferior performance to an MCSA counterpart in a multipath environment.

Figure 3. Comparison between the array pattern of the MFBA and MCSA (SOI: 30°, SNOI: 40°). (a) For MFBA, the output SINR is 1 dB. (b) For MCSA, the output SINR is 11.5 dB.



(a) *(b)*

As an example (Li, 2007), we present a performance comparison between an MFBA and an MCSA operating in a multipath propagation scenario as depicted in Fig. 4(a), where each of the four ANNs has two signal paths. Consider that the SOI arrives at –60º and 0º, whereas the three SNOIs arrive at 30º and 90º, 120º and 180º, and 210º and 270º, respectively. Assume that each path has the same receive power with an input SNR of 20 dB evaluated at the TN. The antenna array model depicted in Fig. 3 is used. For the MFBA, the beam with maximum gain toward 0º is selected to serve the SOI, and the resulting output SINR is very low (3.9 dB). A rather promising result is obtained when the MCSA is used, where a dynamic beam is formed as shown in Fig. 4(b) for the SOI, and an output SINR of 24.5 dB is yielded.

In this example, the four ANNs have the same output SINR due to the symmetric incidence. Therefore, the MCSA can provide high quality links to concurrently communicate with all four ANNs, whereas the MFBA fails.

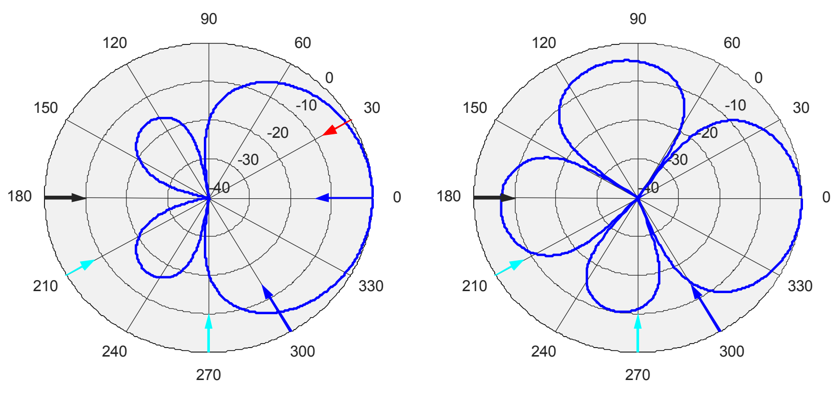
IV. RANDOM-ACCESS SCHEDULING TECHNIQUES

In an ad hoc network exploiting MBAs, it is crucial to use a proper RAS scheme in contention resolution to coordinate the node access and resolve the contention (Li, 2004). Although several control schemes have been proposed for wireless networks (Bao, 2002; Choudhury, 2002), few are feasible for MBAs, particularly when operating in a multipath propagation environment (Jain, 2006b). This section discusses RAS techniques that support MBAs in both single-path and multipath propagation environments.

Without loss of generality, consider a scenario where a TN has *N* neighboring nodes, which are independently and randomly located around the TN with a uniform angular distribution. In a single-path propagation environment, the signal transmitted from each ANN falls into only one beam of the TN. In a multipath environment, on the other hand, the received signals transmitted from an ANN may fall into multiple beams of the TN. Regardless of the propagation environment, when multiple signal arrivals originated from different ANNs fall into the same beam, collisions occur in the beam. As a result, this beam cannot successfully receive packets and thus does not contribute to the node throughput. Only those beams that successfully receive packets contribute to the node throughput. It is evident that, in the absence of a proper contention resolution scheme, collisions may occur as a result of random packet transmission. Furthermore, multipath propagation is likely to yield more frequent collisions. When the contention resolution scheme utilizes proper RAS, collisions can be avoided and, as a result, network performance can be significant improved.

To take advantages of concurrent link capability of MBAs achieved through the exploitation of multiple beams, we focus on RAS schemes which are incorporated into contention resolution to utilize the spatial dimensionality. Assume that all nodes in a region of interest share the same wireless channel (i.e., the same frequency, code, or time channel). Moreover, time is assumed to be slotted and all data packets have the same length *T*. Data packets, including both newly generated and retransmitted ones, arrive at each node according to a Poisson process with an arrival rate λ packets/sec. Thus, the corresponding offered load of each node is $R=\lambda T$. Each arrived packet is intended for a single TN. In order to illustrate the performance of RAS schemes, we focus on the one-hop case.

Figure 4. Comparison of the array pattern of the MFBA and MCSA operating in multipath environment in the presence of four ANNs (SOI: –60º and 0º; SNOI 1: 30º and 90º; SNOI 2:120º and 180º; SNOI 3: 210º and 270º). (a) For MFBA, the output SINR is 3.9 dB. (b) For MCSA, the output SINR is 24.5 dB.



(a) *(b)*

For convenience, denote p as the probability that each neighboring user attempts to transmit a packet in a time slot. During a time slot, the probability that n out of the N neighboring nodes simultaneously attempt to transmit a packet is given by (Li, 2007)

$$P_a(N, n, p) = C_n^N p^n (1-p)^{N-n}, \quad (13)$$

where C_n^N denotes the combination operation representing the number of different ways of selecting n out of N neighboring nodes. Note that, when p is sufficiently small, the offered load R can be approximated by $R=Np$.

To simplify the problem, we first introduce a relatively simple sector model. Under this model, two RAS techniques, respectively based on packet prioritization and throughput-maximization, are developed and compared. RAS techniques based on output SINR are then discussed.

Sector-Based RAS

Sector-Based Beam Model

For an MFBA, each node is equipped with M fixed-beam antennas, each forming a conical beam that spans a sector of $\theta_{BW}=2\pi/M$ radians. Hence, all antennas of the TN collectively form M non-overlapping beams that cover the entire azimuth plane. The antenna gain is considered constant within the beam region whereas it drops to zero outside this region. As such, interferers arriving from outside of the beamwidth are entirely filtered out and do not affect the signal received in the beam. This is known as the sector-based beam model or pie-type model. When multiple neighboring nodes simultaneously transmit packets which fall into the same beam at the TN, the MFBA cannot avoid collisions between these packets because the angular resolution of the beams, once they are predefined, cannot be adjusted.

An MCSA, on the other hand, independently forms multiple dynamically defined and real-time steered beams toward different ANNs. The angular resolution, or the beamwidth, of each beam is adaptively adjusted corresponding to the signal environment. To perform a sector-based analysis, an equivalent sector-based MCSA model can be used (Zhang, 2006). Similar to the sector-based beam model developed for an MFBA, an MCSA with M antennas forms up to M/β virtual beams, each with beamwidth $\alpha=\beta\theta_{BW}$, where $\beta \le 1$ is the beamwidth ratio that reflects the capability of the MCSA to form narrower beams. When the angular separation between any adjacent signal arrivals is larger than a threshold $\alpha/2$, the MCSA can filter out the interfering signals. Note that, for the MCSA, the maximum number of actual beams remains to be M, and the exact value of α depends on the array configuration, required SINR, and the number and type of interferers.

Single-Path Propagation Environment

In a single-path environment, the signal transmitted from each ANN falls into only one beam of the TN. Collision occurs when two or multiple signals fall into a beam when on-demand protocols are used. In order to avoid such collisions, a proper RAS scheme incorporated into contention resolution can be exploited such that the TN only accepts one ANN in each non-empty beam and denies all others.

Assume that, at a certain time, all $n \le N$ ANNs occupy $m \le \min(M, n)$ beams of the TN, say $B_1, \ldots, B_m$. In this case, up to m ANNs can be accepted without collisions. In the contention resolution, the TN decides the acceptance or denial of an ANN according to the following algorithm:

i) Find the m non-empty beams, $B_1, \ldots, B_m$, occupied by all the ANNs;
ii) Initialize i as $i=1$;
iii) Accept one ANN in B_i and deny all other ANNs in this beam;
iv) Update i as $i \leftarrow i+1$, then repeat iii) until $i>m$ holds;
v) Output the accepted ANNs.

In a single-path environment, the selection criterion of accepting an ANN in a non-empty beam does not affect the total number of accepted ANNs in the TN. Therefore, when the ANNs have different priority classes, proper prioritization can be performed without sacrificing the overall node throughput.

Multipath Propagation Environment

Compared to the single-path propagation case, the RAS becomes more complicated in a multipath propagation environment. In this case, the signal transmitted from an ANN may arrive at the TN through multiple paths and fall into multiple beams.

Similar to the single-path case, we can exploit proper RAS to deny some ANNs such that collision-free communications from the accepted ANNs to the TN are guaranteed. Depending on the design criteria, different RAS schemes can be implemented. In the following, we first discuss the RAS scheme that is based on priority consideration, and that based on the throughput-maximization is then introduced.

Priority-Based Algorithm

With the growth of real-time applications, supporting real-time flows with delay constraints is an important and challenging issue in ad hoc wireless networks. In order to provide differentiated services for real-time and non-real-time packets, the employed RAS schemes must adopt certain mechanisms to incorporate differentiated priority-based access, such that the packets with higher priority can be transmitted in preference to packets with lower priority (Deng, 1999; Barry, 2001; Veres, 2001; Aad, 2001; Kanodia, 2001; Yang, 2002; Yin, 2003; Xiao, 2003). Priority-based RAS is discussed below.

Assume that, at a certain time, there are $n \le N$ ANNs, each transmitting its respective signal through K quasi-stationary paths and each path signal has sufficiently high strength since all node are located in a similar multipath environment (Note that such assumption of equal number of paths is only for the convenience of analysis, and it does not affect the effectiveness of the RAS algorithm.). The K paths are assumed to follow a uniform angular distribution and some or all of these paths may fall into the same beams. Denote B_a as the number of beams occupied by the signal arrivals from all the n ANNs. It is obvious that $B_a \le \min(Kn, M)$. In the priority-based algorithm, first of all, the TN sorts the n ANNs based on their priority classes to form a queue: U_1, U_2, …,U_n, where U_1 has the highest priority and U_n has the lowest priority. To solve the contention problem, the ANNs accepted by the TN are determined according to the following RAS algorithm:

i) Unconditionally accept U_1;
ii) Accept U_2 only if none of its paths falls into the beams occupied by U_1, otherwise deny it;
iii) For $i > 2$, accept U_i only if none of its paths falls into the B_{oc} beams, where B_{oc} is the number of beams occupied by the previously accepted ANNs. Update B_{oc} to include the beams occupied by the newly accepted user;
iv) Update i as $i \leftarrow i+1$, then repeat iii) until either $B_{oc}=B_a$ or $i>n$ holds;
v) Deny all the remaining ANNs if there are any.

It can be seen that this RAS scheme protects the accepted ANNs to the maximum extent by denying the ANNs that have paths falling into any beams occupied by the previously accepted ANNs. That is, all accepted ANNs individually have mutually exclusive beam occupancies.

Throughput-Maximization Algorithm

In some applications, the priority issue of the ANNS may have less importance compared with the overall network throughput. Rather, the RAS scheme should aim to maximize the node throughput (Li, 2001; Toumpis, 2003; Spyropoulos, 2003a/b). Below, a throughput-maximization (TM) RAS scheme is developed to maximize the node throughput gain (NTG) of an MFBA-equipped node in various propagation environments. The NTG is defined as the mean number of ANNs accepted by the TN of interest.

Assume that, at a certain time, there are $n \le N$ ANNs, each transmitting its respective signal through K quasi-stationary paths. Denote B_o as the number of beams occupied by the signal arrivals from all the n ANNs, and S as the maximum number of the accepted ANNs. Towards the contention resolution, the accepted ANNs are determined according to the following RAS algorithm:

i) If each ANN occupies all the M beams, let S=1, select one ANN and deny the other n–1 ANNs. Go to v);
ii) Deny any ANNs that individually occupy all the M beams. Update the number of beams, m, occupied by the remaining ANNs;

iii) When redundant ANNs with overlapping occupancy (i.e., they exactly occupy the same number and indices of beams) exist, only one ANN is preserved and the others are denied;
iv) Update n, the number of remaining ANNs, let S=1 and determine the possible acceptance of ANNs according to the following procedure:
   1) Go to v) if n=1, otherwise let N_s=min(n,m) and go to 2);
   2) Search in the entire search space composed of $C_{N_s}^{n}$ possible ways to determine whether N_s out of the n ANNs can be accepted simultaneously, i.e., at least one path of each of the N_s ANNs does not collide. Once one possible way that N_s out of the n ANNs can be accepted is found, then stop searching, let S=N_s, and go to v). If no way for simultaneously accepting N_s out of the n ANNs can be found, go to 3);
   3) Update N_s as $N_s \leftarrow (N_s - 1)$ and repeat 2) until N_s=1.
v) Output the S ANNs accepted by the TN.

Note that the complexity of the TM search process is high. A simplified search procedure can be developed based on the concept of *mutually exclusive set* (Li, 2008).

SINR-Based RAS

The sector-based model provides a simple platform to analyze the collision problem and develop RAS approaches. However, as we discussed in Section III, this model is approximate and does not precisely represent actual array beams. The use of actual output SINR is an appropriate measure to accurately determine the reliability performance of communication links. In this following, we consider output SINR-based RAS schemes. We focus on two perspectives: the priority class of an ANN and the output SINR.

Two criteria should be satisfied for an ANN to be accepted at a TN. First, to decode the SOI, the ANN should yield sufficiently high output SINR in the presence of other ANNs. Second, it should not impose significant interference to the nodes that are already accepted. Similar to the sector-based model, the TN first sorts all the ANNs according to their priority classes to form a queue: U_1, U_2, ... , U_n. For convenience, we define the following parameters:

γ_0 : output SINR threshold required to accept an ANN
γ_i : ouput SINR of U_i
U_a: a set of ANNs that are accepted by the TN
S: number of elements of U_a (i.e., the number of accepted ANNs)

In the following, priority-based RAS algorithms are considered in the contention resolution and the output SINR is analyzed respectively for MCSAs and MFBAs.

MCSA-Based RAS Algorithm

For a TN exploiting an MCSA, the following procedure is used to determine the acceptance of the ANNs:

i) Initialization: $U_a=\Phi$ (empty set), S=0, i=1;
ii) Calculate γ_1 in the absence of U_2, ..., U_n. If $\gamma_1 \geq \gamma_0$, accept U_1 by rendering both $U_a=U_1$ and S=1, otherwise deny U_1;
iii) Update i as $i \leftarrow i+1$. In the presence of all U_a and U_i, recalculate the output SINR of the S already accepted ANNs and γ_i. If the output SINR for each of the S+1 users exceeds γ_0, accept U_i by appending U_i into U_a and updating S as $S \leftarrow S+1$, otherwise deny U_i;
iv) Repeat iii) until either $S=M$ or $i=n$ holds;
v) Deny all the remaining ANNs if there are any.

Clearly, this RAS scheme takes the priority class of ANNs into account and satisfies the abovementioned output SINR and interfering criteria.

MFBA-Based RAS Algorithm

When considering the output SINR of MFBAs, we exploit actual antenna beams with actual antenna patterns and sidelobes, rather than idealized sectors. For example, in Fig. 3(a), four actual fixed beams are formed. In a multipath environment, the signal arrivals originated from an ANN may fall into multiple beams. The output SINR corresponding to an ANN is evaluated at the beam that provides the maximum output SINR. For convenience, we define the following parameters.

N_i: number of beams occupied by U_i
U_a: a set of ANNs that are accepted by the TN
b_{Ui}: the beam corresponding to maximum output SINR for U_i
B_a: a set of beams that respectively yield the highest output SINR for the accepted ANNs

For an MFBA, the following RAS procedure is used in the contention resolution to determine the accepted ANNs:

i) Initialization: $U_a=\Phi$, $B_a=\Phi$, $S=0$, $i=1$;
ii) Calculate the output SINR for each of the N_1 beams occupied by U_1 in the absence of U_2, …, U_n. If the highest output SINR corresponding to beam b_{U1} exceeds γ_0, accept U_1 by rendering $U_a=\{U_1\}$ and $B_a=\{b_{U1}\}$ as well as $S=1$, otherwise deny U_1;
iii) Update i as $i\leftarrow i+1$. In the presence of all U_a and U_i, recalculate the output SINR of all the S accepted ANNs. If the output SINR for any of the S ANNs is lower than γ_0, deny U_i and go to iv); otherwise find the remaining N_{ri} beams B_{ri}, by excluding the beams B_a from the N_i beams occupied by U_i, calculate the output SINR for each of the B_{ri} beams, and obtain the maximum value $\gamma_{i\max}$ corresponding to beam b_{Ui}. If $\gamma_{i\max}$ exceeds γ_0, accept U_i by appending U_i into U_a, appending b_{Ui} into B_a, and updating S as $S\leftarrow S+1$, otherwise deny U_i;
iv) Repeat iii) until either $S=M$ or $i=n$ holds;
v) Deny all the remaining ANNs if there are any.

Similarly, this RAS scheme also considers the priority class of the ANNs and their mutual interference impact. In contrast to the MCSA-based RAS algorithm, the throughput performance may, however, degrade due to the fact that the beams are predefined, i.e., they cannot adapt to time-varying propagation channels.

The performance of the above two RAS algorithms is evaluated in the next two sections.

V. SECTOR-BASED PERFORMANCE EVALUATION

In this section, we use the sector-based model to evaluate the performance, in terms of the probability of concurrent packet reception (CPR) and NTG, of MBAs with both MFBA and MCSA structures, operating in single-path and multipath environments.

Probability of Concurrent Packet Reception

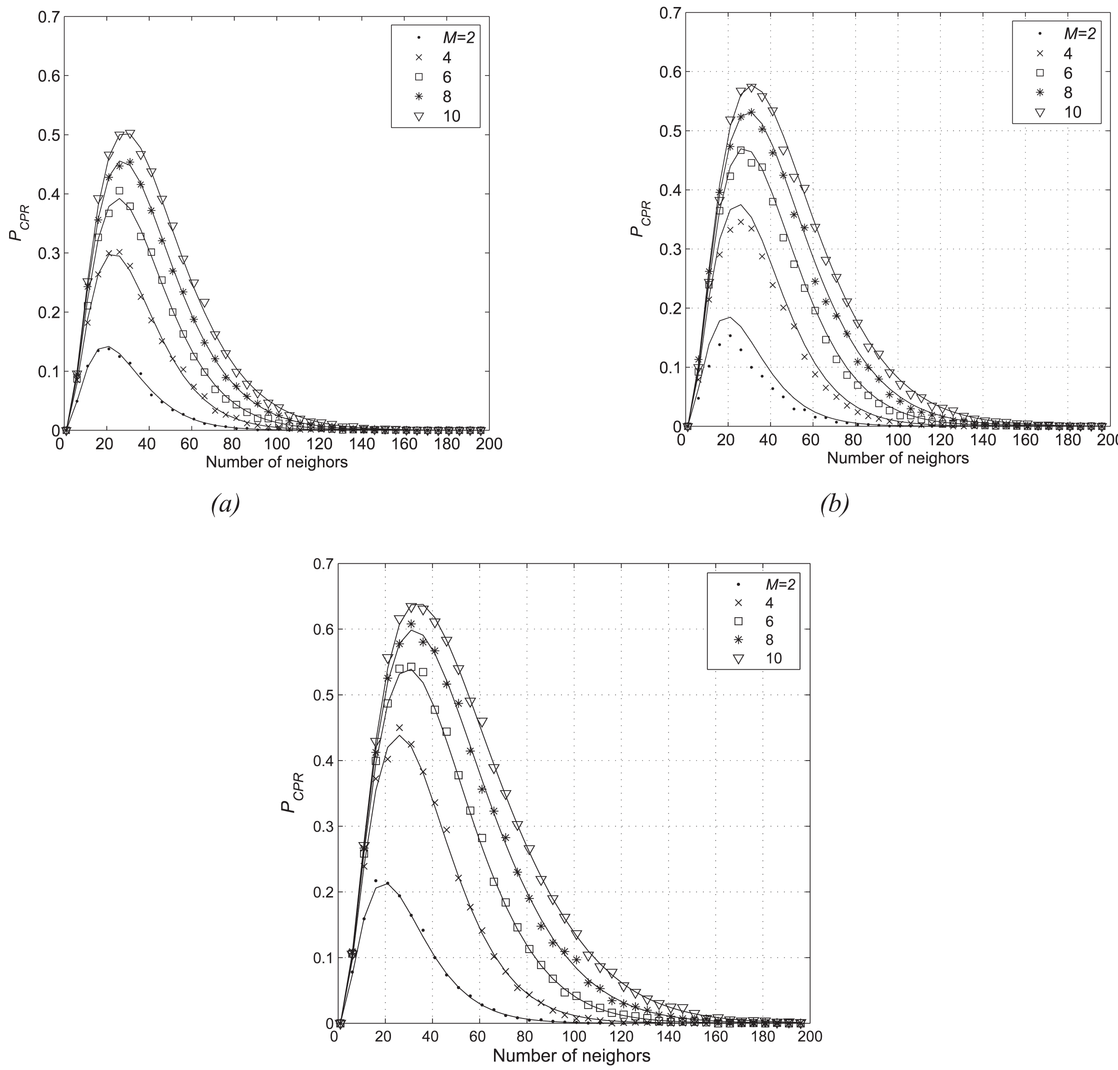
Consider a TN equipped an M-beam MBA with N neighboring nodes. Each of these neighboring nodes attempts to transmit packets to the TN with a probability p. A TN beam is considered collided when signal arrivals from more than one ANNs fall into this beam when the on-demand protocols are used. The probability of CPR is defined as the probability that two or more ANNs are successfully received by the TN (Zhang, 2006; Jain, 2006b), which can be expressed as

$$P_{cpr} = \sum_{n=2}^{M} P_a(N,n,p)\cdot Q(M,M_a,n), \qquad (14)$$

where $P_a(N,n,p)$ is defined in (13), and $Q(M,M_a,n)$ is the probability that all the packets transmitted from the n nodes are successfully received without collision at some M_a beams, where $n\leq Ma\leq M$.

For MFBA-based and MCSA-based TNs, respectively, $Q(M,M_a,n)$ is given by

Figure 5. Comparison of the CPR probability (p = 0.1). Markers: simulations, lines: analytical



(a) *(b)* *(c)*

$$Q_{\mathrm{MFBA}}(M, M_a, n) = \prod_{i=0}^{n-1}\left(1 - \frac{i}{M}\right), \qquad Q_{\mathrm{MCSA}}(M, M_a, n) = \prod_{i=0}^{n-1}\left(1 - \frac{i\beta}{M}\right). \tag{15}$$

Figure 5 shows the probability of CPR for different values of N and M, where M=M_a and p=0.1 are assumed, and β is set to 1 for the MFBA and to 0.7 and 0.5 for the MCSA, respectively. The improvement of the probability of CPR of the MCSA over the MFBA is evident.

Node Throughput Gain

In addition to the probability of CPR, another important measure of the network performance is the NTG, denoted as G (Chockalingam, 1998; Li, 2007). This measure highlights the effect of the RAS schemes used in the contention resolution and important MAC layer parameters, and diminishes some physical layer parameters. As such, it reflects not only the advantage of the MBAs over omnidirectional antennas and single-beam directional antennas, but also the efficiency of the employed MAC protocols. When the application is specified, the NTG can be mapped to the real data rates so as to directly indicate the channel utilization efficiency.

Single-Path Propagation Environment

On-Demand Protocol Case

For on-demand protocols, the NTG can be derived from the number of beams of a TN where signal arrivals are accepted. We first consider the probability that m out of the M beams accept packets transmitted from n ANNs ($m \le \min(M,n)$), i.e., the probability that the signal arrivals from m out of n ANNs are collision-free, whereas those from the other $n-m$ ANNs are collided. This probability can be expressed as

$$P_m(M,n,m) = C_m^M \cdot {}^nP_m \cdot N^c(M-m, n-m)/M^n, \tag{16}$$

where ${}^nP_m$ denotes the permutation operation representing the number of different ways of selecting m neighboring nodes from all the n ANNs, and

$$N^c(M-m, n-m) = (M-m)^{n-m} \cdot \left[1 - \sum_{i=1}^{\min(M-m,n-m)} (-1)^{i+1} C_i^{M-m} \cdot {}^{n-m}P_i \cdot \frac{(M-m-i)^{n-m-i}}{(M-m)^{n-m}}\right] \tag{17}$$

is the number of different possible ways that the remaining $n-m$ ANNs fall into the other $M-m$ beams and collide (there may exist empty beams in the $M-m$ beams).

When n neighboring nodes attempt to transmit, the mean number of beams at the TN that successfully receive collision-free signals from different ANNs can be written as

$$G_n^{\text{on}}(M,n) = \sum_{m=1}^{\min(M,n)} m \cdot P_m(M,n). \tag{18}$$

Therefore, the NTG of an MFBA, i.e., the mean number of collision-free non-empty beams, is expressed as

$$G_{\text{MFBA}}^{\text{on}}(M,N,p) = \sum_{n=1}^{N} P_a(N,n,p) \cdot G_n^{\text{on}}(M,n). \tag{19}$$

In the case of an MCSA with M directly available beams, there are $M_e = \lfloor M/\beta \rfloor$ dynamic virtual beams due to the beamwidth reduction. Thus, similar to (16), the probability that m out of the M_e beams are accepted in the presence of n ANNs ($m \le \min(M,n)$) can be written as $P_m(M_e,n,m)$. Consequently, for an MCSA, when n neighboring users attempt to transmit, the mean number of beams at the TN that successfully receive collision-free signals from different ANNs can be expressed as

$$G_n^{\text{on}}(M_e,n,\beta) = \sum_{m=1}^{\min(M_e,n)} \min(m,M) \cdot P_m(M_e,n,m). \tag{20}$$

Finally, the NTG of an MCSA is given by

$$G_{\text{MCSA}}^{\text{on}}(M,N,p,\beta) = \sum_{n=1}^{N} P_a(N,n,p) \cdot G_n^{\text{on}}(M_e,n,\beta). \tag{21}$$

Figure 6. Comparison of NTG in the presence of on-demand protocols (p = 0.1). Markers: simulations, lines: analytical

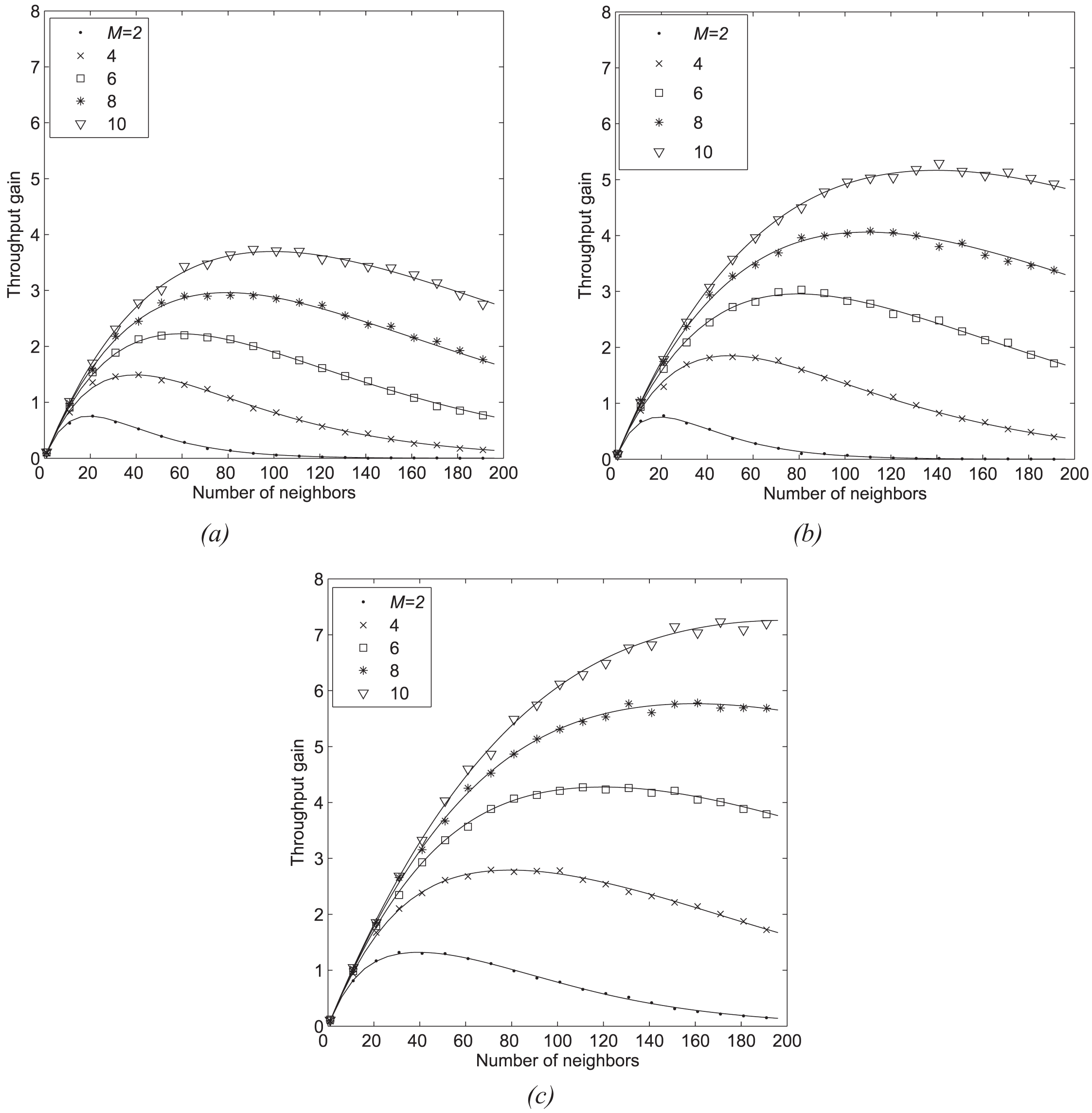
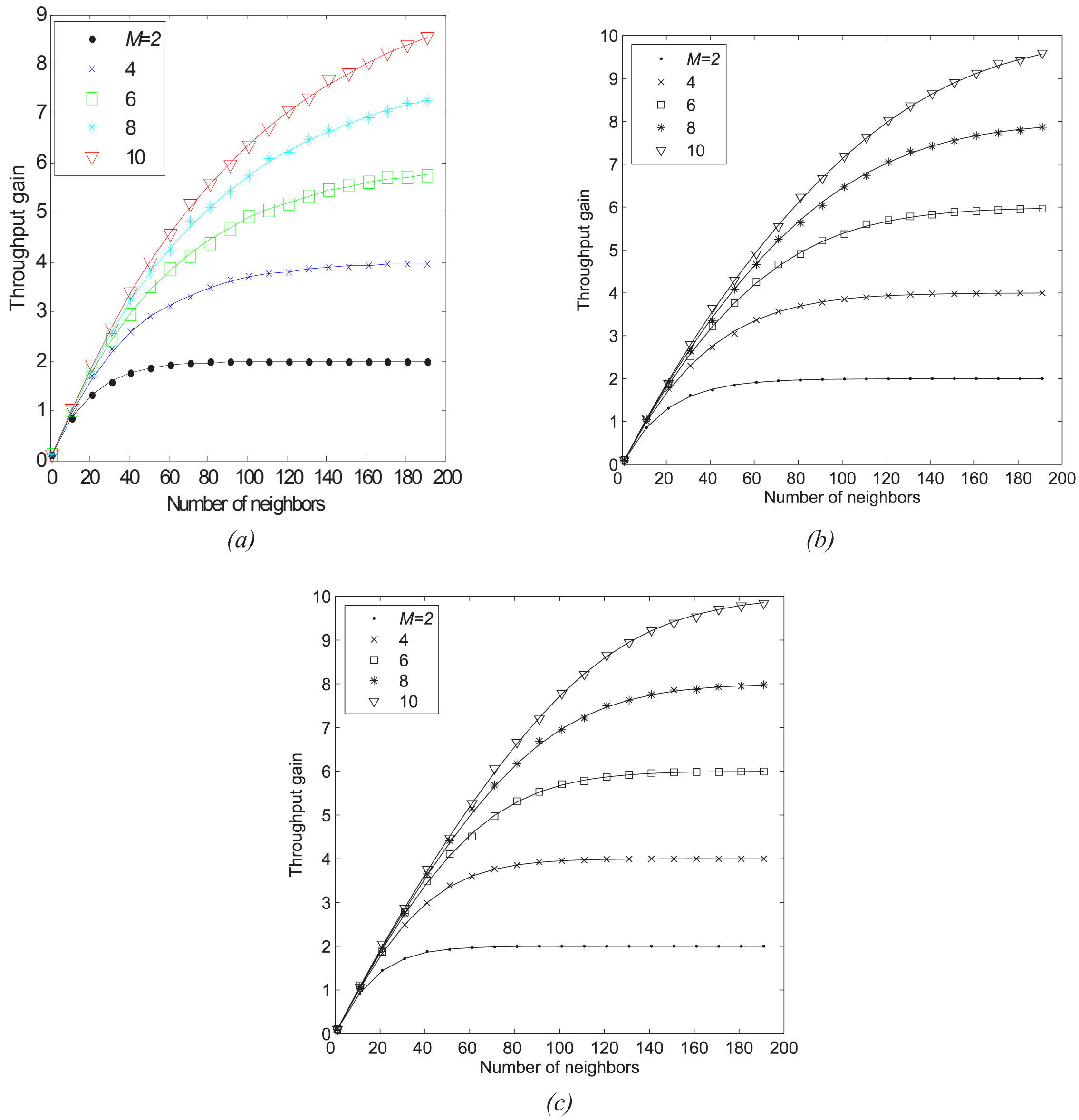


Figure 6 compares the NTG for different values of N and M under conditions of M=M_a and p=0.1. Again, we set β to 1 for the MFBA and to 0.7 and 0.5 for the MCSA, respectively. The improvement of the NTG of the MCSA over the MFBA is significant.

RAS Case

When a certain kind of RAS is employed for the contention resolution, the TN may deny some attempted transmissions to avoid collisions. That is, each beam can accept only one ANN that has a path falling in that beam. In a single-path environment, both priority-based and TM RAS algorithms reach this goal and yield the same NTG. It is clear that the NTG becomes the mean number of non-empty beams and is expressed for the MFBA and MCSA as (Zhang, 2006)

Figure 7. Comparison of NTG upper bounds in the presence of RAS schemes (p = 0.1). Markers: simulations, lines: analytical



$$G_{\text{MFBA}}^{\text{RAS}} = \sum_{n=1}^{N} P_a(N,n,p) \cdot G_n^{\text{RAS}}(M, M_a), \qquad G_{\text{MCSA}}^{\text{RAS}} = \sum_{n=1}^{N} P_a(N,n,p) \cdot G_n^{\text{RAS}}(M_e, M_a), \tag{22}$$

respectively, where $P_a(N,n,p)$ is defined in (13), and

$$G_n^{\text{RAS}}(M, M_a) = \sum_{m=1}^{M} \min(n, M_a) \cdot C_m^M \cdot \frac{m!\,\text{S}(n,m)}{M^n}, \tag{23}$$

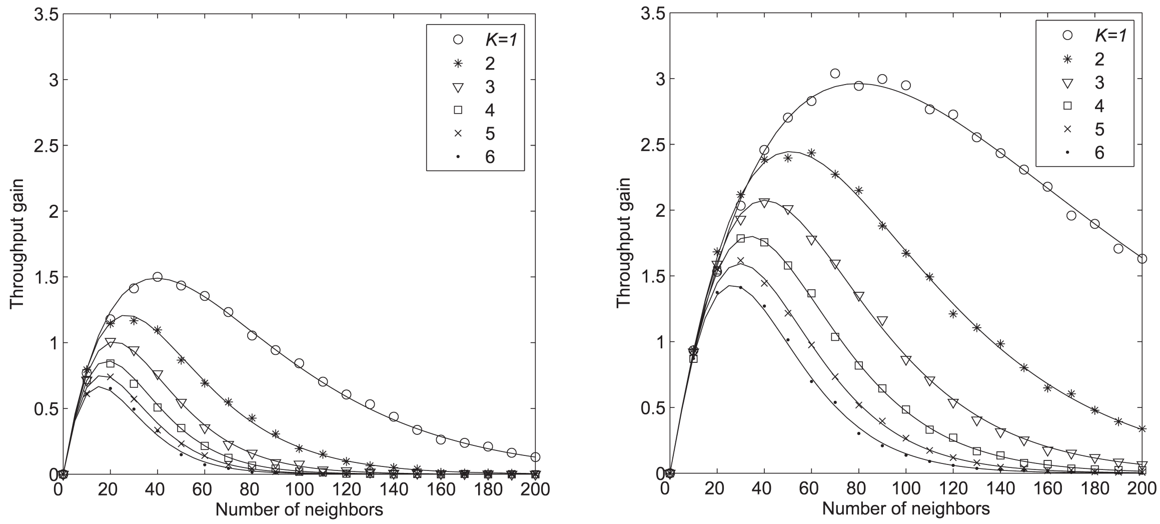
where $\text{S}(n,m) = \frac{1}{m!} \sum_{i=0}^{m-1} (-1)^i \cdot C_i^m \cdot (m-i)^n$ is the Stirling number of the second kind (Graham, 1994), representing the number of different ways that n ANNs occupy m beams without empty beams.

Figure 7 compares the NTG performance in the presence of RAS schemes (Zhang, 2006). Again $M=M_a$ and $p=0.1$ are assumed, and β is chosen as 1 for the MFBA and as 0.7 and 0.5 for the MCSA. It shows that, when the MCSA is used, the throughput gain increases at a higher rate.

Multipath Propagation Environment

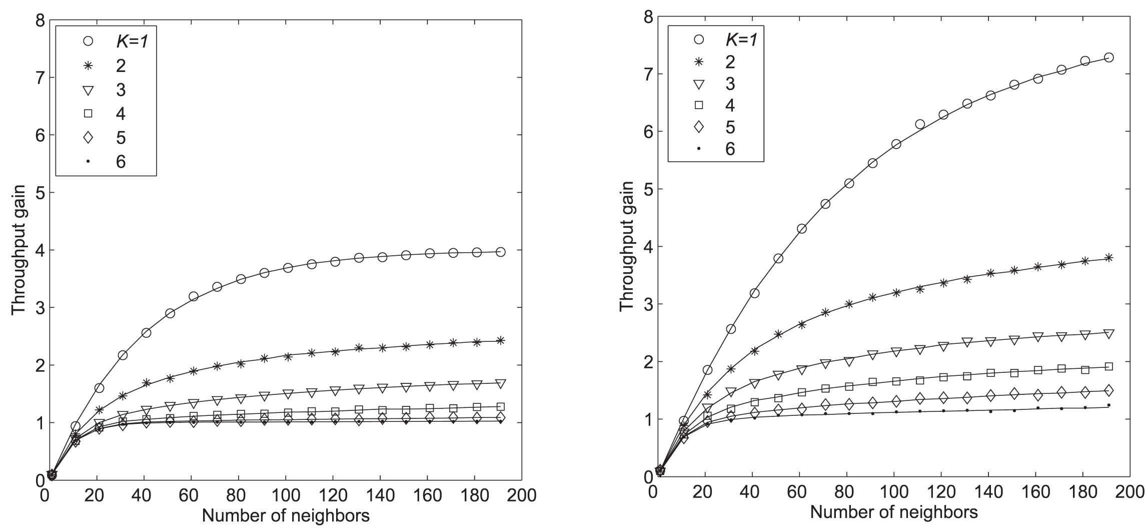
In a multipath environment, the arriving signals from an ANN may fall into multiple fixed-beams and result in more frequent collisions. As a result, the NTG performance may degrade. In this case, the importance of using proper RAS methods becomes more significant. In addition, different RAS techniques yield varying performance.

Figure 8. Comparison of NTG in the presence of multipath (p = 0.1). Markers: simulations, lines: analytical



(a) *(b)*

Figure 9. Comparison of NTG in the presence of multipath and priority-based RAS. Markers: simulations, lines: analytical



(a) *(b)*

On-Demand Protocol Case

For on-demand protocols, the collision analysis developed for multi-beam operations in a single-path propagation environment can be extended to multipath propagation scenarios. Assume that at a certain time, there are $n \le N$ ANNs, each transmitting its respective signal through K quasi-stationary paths. As such, the signal arrivals from an ANN may fall into at most B=min(K,M) fixed beams. In this case, the ith ANN, denoted as u_i, is considered collided if all its b beams collide with signal arrivals transmitted from the other nodes. The NTG in the multipath propagation environment can be expressed as

$$G_{\text{MFBA}}^{\text{on-mp}} = \sum_{n=1}^{N} n \cdot P_a(N,n,p) \cdot P_s(M,K,n)\, G_{\text{MFBA}}^{\text{on-mp}} = \sum_{n=1}^{N} n \cdot P_a(N,n,p) \cdot P_s(M,K,n), \tag{24}$$

where $P_s(M,K,n)$ is the probability that each ANN is accepted by the TN in the presence of n ANNs, each with K-path. The probability is given by

$$P_s(M,K,n) = 1 - \sum_{b=1}^{B} \frac{\text{S}(K,b) \cdot {}^{M}P_b}{M^K} \cdot \left[1 - \sum_{i=1}^{b} (-1)^{i+1} \cdot C_i^b \cdot \left(1 - \frac{i}{M} \right)^{K(n-1)} \right]. \tag{25}$$

As an example, Fig. 8 shows the NTG with four and eight fixed beams, respectively, operated in a quasi-stationary multipath environment with different number of paths. It is evident that the performance of the MFBA degrades as the number of paths, K, increases due to the increased probability of collision among different ANN signals. Note that, as K increases, the maximum NTG decreases and corresponds to a smaller number of neighboring nodes (N). The negative impact of multipath propagation on the NTG becomes insignificant in an under-saturated situation, i.e., the number of ANNs is sufficiently small and thus collision is not the primary limiting factor of the NTG.

Priority-Based RAS Case

When the priority-based and throughput maximization RAS schemes are used, the analytical expressions of the NTG are rather complicated and thus are omitted due to the space limitation (Li, 2008). The NTG of an ad hoc network with four (M=4) and eight (M=8) fixed beams in a quasi-stationary environment using the priority-based RAS is shown in Fig. 9, where the number of paths (K) varies from 1 to 6, and p=0.1 is assumed. The results show that, due to the use of RAS strategy, the NTG becomes a non-decreasing function of the number of neighboring nodes (N), as opposed to the on-demand protocol case where the NTG is not monotonic with N. It is also evident that the NTG improves as the number of beams increases, since a higher number of available beams can concurrently support more users.

When the number of paths is large, each ANN is likely to occupy a high number of beams, thus yielding a low saturation value of the NTG. Note that the asymptotical NTG for K>>1 is one, i.e., only the ANN with the highest priority is accepted.

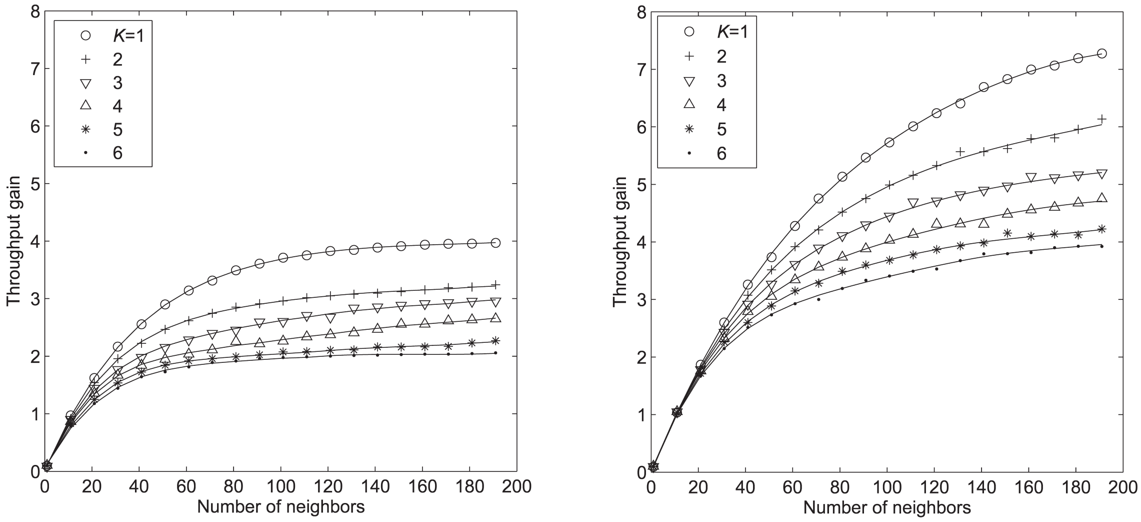
Throughput-Maximization RAS Case

The NTG of an ad hoc network with four (M=4) and eight (M=8) fixed beams in a quasi-stationary environment using the TM is plotted in Figs. 10 and 11, where p is set to 0.1. It is seen that, compared to the priority-based algorithm, the TM algorithm achieves a higher NTG. Similar to the priority-based RAS, the NTG improves as M increases. The NTG remains a decreasing function with respect to K. For both priority- and TM-based RAS schemes, the asymptotic NTG for K>>1 is unity.

VI. OUTPUT SINR-BASED PERFORMANCE EVALUATION

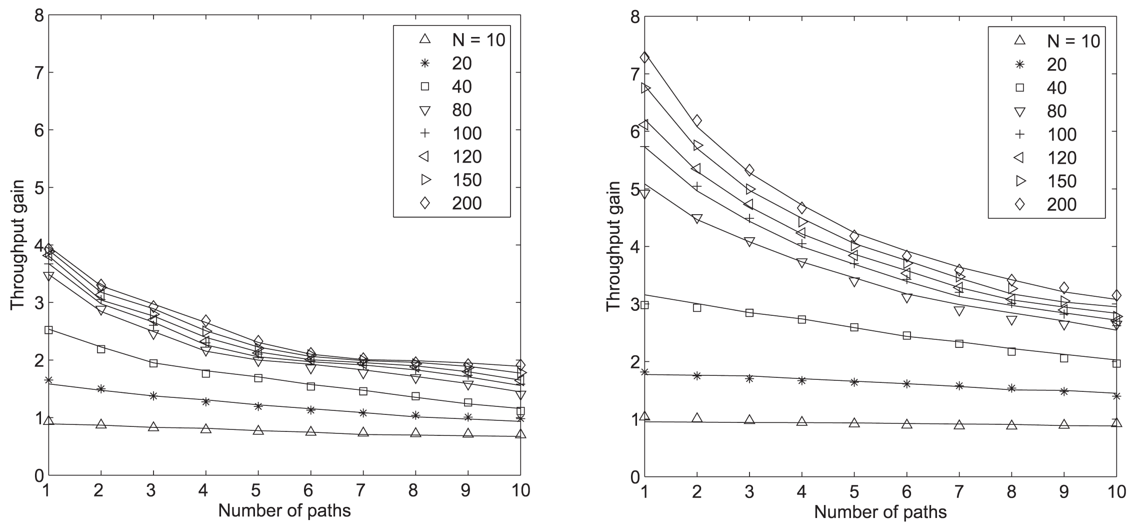
In this section, the NTG is considered from a practical output SINR perspective. That is, only the ANNs whose signals achieve sufficiently high output SINR at the TN are accepted and contribute to the NTG. The probability that an ANN

Figure 10. Comparison of NTG in the presence of TM RAS in a multipath environment. Markers: simulations, lines: analytical



(a) *(b)*

Figure 11. Comparison of NTG in the presence TM RAS in a multipath environment. Markers: simulations, lines: analytical



(a) *(b)*

is accepted can be defined as

$$P_{acc}(n,\gamma_0) = \Pr(\gamma_{out} \geq \gamma_0). \tag{26}$$

where γ_{out} is the output SINR of this ANN if it is accepted, and γ_0 is the required output SINR threshold. Thus, the mean number of accepted ANNs in the presence of *n* ANNs is obtained as

$$N_a\left(n, P_{acc}(n,\gamma_0)\right) = \sum_{i=1}^{n} i \cdot C_i^n \cdot P_{acc}(n,\gamma_0)^i \cdot \left(1 - P_{acc}(n,\gamma_0)\right)^{n-i}. \tag{27}$$

Further, the NTG in the presence of N neighboring users is given by (Li, 2007)

$$G(M,N,p) = \sum_{n=1}^{N} P_a(N,n,p) \cdot N_a\left(n, P_{acc}(n,\gamma_0)\right) = \sum_{n=1}^{N} n \cdot P_a(N,n,p) \cdot P_{acc}(n,\gamma_0). \tag{28}$$

This result shows that the NTG depends on the number of neighboring users (N), each neighboring user's transmission probability (p), and the probability of acceptance for each ANN (P_{acc}).

In the following, the probability of acceptance and the NTG are evaluated through numerical simulations. Each path is assumed to have the same propagation gain and yields an input SNR of 20 dB at the TN. The number of paths of each ANN varies from K=1 to 3, and p is set to 0.1.

Figure 12 shows the probability of acceptance of each ANN for a four-beam MFBA and MCSA, respectively, where γ_0 is set to 16 dB, which implies a 10 dB SINR degradation tolerance to co-channel interference. The results demonstrate that, while the probability of acceptance decreases for both MFBA and MCSA as n, the number of ANNs, increases, the MFBA shows much sharp reduction. For the MFBA, the probability of acceptance reduces as K increases, since more paths of each ANN are likely to yield higher number of collisions and reduced output SINR. On the contrary, for the MCSA, the probability of acceptance slightly increases with K as a result of enhanced output SINR due to the combining gain of multiple coherent SOI paths. The MFBA has a low probability of acceptance even when there are only two ANNs, whereas the MCSA maintains a high probability of acceptance when n ranges from 2 to 4.

Figure 13(a) compares the corresponding NTG, where K is 1 and 2, and the required output SINR threshold is set to γ_0=23 and 16 dB, respectively, in the on-demand protocol case. This figure clearly shows that, as K increases from one to two, the NTG of an MFBA-based network is reduced, whereas the MCSA achieves a higher throughput. For example, when γ_0=23 dB, the maximum NTG of the MCSA in the presence of two paths is 30% higher than that in the case of single path. Fig. 13(a) illustrates that more ANNs results in higher NTG loss once the NTG reaches the corresponding maximum value.

Figure 13(b) compares the corresponding NTG when the priority-based RAS scheme is used. γ_0 is set to 16 dB. While the NTG curves become a non-decreasing function of N for both MFBA and MCSA, the advantage of MCSA

Figure 12. Comparison of the probability of acceptance and NTG for four-beam MFBA and MCSA (p=0.1, γ_0=16 dB)

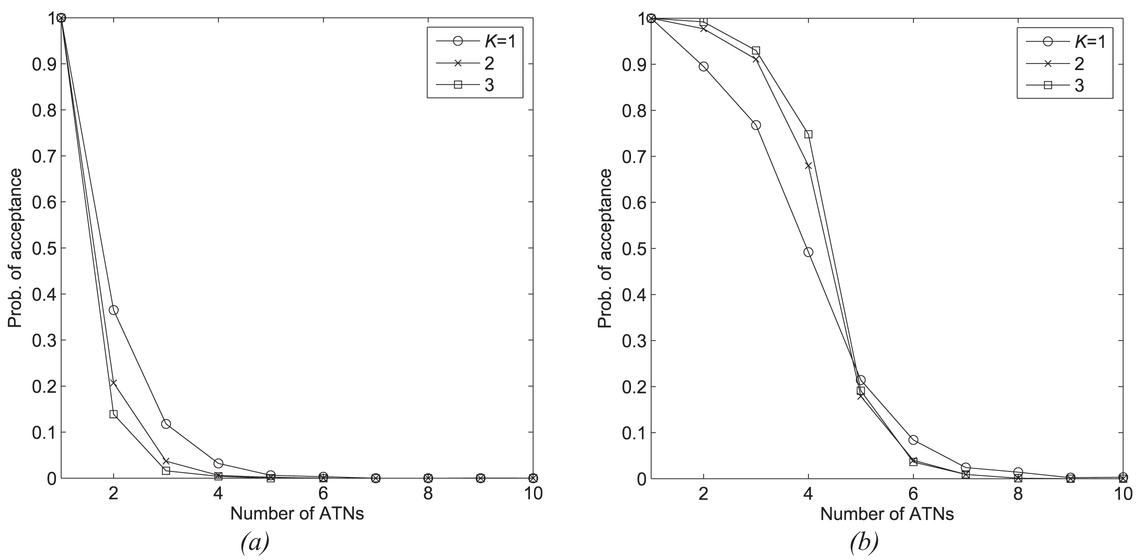
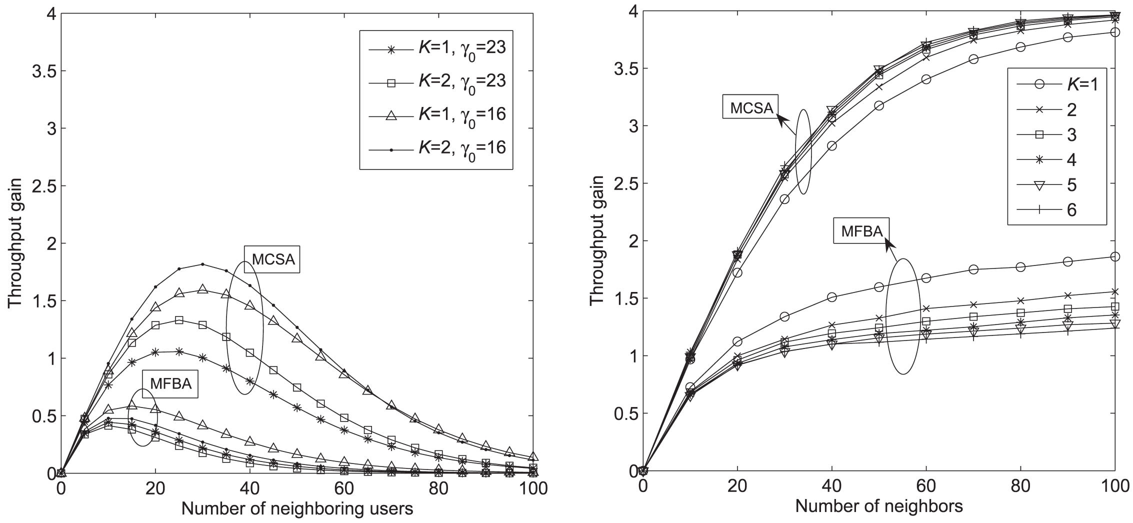


Figure 13. Comparison of the simulated NTG for the MFBA and MCSA operated in a multipath environment where the on-demand protocol and the priority-based RAS schemes are used, respectively



(a) *(b)*

over MFBA is evident. In the former, the NTG approaches 4 for a large value of *N*. The multipath effect reduces the NTG for the MFBA, whereas the MCSA benefits from the multipath propagation.

VII. RELEVANT ISSUES

Having discussed the offerings and performance of MBAs and the impacts of using proper RAS schemes in ad hoc networks, we summarize some relevant issues in this section.

Node synchronization. Concurrent communication with different neighboring users requires more strict constraint on the node synchronization. If all the nodes share the same frequency band in a time-division manner, it is undesirable for a node to transmit and receive simultaneously. As such, time synchronization is an issue not only related to two communicating nodes, but rather involves a group of nodes which are connected through communication links (Jain, 2006b).

Channel estimation. The estimation of the channel state information in the presence of multiple ANNs is another important issue. Blind separation of signals transmitted from multiple nodes has been examined in a wireless network perspective in (Paulraj, 1998). Further, estimation errors in the transmit and receive channels may cause performance degradation. Depending on the channel estimation quality, the use of robust beamforming techniques may prove necessary (Li, 2006).

Beamforming-related issues. When a TN has more degrees-of-freedom than the number of users to be communicated or a user has an urgent need to transfer a high volume of data, the TN can form multiple beams towards certain neighboring nodes to achieve higher diversity or multiplexing gains for enhanced data rate and link reliability (Chen, 2006). The incorporation of opportunistic and individual SINR constraint based beamforming techniques may guide the determination of transmit power over different users to achieve multiuser diversity (Viswanath, 2002; Schubert, 2004).

Neighbor discovery. Unlike conventional mobile ad hoc networks, where each node is equipped with an omnidirectional antenna and does not require directional information of neighboring nodes, node angular positions are maintained in MBAs for effective beamforming and random-access scheduling. Several efforts have been made to support neighbor discovery to locate and track the TN's neighbors (Jakllari, 2005; Zorzi, 2006; Bandyopadhyay, 2006).

Scheduling schemes. When MBAs are employed, more sophisticated MAC and routing mechanisms including power control are necessary so as to exploit spatial reuse and control the amount of interference and collision. Our discussion in this chapter was focused on the space-domain approaches, whereas most current work is involved in the design of frame structures in the time domain (Bandyopadhyay, 2006). Scheduling schemes combining the spatial and time dimensionality may increase the network flexibility and efficiency. Furthermore, cross-layer design is desirable to yield joint physical layer, MAC, and routing optimization (Chen, 2002; Martinez, 2004; Zorzi, 2006).

VIII. CONCLUSION

Multi-beam antenna (MBA) techniques for wireless ad hoc network applications were introduced in this chapter. Two implementations, namely, multiple fixed-beam antennas (MFBAs) and multi-channel smart antennas (MCSAs), were discussed. The performance in terms of the node throughput and the probability of concurrent communications was examined with the exploitation of two random-access scheduling (RAS) schemes incorporated into the contention resolution process, respectively, for the node priority consideration and throughput maximization. Two antenna models were used in the performance analysis. The sector-based model is relatively simple, whereas the output SINR based model provides accurate performance evaluation. In time-varying multipath propagation environments, MFBAs show significant throughput degradation, whereas MCSAs achieve path gain that enhances the output SINR. The impact of using proper RAS in the contention resolution schemes becomes more evident in a multipath propagation environment. Finally, some important issues relevant to the MBAs are addressed for broad understanding of the challenges in this area of research and development.

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