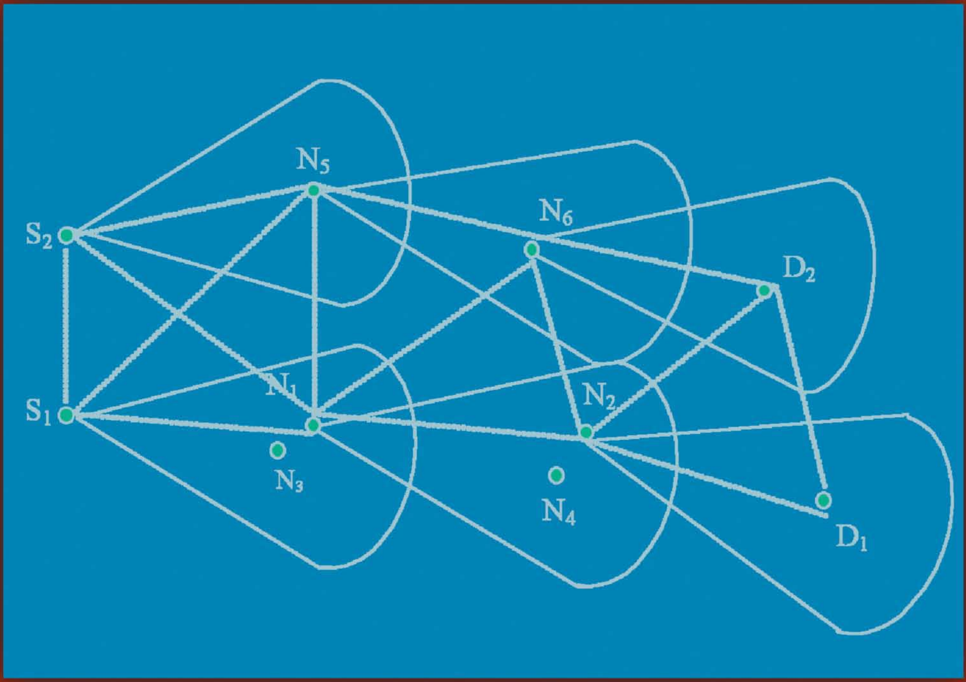
Enhancing the Performance of Ad Hoc Wireless Networks with Smart Antennas



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Preface

A mobile ad hoc network (MANET) is a new paradigm of wireless local area networks that enables instantaneous group communications immediately and easily without the aid of any established infrastructure or centralized administration. Usually, the user terminals in ad hoc networks are equipped with omni-directional antennas. However, ad hoc networks with omni-directional antennas normally use a medium access mechanism that wastes a large portion of the network capacity by reserving the wireless media over a large area. To overcome this problem, researchers have proposed to use directional or adaptive antennas that would largely reduce radio interference, thereby improving the utilization of wireless medium and consequently the network throughput. This book will first present an overview of basic Media Access Control (MAC) and routing protocols in ad hoc networks with omni-directional antennas to discuss the issues and challenges. Subsequently, the book will focus on the use of smart antennas in ad hoc networks and discuss the strategies and techniques to be used in designing MAC and routing protocols for improved medium utilization and improved routing performance with effective load balancing. Finally, it will discuss some of the design issues related to priority-based quality-of-service (QoS) routing protocols with smart antennas to illustrate the potential of these antennas vis-à-vis omni-directional antennas in the context of ad hoc networks. Open problems and challenges for ad hoc networks with smart antennas will conclude the book.

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Tetsuro Ueda received his B.E. degree in electrical and communications engineering and an M.E. degree from Tohoku University and joined NEC Corporation. He has researched channel allocation schemes and worked on the IMT-2000 standardization. He joined KDDI Corporation in 1997 and moved to ATR Adaptive Communications Research Laboratories in 2001. Currently, he is in the YRP Research Center of KDDI R&D Laboratories, Inc. His research interest is wireless ad hoc networks.

Chapter 1

Introduction

1.1 Ad Hoc Networks: A Preamble

Most of the wireless mobile computing applications today require single-hop wireless connectivity to the wired network. This is the traditional cellular network model that supports the current mobile computing needs by installing base stations and access points. In such networks, communications between two mobile hosts rely completely on the wired backbone and the fixed base stations. A mobile host is only one hop away from a base station.

However, at times, no wired backbone infrastructure may be available to support communications among a group of mobile hosts. Also, there might be situations in which setting up fixed access points is not a viable solution due to cost, convenience, and performance considerations. Still, the group of mobile users may need to communicate with each other and share information between them. In such situations, an ad hoc network can be formed.[1,2] An ad hoc network is a temporary network of autonomous nodes that self-organize and self-manage the network without infrastructure support. Nodes in ad hoc networks are computing and communication devices, which can be laptop computers, PDAs, mobile phones, or even sensors. An ad hoc network can be envisioned as a collection of mobile routers, each equipped with a wireless transceiver. The basic assumption in an ad hoc network is that if two nodes willing to communicate are outside the wireless transmission range of each other they may still be able to communicate if other nodes in the network are willing to forward those packets from them. Applications of ad hoc networks include military tactical communication, emergency relief operations, commercial and educational use in remote areas, and in meetings and other situations where the networking is mission oriented or community based.

Usually, the user terminals in ad hoc wireless networks use omni-directional antennas. However, it has been shown that the use of smart directional antennas can largely reduce radio interference, thereby improving the utilization of wireless media and consequently the network throughput.[3–7] Directional antennas have a much higher gain than their omni-directional counterparts, so they significantly reduce the RF power necessary to transmit packets. They can suppress co-channel interference and can therefore enlarge the capacity in terms of node density (more terminals per unit area) in the network. However, in the context of ad hoc networks, it is difficult to find ways to control the direction of such antennas for transmission and the reception in each terminal to achieve an effective multi-hop communication between any source and destination. This difficulty is mainly due to mobility and a lack of centralized control in ad hoc networks. Thus, developing suitable Media Access Control (MAC) and routing protocols in an ad hoc network using directional antennas is a challenging task.

1.2 Characteristics of Ad Hoc Networks

Ad hoc networks have several salient characteristics:[8]

- Infrastructureless, decentralized operation: Usually, ad hoc networks do not rely on any kind of infrastructure support for routing, network management, etc. In other words, ad hoc networks are basically self-organizing and self-managing networks. The lack of centralized control in ad hoc networks requires more sophisticated distributed algorithms to perform all network-related functions.
- Mobility: Mobility causes frequent change in network topology when new nodes join in, some nodes leave or some links break down.
- Multi-hop routing: A node may want to connect to a distant node that is out of its transmission range. Because each node in ad hoc networks can route traffic for the others, multi-hopping

is possible. Multi-hopping is a desirable capability in an ad hoc network because a single-hop ad hoc network does not scale large, thus limiting the communications among the nodes.

- Power-constrained operation: Because nodes can be mobile, they have to rely on battery power, which is a limited resource.
- Heterogeneity: Each node may have different capabilities. In some cases, to be able to connect to an infrastructure-based network (to form a hybrid network), some nodes can communicate with more than one type of network.
- Link asymmetry: In a wireless environment, communication between two nodes may not work equally well in both directions. In other words, even if node n is within the transmission range of node m, the reverse may not be true.
- Bandwidth-constrained, variable capacity links: Wireless links will continue to have significantly lower capacity than their hardwired counterparts. In addition, the realized throughput of wireless communications is often much less than a radio's maximum transmission rate because of the effects of multiple access, fading, noise, and interference conditions, etc. One effect of the relatively low to moderate link capacities is that congestion is typically the norm rather than the exception.

1.3 Some Prospective Usages of Ad Hoc Networks

An ad hoc network complements an infrastructure-based network where infrastructure is not available. Network infrastructure may not be available or viable everywhere, mainly for the following reasons:

- Traffic demand and the forecasted revenue are too low.
- Traffic demand is inconsistent with time (i.e., only existent for a short term).
- It is too costly to build a network infrastructure due to geographical or terrestrial difficulty (e.g., to provide coverage on a highway, in a forest, in remote locations, etc.).

In these cases an ad hoc network can serve as an extension to the network reach. It addresses the need of transporting unplanned or unexpected traffic that is impermanent, or simply, ad hoc based.

The following are some examples where ad hoc networks can be formed without the help of any centralized infrastructural support:

- Community networks are formed in college campuses, city blocks, neighborhoods, and conferences, etc., satisfying intra-community communication needs.[9] A user can be accepted into the network on the spot easily. Community networking allows the formation of local communities (who chat and use a shared whiteboard or who travel in groups) for resource sharing. Community networks tend to be deployed in a very ad hoc manner, wherever resources such as wired Internet access and antenna/radio mounting locations happen to be available. The client node may connect directly to an access point (AP) or use ad hoc routing to leverage other nodes to connect to an AP.
- Enterprise networks are built within corporate environments as low-cost and easy-to-install methods to facilitate the mobility of workers. For example, during a meeting or conference presenters can multicast slides and audio to intended recipients. Wireless multi-hop technology may exist between WLAN APs or between client nodes, or a hybrid ad hoc network can be formed between a WLAN AP network and a client ad hoc network. This is to accommodate the changes caused by human mobility and to allow easy expansion and reconfiguration of network topology (e.g., caused by growth of enterprise staff or indoor renovation).
- Sensor networks[10] can be one of the following: a military sensor network to detect the enemy's movement or chemical/biological weapon detection, an environmental sensing network, a traffic sensor network to monitor traffic congestion in a city, or a surveillance network.
- Emergency response networks can be used for search-and-rescue operations, law enforcement, and disaster relief efforts. As an example of a search-and-rescue operation, each firefighter can carry a communication radio that forms an ad hoc network on site. Also, "breadcrumb routers" can provide connectivity as the firefighters enter the building on fire. As for law enforcement, an ad hoc network can immediately be formed among the patrol cars and handheld radios of police officers at the incident site. Supporting personnel, who later join in, can immediately connect to the ad hoc network that is already formed. In disaster relief operations, ad hoc networks can replace the damaged infrastructure-based network. The ad hoc network addresses the need of immediately deploying a network with high data connectivity on scene.

- Vehicle networks are formed among moving vehicles and land transportation infrastructure (e.g., traffic lights and electronic road signs) and can divert traffic away from congested areas, thus ensuring smooth traffic flow. Intervehicular communication using ad hoc networking is suitable on highways where there is very limited network coverage.[11]

1.4 Some Research Challenges

1.4.1 Use of Smart Antennas in Ad Hoc Networks

There are basically two types of smart antennas used in the context of wireless networks: switched-beam (or fixed-beam antennas) and steerable adaptive array antennas.[12–14] A switched-beam antenna generates multiple predefined fixed directional beam patterns and applies one at a time when receiving a signal. It is the simplest technique and comprises only a basic switching function between separate directive antennas or predefined beams of an array of N antenna elements which are deployed into non-overlapping fixed sectors, each spanning an angle of $360/N$ degrees. Signals will be sensed in all sectors and the antenna is capable of recognizing the sector with the maximum gain. When receiving, exactly one sector, which usually is the one chosen by the sensing process, will collect the signals.

In a steerable adaptive array antenna, which is more advanced than a switched-beam antenna, the beam structure adapts to the radio frequency (RF) signal environment and directs beams toward the signal of interest to maximize the antenna gain, simultaneously depressing the antenna pattern (by setting nulls) in the direction of the interferers.[13] In adaptive array antennas, an algorithm is needed to control the output, i.e., to maximize the signal to interference and noise ratio (SINR). The difference between both kinds of smart antennas is as follows: fixed-beam antennas focus their smartness in the strongest strength signal beam detection, and adaptive array antennas benefit from all the received information within all antenna elements to optimize the output SINR through a weight vector adjustment.

Sundaresan and Sivakumar[15] discussed that superior transmission, reception, and interference suppression capabilities of smart antennas have inspired the consideration of their use in wireless ad hoc networks that are inherently interference limited. However, the capabilities of the antennas can be effectively leveraged only through appropriate changes to higher layer network protocols. Hence, in recent years, several researchers have investigated the following question: What changes need to be made at the MAC layer and above to leverage the unique capabilities of smart antenna technologies?[3,5–7,16–18]

1.4.2 Media Access Control

There are two types of Media Access Control: random or controlled. In random access, all stations compete for a channel in an uncontrolled way (which suits the ad hoc network scenario) and thus collision cannot be avoided. In controlled access, the competition for a channel is controlled (in most cases by a master node) and thus collision can be avoided. Random access suffers from both hidden and exposed terminal problems. The current solution to the hidden terminal problem is to use virtual carrier sensing, which consists of two additional control frames, request to send (RTS) and clear to send (CTS). A terminal that wishes to transmit first sends out an RTS packet. When a destination replies with CTS, all the terminals within its transmission range receive this message and thus the problem of a hidden terminal can be alleviated. The problem with virtual carrier sensing is that many nodes in the vicinity are blocked, and by extending the area in which carrier sensing is effective, although the hidden terminal phenomenon is diminished, the exposed terminal phenomenon increases. One of the solutions to alleviate this problem is to use directional antennas.[4,5,19] This will be discussed in detail in Chapter 2.

1.4.3 Routing

Routing is one of the most important aspects in ad hoc networks because ad hoc network topology frequently changes and multi-hop communication is required. There are two types of routing protocols: proactive and reactive.[1,20–22] Proactive routing protocols are table driven where every node keeps a table of routing information of all the nodes it knows. The routing information is updated periodically. Reactive routing protocols are on demand basis where a route is only formed upon request. Utilizing proactive routing protocols basically gives shorter end-to-end delays because route information is always available and up-to-date as compared to reactive ones. However, the disadvantage is that it consumes more resources (more overhead) in updating the route information. Researchers are now trying to find out the optimal balance between proactive and reactive protocol mechanisms and working on power-aware routing and scalable routing so that routing protocols can still perform under heavy traffic or large numbers of nodes. Provisioning quality of service (QoS) is also being considered as a challenging issue in ad hoc routing. To make an optimal routing decision, QoS routing requires constant updates on link state information such as delay, bandwidth, cost, loss rate, and error rate to make policy decisions, resulting in a large amount of control overhead. This can be prohibitive for bandwidth-constrained ad hoc environments. In addition, the dynamic nature of ad hoc networks makes it extremely difficult to maintain the precise link state information. Finally, even after resource reservation, QoS still cannot be guaranteed due to the frequent disconnections and topology changes. The routing issues and different proposals for routing in ad hoc networks are discussed in detail in Chapter 2.

1.4.4 Power Conservation

Power is a precious resource in mobile devices and networking is one of the most energy-consuming operations. According to an experiment conducted by Kravets and Krishnan,[23] power consumption caused by networking-related activities is approximately 10 percent of the overall power consumption of a laptop computer. This figure rises to 50 percent in handheld devices. The aim of saving power in an infrastructure-based network is to minimize energy consumption in the hosts or nodes. The tactic is to move the communication and computation efforts to the fixed infrastructure, thus keeping the network interface of the devices in sleep state as long as possible. In an ad hoc network every node has to contribute to maintain the network connections. Hence the aim of minimizing the energy consumption of each node is inadequate. An additional aim is to maximize network lifetime. There are two scenarios with regards to energy in ad hoc networks: (1) energy is an expensive, but not a limited resource (batteries can be recharged or replaced easily) and (2) energy is limited, or finite.

The first scenario occurs mostly in community networks and enterprise networks. Thus the objective of the networks belonging to this scenario is to minimize the total energy consumed per packet to forward it from source to destination, without considering the residual energy of individual node. The scenario of finite energy is true in sensor networks. The objective is thus to maximize network lifetime besides conserving energy for individual nodes. Residual energy of individual nodes thus needs to be considered.

1.4.5 Security

Several characteristics of an ad hoc network make it much more difficult to keep its security as compared to the infrastructure-based network:

- Channel vulnerability — broadcast wireless channels allow message eavesdropping and injection easily.
- Node vulnerability — when nodes do not reside in physically protected places, they easily fall under attack.
- Absence of infrastructure — certification/authentication authorities are absent.
- Dynamically changing network topology — this puts security of routing protocols under threat.
- Power and computational limitations — these can prevent the use of complex encryption algorithms.[24]

1.5 Performance Evaluation Techniques

Two approaches can be taken to evaluate the performance of ad hoc networks: by taking measurements from real systems or via modeling and computer simulations.

For the first method, a testbed has to be constructed. The advantage of a testbed is that it is able to reveal problems that cannot be detected by modeling, for example, the communication gray zones problem that has been discovered in AODV implementation.[25] The problem is caused by different transmission ranges for IEEE 802.11b control and data frames, which has been assumed the same in network simulators like NS-2. The disadvantage is that the construction of a testbed is expensive. Moreover, some parameters are difficult to investigate on a real system (e.g., protocol scalability and sensitivity to users' mobility patterns and speeds). Most of the time, measurement results are hardly repeatable. Also a testbed cannot scale to a different size. One of the largest testbeds, the Uppsala University APE testbed, only includes 37 laptop computers in its experiment.[25]

Modeling, on the other hand, makes the study of the network system behavior easy by simply varying the system parameters. Moreover, a large spectrum of network scenarios can be considered. Its disadvantage is associated to its failure to reveal some problems encountered in real implementation. There are two types of modeling: analytical or simulation. Analytical modeling is useful, especially in the study of network or protocol scalability. Simulation studies of scalability