Multiple Access Protocols with Smart Antennas in Multihop Ad Hoc Rural-Area Networks

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Abstract

Multihop ad hoc networking is a very appealing technology for the deployment of wireless data networks. It eliminates the need for network planning and the reliance on fixed infrastructure. Multihop ad hoc networks are designed with a self-configuring capability and are able to adapt to the addition or removal of network radio units (nodes). This capability makes them simple to install, allowing unskilled users to quickly set up the network. These characteristics make multihop ad hoc networks very attractive for both civilian and military applications, e.g. in rescue operations.

The type of multihop ad hoc networks studied in this thesis consist of identical nodes using the same frequency band for transmission. To control the Multiple Access Interference produced by sharing the same radio channel, a Medium Access Control (MAC) protocol must be used. Much work has been done in the MAC protocols area but the work has concentrated on generic nodes, whereas this thesis considers nodes with smart antennas, an enhanced capability. To fully exploit the additional capability the design of the MAC protocol needs to be considered. Hence, the results of a system level study into MAC protocols and smart antennas is presented in this thesis.

Two different MAC protocols were examined, Spatial Time Division Multiple Access (STDMA) which shows much potential in multihop ad hoc networks and Carrier Sense Multiple Access Collision Avoidance (CSMA/CA) with handshaking which currently has much popularity as a result of its adoption in the IEEE 802.11 standard. STDMA is a conflict-free MAC protocol where links or nodes are scheduled to transmit in periodical slots making the integration of smart antennas relatively simple. Routing was found to be critical when utilizing smart antennas and a new procedure to create the link schedule is presented. In addition, it is shown that the terrain roughness influence the network connectivity. However, for the same network connectivity similar performance was obtained independently of the terrain roughness.

Although STDMA has been found to be efficient and fair, the drawback is that it does not offer a quick response to peak rates for bursty data traffic. CSMA/CA with handshaking protocol provides a quick response to bursty traffic. The handshaking procedure within this MAC allows the use of smart antennas at both the transmitter and the receiver. How to effectively use smart
antennas in CSMA/CA with handshaking is one of the key issues in the thesis. Different beam selection policies using switch beam antenna systems were therefore investigated. It was discovered that the policy called Di-RTS was the best in all the studied sample networks.

It is likely that multihop ad hoc networks with smart antennas will be used in many applications and the results of this thesis will be of considerable assistance to system designers.
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<th>Abbreviation</th>
<th>Description</th>
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<tr>
<td>BFA</td>
<td>Beam Forming Antenna</td>
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<tr>
<td>BER</td>
<td>Bit Error Rate</td>
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<td>BFN</td>
<td>Beamforming Network</td>
</tr>
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<td>BPSK</td>
<td>Binary Phase Shift Keying</td>
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<td>BTMA</td>
<td>Busy Tone Multiple Access</td>
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<td>BW</td>
<td>Antenna beamwidth</td>
</tr>
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<td>CDMA</td>
<td>Code Division Multiple Access</td>
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<tr>
<td>CS</td>
<td>Carrier Sense</td>
</tr>
<tr>
<td>CSMA</td>
<td>Carrier Sense Multiple Access</td>
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<tr>
<td>CSMA/CA</td>
<td>Carrier Sense Multiple Access/Collision Avoidance</td>
</tr>
<tr>
<td>CTS</td>
<td>Clear-To-Send</td>
</tr>
<tr>
<td>DBTMA</td>
<td>Dual Busy Tone Multiple Access</td>
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<td>DSP</td>
<td>Digital Signal Processing</td>
</tr>
<tr>
<td>FAMA</td>
<td>Floor Acquisition Multiple Access</td>
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<tr>
<td>FBN</td>
<td>Fixed Beamforming Network</td>
</tr>
<tr>
<td>FDMA</td>
<td>Frequency Division Multiple Access</td>
</tr>
<tr>
<td>FIFO</td>
<td>First In First Out</td>
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<tr>
<td>ISM</td>
<td>Industrial, Scientific, Medical band</td>
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<tr>
<td>LAN</td>
<td>Local Area Network</td>
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<tr>
<td>LES</td>
<td>Linear Equally Spaced</td>
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<tr>
<td>MAC</td>
<td>Medium Access Control</td>
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<tr>
<td>MACA</td>
<td>Multiple Access Collision Avoidance</td>
</tr>
<tr>
<td>MACAW</td>
<td>Multiple Access, Collision Avoidance for Wireless</td>
</tr>
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<td>MAI</td>
<td>Multiple Access Interference</td>
</tr>
<tr>
<td>MHA</td>
<td>Minimum Hop Algorithm</td>
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<tr>
<td>PAN</td>
<td>Personal Area Networking</td>
</tr>
<tr>
<td>QoS</td>
<td>Quality of Service</td>
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<tr>
<td>RA-MHA</td>
<td>Reuse Adaptive Minimum Hop Algorithm</td>
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<tr>
<td>RF</td>
<td>Radio Frequency</td>
</tr>
<tr>
<td>RTS</td>
<td>Request-To-Send</td>
</tr>
<tr>
<td>Abbreviation</td>
<td>Full Form</td>
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<tr>
<td>SDMA</td>
<td>Spatial Division Multiple Access</td>
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<tr>
<td>SFIR</td>
<td>Spatial Filtering for Interference Reduction</td>
</tr>
<tr>
<td>SIR</td>
<td>Signal-to-Interference Ratio</td>
</tr>
<tr>
<td>SINR</td>
<td>Signal-to-Interference plus Noise Ratio</td>
</tr>
<tr>
<td>SNR</td>
<td>Signal-to-Noise Ratio</td>
</tr>
<tr>
<td>STDMA</td>
<td>Spatial Time Division Multiple Access</td>
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<tr>
<td>TCS</td>
<td>Traffic Controlled Schedule</td>
</tr>
<tr>
<td>TDMA</td>
<td>Time Division Multiple Access</td>
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<tr>
<td>WLAN</td>
<td>Wireless Local Area Network</td>
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List of Notations

\( A_i(\cdot) \)  Antenna pattern used by node \( i \).
\( A_{\text{max}} \)  Antenna gain.
\( A_{\text{RTS}} \)  RTS reception area.
\( a_{sl} \)  Antenna side lobe attenuation.
\( B \)  Effective noise bandwidth.
\( C_{ij} \)  Capacity of link \((i, j)\).
\( C \)  Network capacity Matrix.
\( d_{ij} \)  Distance between node \( i \) and node \( j \).
\( d_{\text{cap}} \)  Capture range.
\( d_{cs} \)  Maximum range of carrier sensing.
\( d_{\text{RTS}} \)  Maximum range of error free reception of RTS.
\( D_{ij} \)  Packet delay over link \((i, j)\).
\( E[\cdot] \)  Statistical expectation.
\( F_{\text{sys}} \)  Receiver noise figure.
\( i \)  Node identification number.
\( (i, j) \)  Unidirectional link from node \( i \) to node \( j \).
\( k \)  Boltzmanns constant \((k = 1.38 \cdot 10^{-23})\).
\( (S, D) \)  Packet from source \( S \) to destination \( D \).
\( G_{ij} \)  Path gain on link \((i, j)\).
\( G \)  Path gain matrix.
\( h_{ij} \)  Number of hops from node \( i \) to node \( j \).
\( L_{ij} \)  Radio propagation path loss on link \((i, j)\).
\( L_{\text{max}} \)  Maximum propagation path loss for connectivity.
\( L_n \)  Set of links assigned to transmit during slot \( n \).
\( M \)  Number of antenna elements.
\( N \)  Number of nodes that form a particular network.
\( N_f \)  Schedules’s period.
\( n_{ij} \)  Number of slots assigned to link \((i, j)\).
\( N_i \)  Number of neighbors to node \( i \).
\( P_i \)  Transmission power level used by node \( i \).
\( P_{ij} \)  Received power level at node \( j \) from node \( i \)’s transmission.
List of Notations

\( P_{\text{Noise}} \)  Background noise power level at the receiver.
\( P_{\text{omni}} \)  Transmission power with omnidirectional antenna.
\( P_{Th} \)  Carrier detection power level threshold.
\( r \)  Routing table.
\( s \)  Antenna selected sector.
\( S \)  Time schedule.
\( T_0 \)  Reference temperature \((T_0 = 290\text{K})\).
\( T_{ij} \)  Relative traffic load on link \((i,j)\).
\( T \)  Relative Traffic Load matrix.
\( \alpha \)  Path loss exponent.
\( \alpha_i \)  Array phase shifter \(i\).
\( \Gamma_{ij} \)  Signal-to-Interference plus Noise Ratio for a packet transmitted from node \(i\) to node \(j\).
\( \gamma_0 \)  Minimum SINR required for correct reception.
\( \gamma_{cs} \)  SNR for carrier sensing.
\( \lambda \)  Average total external traffic load.
\( \Lambda_i \)  Average external traffic load on node \(i\).
\( \lambda_{ij} \)  Average traffic load through link \((i,j)\).
\( \lambda^* \)  Maximum End-to-end throughput.
\( \lambda^*_{ij} \)  Maximum throughput for link \((i,j)\).
\( \rho \)  Terrain smoothness parameter.
\( \sigma \)  Terrain height standard deviation.
\( \theta_{ij} \)  Angle to node \(j\) as seen from node \(i\).
\( \phi_h \)  Horizontal antenna beamwidth.
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Chapter 1

Introduction

The development and success of mobile computing devices such as laptops and personal Digital Assistants (PDAs), and their continuous cost and size reduction has made the design of wireless data communication networks increasingly important. One significant factor that is changing the traditional way of designing wireless technologies is the availability of deregulated spectrum e.g. the Industrial, Scientific, Medical (ISM) frequency band. Deregulated frequency bands can be utilized by users to deploy their own wireless data network. Users of this band are only permitted to transmit with very low powers. This leads to a compromise between having either a high data rate or a large range. The use of multi-hopping offers the possibility to extend the range while still maintaining a high data rate. In addition to this, the success of wireless technologies and services will be greatly influenced by cost and the simplicity of setting up the network. Hence, self-configuring networks are desirable since they are cheap to deploy because they do not need the intervention of skilled users. Together these factors make the study of multihop ad hoc networks very interesting.

In this thesis, the term *ad hoc* is used to indicate that the network is self-configuring and setup without needing any central administration. The network is composed by mobile, nomadic, or static communicating radio units (nodes) that send data packets via the wireless medium. The term *multihop* is used to indicate that the information is conveyed through the network using data packets that may be forwarded through a number of nodes between their *source* and *destination*. Fig. 1.1 illustrate a typical *multihop ad hoc* scenario. In this case for instance, communication between node 3 and node 5 is enable using nodes 2 and 4 as relying nodes.

*Multihop ad hoc* networks were formerly known as Multihop Packet Radio Networks (MHPRN) having its origins in the early 1970s with the establishment of the ALOHA network in Hawaii. Driven by the technological advances in personal computing there has been a surge of renewed interest in *Ad hoc* networks within the last few years [[1], pages 1-14] due mainly to three potential benefits:
Chapter 1. Introduction

Figure 1.1: Example illustrating the Multihop scenario. Here node 3 can communicate with node 5 using nodes 2 and then 4 as relaying nodes.

- **Radio range extension**
  The radio range of a terminal that may be limited by poor radio propagation conditions is effectively extended to the full range of the network.

- **Power Saving**
  Less total transmit power is needed in conveying the data. Power saving is of paramount importance for portable devices that are usually powered by batteries.

- **Self-configuring**
  The network is designed with the capability to adapt to the addition or removal of network nodes.

The addition or removal of network nodes is a feature which is critical for instance in military and emergency applications. In fact, one of the original motivations for multihop ad hoc Networks comes from the military need for battlefield survivability [[1], Chapter 2], i.e. to survive in the battle field a wireless communication system is needed to coordinate distributed group actions without relying upon any centralized administration which could be the first target for the enemy.

In the civilian arena, there are many other potential applications of multihop ad hoc networks including Wireless LAN (WLAN), home networking, and personal area networking (PAN) [2]. Another important application can be found in developing countries where long distances, difficult terrain, and poverty limit the availability of land-base communication infrastructure. The deployment of multihop ad hoc rural-area networks could provide a cost-effective solution to their needs.

The main constraint set by civilian applications is to provide low cost for both terminals and services. Base on this constraint, the type of multihop ad hoc network considered in this thesis assumes half-duplex transmission over a common frequency band for the whole network. The results are based but not limited to the rural scenario (results can be extended to e.g. indoor wireless local area networks).
In the rural scenario, due to low user densities, nodes may be distributed over a wide geographical area of irregular terrain limiting mobility. Propagation losses may limit the direct radio range of a node. However, due to the routing functionality added to each node, the range can be extended. A message may travel long distances by means of forwarding through a number of nodes between the source and destination. This means that each node must perform critical network topology functions that in wired networks (e.g., the Internet) are proper functions of routers. The addition, removal of nodes, or link failures can create topological changes that require routing updates as part of the self-configuring and self-healing capability of a node. This problem is exacerbated in networks with high mobility (like in urban and suburban environments) and is currently the subject of much research [3].

An additional problem is created by access to the shared radio channel. Transmitting in the shared wireless channel results in multiple nodes receiving the information that may be destined to a single node, and in turn, multiple transmission may result in mutually interfering at a given node. In a multihop ad hoc network, simultaneous transmission over the same channel is commonly referred as packet "collision"[4]. Since nodes could be spread over a large area, packets involved in a collision may survive provided that the Signal-to-Interference Ratio (SIR) at the receiver site is high enough for the reception with allowable or correctable errors. However, since a node can receive from only one of its neighbors (nodes within its radio range) the packet that survives is not always the desired one. When using half-duplex transceivers, another important problem and limiting factor comes from the fact that a node cannot receive and transmit at the same time. In order to deal with these problems a Medium Access Control (MAC) protocol must be used at the bottom level of the link layer. The link layer guarantees a virtual point-to-point error-free packet link to higher layers [[5], page 24].

## 1.1 Medium Access Control protocols

The medium Access protocol moderates access to the shared radio channel by defining a set of rules that allows nodes to communicate to each other in a relatively efficient manner. Wireless MAC protocols have been studied intensively since the 1970s and there exist different ways to classify them including if they are distributed or centralized [6]. Our classification is presented in Fig.1.2 as conflict-free MAC protocols (Centralized, Scheduled) or contention MAC protocols (Random, Distributed) [7]. The main different between these two categories is that in contention MAC protocols a transmitted packet from a node is not guaranteed to be successfully received.

In contention MAC protocols nodes compete for access to the channel. When only one node makes a transmission attempt the packet is received successfully.

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1. Multuser detection enables simultaneous reception but it is out of the scope of the thesis.
When multiple nodes transmit simultaneously a collision results and a contention resolution algorithm is used to try and resolve the conflict. This resolution process does consume resources but for bursty traffic the small loss of resources is usually worthwhile when compared to conflict-free MAC protocols [7], page 4. Within contention MAC protocols we can find the first MAC protocol proposed for packet radio networks called ALOHA [6, 8]. ALOHA is the simplest contention MAC protocol where a node transmits randomly without verifying if the channel is either idle or busy. Due to this completely uncoordinated functionality packet collisions on the channel may occur frequently under moderate traffic loads resulting in relative poor channel utilization. An improved version of ALOHA is called Slotted-ALOHA where the time space is divided into slots and nodes randomly decide whether to transmit or not during each slot. By this mechanism the vulnerability period of a packet to be successfully received is reduced to a single slot doubling the capacity respect to ALOHA [8]. An attempt to avoid collisions by listening to the channel to detect other users’ transmissions is done with Carrier Sense Multiple Access (CSMA) [9], by this way a local estimation of the Multiple Access Interference is done resulting in increased channel utilization compared to Slotted ALOHA, provided that all nodes are able to detect other nodes transmissions. However, the performance of CSMA starts to degrade in multihop ad hoc due to the hidden terminal problem, i.e. the lack of a node of hearing all other nodes in the network. A possible solution for this problem was presented by by Kleinrock and Tobagi in [10] where the receiving node broadcasts (on a different channel) a tone to indicate to its neighbors that
the channel is busy, thus potentially improving the performance with respect to CSMA in multihop ad hoc networks; this MAC protocol was denominated the Busy Tone Multiple Access (BTMA). In order to provide a solution to the hidden terminal problem without the need of a separate channel, Carrier Sense Multiple Access Collision Avoidance (CSMA/CA) with handshaking has been proposed. In CSMA/CA with handshaking the data transmission is preceded by transmitting a short Request-To-Send (RTS) packet to the intended receiver which in turn answers with a short Clear-To-Send (CTS) packet if the channel is idle at the receiver site. This procedure reduces the probability of collision but does not eliminate them. CSMA/CA with handshaking is studied in chapter 4. Several variants of CSMA/CA with handshaking can be found in the literature, the most relevant are MACA [11], IEEE802.11 [12], FAMA [13, 14], and MACAW [15, 16]. However, most of these studies do not address the rural multihop scenario because wireless LAN has been the main focus. In indoor propagation environment walls may produce high attenuation. Hence, graph based simulations have commonly been used where as SIR based methods more accurately model the radio channel, especially in the rural environment.

On the other hand, conflict-free MAC protocols are those ensuring that a transmission, whenever made, is successful one, that is, will not be impaired by another transmission. Conflict-free transmission can be achieved by allocating the channel to the user either statically or dynamically. MAC protocols within this category are:

- **Time Division Multiple Access (TDMA)**
  Interference is controlled by separating transmission in time. The time axis is divided into time intervals of equal length called *slots* or time slots and each node receives its own time slot.

- **Frequency Division Multiple Access (FDMA)**
  The radio spectrum is divided into orthogonal channels. Each node is assigned a unique frequency channel to transmit.

- **Code Division Multiple Access (CDMA)**
  Reduction of interference is performed by the use of a unique spreading code assigned to a node for transmission.

In order to take advantage of the spatial separation that may exist between nodes in large networks and increase efficiency by spatial reuse of time slots in TDMA, Spatial Time Division Multiple Access has been proposed in [17] and it is studied in chapter 3. Spatial Time Division Multiple Access is a MAC protocol where conflicts are avoided by assigning node transmissions into a repetitive pattern of slots of finite length called *schedule*. The design of STDMA scheduled has received some attention in the literature in multihop scenarios. Short (low delay) link schedules adapted to the traffic pattern have been discussed in [18–20]. Distributed implementation has also been an important subject [21]. Most early contributions in the field describe the network as a binary graph, i.e. two
nodes are either connected and able to communicate reliably, or disconnected and not even able to disturb the transmissions of one another. Schedules were base on pair-wise link compatibility. Relaxation of this assumption has be investigated in [19, 20, 22]. In reference [19] by Somarriba and [22] by Grönkvist, schedules for multihop ad hoc networks in actual (or simulated) terrains were studied. The investigations in [19] show that the character of the terrain has significant impact on the performance (in terms of delay and network capacity) of these networks. Rough (mountainous) terrain makes it more difficult to achieve a fully connected network, but when this is achieved, it has the advantage of "shielding" the nodes from interference yielding more efficient STDMA schedules.

Although much work has been done in MAC protocols area, it is possible to improve performance with the use of smart antennas. The use of smart antennas within multihop ad hoc networks will increase cost but promises to significantly increase throughput. The effective use of smart antennas is integrally linked to the MAC protocol, therefore a combined study is carried out in this thesis.

1.2 Smart Antennas Overview

Smart antennas can be used in multihop ad hoc networks to improve the system performance [23, 24] but its effectiveness is closely linked with the MAC protocol utilized. As illustrated in Fig. 1.3, a smart antenna consists of several antenna elements (array) whose signals are processed adaptively by a combining network. Here, the signals received at the different antenna elements are multiplied with complex weights and then summed to create a steerable radiation pattern.

Smart antennas systems can include adaptive antennas and switched beam antenna systems. An adaptive antenna is able to change its antenna pattern dynamically to adjust to noise, interference, and multipath [25, page 8]. On the

![Figure 1.3: Smart antenna with Linear Equally Space (LES) antenna array.](image-url)
1.2. Smart Antennas Overview

other hand, the switch beam antenna system uses a number of fixed beams at an antenna site. The receiver (or transmitter) selects the beam that provides the greatest signal enhancement and interference reduction. Switch beam antenna systems use a linear RF network, called a Fixed Beamforming Network (FBN), that combines \( M \) antenna elements to form up to \( M \) directional beams \cite[page 91]{25} as illustrated in Fig. 1.4. As stated in \cite[page 9]{25}, "Switched beam systems may not offer the degree of performance improvement offered by adaptive systems, but they are often much less complex and are easier to retrofit to existing wireless technologies".

When considering the use of directional antennas in multihop ad hoc networks the MAC protocol is a fundamental parameter. Such networks with contention MAC protocols have been explored by several researchers \cite{23,26–28}. Zanders \cite{23} studied the performance improvement by the use of steerable directional antennas in multihop slotted ALOHA systems. Variants of BTMA with smart antennas has been also investigated in \cite{26} resulting in significant throughput and delay reduction with respect to BTMA. More recent work \cite{27} proposes the use of CSMA/CA with handshaking and multiple directional antennas with one receiver for each beam. A modified MAC scheme was proposed resulting in small throughput improvement despite the large increase in receiver complexity.

How to use a simple switched beam antenna systems and CSMA/CA with handshaking in multihop ad hoc networks has not been adequately addressed. It is expected that smart antennas will improve capacity by increasing the number of simultaneous transmission. However, due to the protocol complexity and
the multihop ad hoc network functionality, how to "best" adapt the antenna radiation pattern is not obvious.

Furthermore, the application of adaptive beam forming antennas to STDMA in multihop ad hoc had not been addressed. The author found that substantial gains, over the omnidirectional case, could be obtained by using simple steerable antennas [24]. How to improve performance in this case warrants further investigation.

The used of more complex adaptive antennas systems and STDMA in multihop ad hoc networks has been investigated and the results show that the performance can be outstanding [29]. This work postdates the work on STDMA in this thesis.

1.2.1 Main Contributions of the Thesis

The main contribution of this thesis are:

- A combined routing and scheduling procedure that improves performance of STDMA in multihop ad hoc networks with smart antennas.

- Investigation and evaluation of possible performance gain from using smart antennas in Spatial Time Division Multiple Access. These results cover both rough and flat terrain.

- Investigation and evaluation of possible performance gain from using simple Switch Beam antennas systems as the smart antenna technology with Carrier Sense Multiple Access with handshaking. Four different Beam selection Policies were evaluated.

1.3 Thesis Outline

This thesis is written as a monograph composed by five chapters and appendixes. In chapter 2 the system models and performance evaluation are described. In chapter 3 the analysis and performance evaluation for Spatial Time Division Multiple Access using adaptive beamforming antennas systems is presented. CSMA/CA with RTS and CTS handshaking and switch beam antenna systems is studied in chapter 4. The conclusions of the thesis are presented in chapter 5.
Chapter 2

System Models

In this chapter the model used for performance evaluation of multihop ad hoc networks in this thesis is introduced. Selection of the models is done to provide a reasonable level of abstraction of the way that the real system operates while at the same time producing easy to analyze results. The physical and link layer operation is modelled through the link quality model and the MAI is influenced by the terrain, MAC protocol, and the type of smart antenna system utilized. Additionally, the information source attached to a node is analyzed through the traffic model and routing as part of the upper layer functionality. The definition of the performance measures employed are also presented in this chapter.

2.1 Link Quality Model

We will refer to the collection of \( N \) nodes that form a particular network by an uppercase case letter (e.g. Network A). A particular node in the network is uniquely identified by its numerical number \( i, (i = 1 \ldots N) \). It is assumed that the network is composed of identical nodes meaning that all nodes in the network have the same capability and that the only way to communicate between nodes is through the wireless medium using a single frequency band.

2.1.1 Received Power

We represent the received power level on link \((i, j)\) by \( P_{ij} \), resulting from node \( i \)'s transmissions with power level \( P_i \) at node \( j \); \( \forall \) node \( j \neq i \). The radio propagation properties of the terrain where the network is deployed are captured by the radio propagation losses. We represent the path losses on link \((i, j)\) by \( L_{ij} \). The inverse of this quantity is commonly referred as the link path gain, \( G_{ij} = 1/L_{ij} \), and constitute the elements of the path gain matrix, \( G \). Hence, \( P_{ij} \) is given by

\[
P_{ij} = \frac{P_i A_i(\theta_{ij}) A_j(\theta_{ji})}{L_{ij}} = P_i G_{ij} A_i(\theta_{ij}) A_j(\theta_{ji}).
\]

(2.1)
$A_i(\cdot)$ denotes the (horizontal) antenna patterns used by node $i$, and $\theta_{ij}$ denotes the angle to node $j$ as seen from node $i$.

To generate easily analyzed results the simple distance dependent propagation model is used. In addition, influence of the terrain irregularity (e.g. mountains) is evaluated using artificial terrains to recreate a more realistic scenario. The terrain model is a modification to the one used in [30] and it is described in Appendix C. In this case, the path gains are then computed according to [31] whereby the radio propagation loss is split into three components: a distance dependent path loss, a plane earth propagation loss and a (multiple knife-edge) diffraction loss due to the mountains in the terrain model.

When using the distance dependent model only, equation 2.1 is given by

$$P_{ij} = \frac{P_i A_i(\theta_{ij}) A_j(\theta_{ji})}{d_{ij}^\alpha},$$

where $d_{ij}$ is the distance between node $i$ and node $j$ and $\alpha$ is the path loss exponent. A value of $\alpha = 3$ that may correspond to the rural scenario will be used to evaluate performance.

### 2.1.2 Multiple Access Interference Model

In the radio environment the probability of a packet arriving error free is dependent on the modulation, coding, multiple access interference (MAI) and background noise. For the purpose of network modelling it is assumed that a packet survives if the Signal-to-Interference plus Noise Ratio (SINR) during the transmission period of the packet is above a specified threshold $\gamma_0$ as defined by

$$\Gamma_{ij} = \frac{P_i G_{ij} A_i(\theta_{ij}) A_j(\theta_{ji})}{\sum_{\forall \text{ link } (k,l) \neq \text{ link } (i,j)} P_k G_{kj} A_k(\theta_{kj}) A_j(\theta_{jk}) x_{kl} + P_{\text{Noise}}} > \gamma_0.$$  

(2.3)

$\Gamma_{ij}$ is the Signal-to-Interference plus Noise Ratio for a packet sent from node $i$ to node $j$ and $P_{\text{Noise}} = kT_0B F_{\text{sys}}$ is the background noise power level at node $j$, $k = 1.38 \cdot 10^{-23} \text{ J/K}$ is the Boltzmann’s constant, $T_0 = 290 K$, $F_{\text{sys}}$ is the receiver Noise Factor and $B$ is the receiver equivalent noise bandwidth. $x_{kl}$ is a random variable defined as

$$x_{kl} = \begin{cases} 1 & \text{if } k \text{ transmit to node } l \\ 0 & \text{otherwise} \end{cases}.$$  

(2.4)

The random variable $x_{kl}$ depends on the MAC protocol being used and if whether or not a node $k$ has a packet to transmit to node $l$. When simulating CSMA/CA with RTS and CTS (see Chapter 4) this equation is used to determine if the packet (that could be an RTS, CTS or DATA packet) survives in presence of other nodes transmissions.
When using STDMA as MAC protocol (see Chapter 3) a link transmission schedule is created in advance. The time domain is divided into slots, each long enough to contain one data packet. The link schedule is created by adding one link at a time to test if all links assigned to transmit in a given slot satisfy (2.3) with $x_{kl} = 1$, i.e. considering the worst case when a node $k$ always has a packet to be transmitted to node $l$. We define $\mathcal{L}_n$ as the set of links $(i, j)$ being tested to transmit during slot $n$ (2.5).

$$\Gamma_{ij} = \sum_{\forall \text{ link } (k, l) \in \mathcal{L}_n \atop \text{ link } (k, l) \neq \text{ link } (i, j)} \frac{P_i G_{ij} A_i(\theta_{ij}) A_j(\theta_{ji})}{P_k G_{kj} A_k(\theta_{kj}) A_j(\theta_{jk}) + P_{Noise}} > \gamma_0 .$$ (2.5)

### 2.1.3 Network Topology

In general, the total number of unidirectional links leaving node $i$ is $(N - 1)$. Therefore, the total number of unidirectional links in the network is $N(N - 1)$. A link $(i, j)$ is said to be feasible if a sufficiently low bit error rate (BER) can be achieved in the absence of MAI. The radio-propagation conditions of the surrounding environment (terrain) where the network is deployed attenuates the transmitted signal. Therefore, since nodes have a limited transmission power, only some links have enough received power to be feasible. The feasible links define the physical network topology, i.e. how the different nodes in the network are connected to each other. By varying the transmission power used by a node the network topology can be changed. The required transmission power to achieve a given SNR ($\gamma_0$) while at the same time overcoming a maximum propagation path loss, $L_{max}$, using isotropic antennas can be computed by

$$P_i = \gamma_0 P_{Noise} L_{max}$$ (2.6)

Fig. 2.1.3, and 2.2 show three network realizations using this procedure with a distance dependent model to achieve a maximum radio range of 40 km. When using smart antennas the transmission power is reduced to keep the same network topology as for the omnidirectional case. This allows us to evaluate the spatial filtering advantage provided by smart antennas.

An important parameter while evaluating multihop ad hoc network is the network connectivity. The study in this thesis was confined to connected networks, i.e. to those networks for which there exists a path with finite number of hops between every pair of nodes in the network. Two parameters are used to indicate the level of connectivity: 1) The average number of neighbors to a node in the network and; 2) The average number of hops to reach every other node.

We say that a node $j$ is a neighbor of node $i$ if a feasible link exist between them; this also means that node $i$ is at a single hop from node $j$. Therefore, if the total number of neighbors to node $i$ is $N_i$, the average number of neighbors
Figure 2.1: Sample networks (Network A, B, C) with N=20 nodes. It can represent static or nomadic behavior simulated by random location over an area of 100x100 km. Lines indicate feasible (or reliable) bi-directional communication links in absence of Multiple Access Interference. The average number of neighbors and the average number of hops needed to reach every other node is indicated.

The average number of neighbors is given by

\[ E[\text{neighbors}] = \frac{1}{N} \sum_{i=1}^{N} N_i \]  

(2.7)

In a fully connected network all links are feasible yielding

\[ E[\text{neighbors}] = N - 1 = N - 1 \quad \forall \ i. \]

On the other hand, the average number of hops is considered to be important since it indicates on average how many relaying nodes a packet has to visit before reaching its final destination. If the minimum number of hops needed to reach node \( j \) from node \( i \) is \( h_{ij} \), then the average number of hops is given by

\[ E[\text{hops}] = \frac{1}{N(N-1)} \sum_{i=1}^{N} \sum_{j=1}^{N} h_{ij}. \]  

(2.8)

Note that \( h_{ii} = 0 \) in the above equation since the packet does not need to be forwarded.

2.1.4 Antenna Models

Smart antennas can help to reduce the MAI and improve the system capacity but the cost per node will be higher. Switch beam technologies can provide cost-
2.1. Link Quality Model

effective implementations \(^1\) of smart antennas in multihop ad hoc networks. On the other hand, Adaptive beamforming antennas (ABF) provides electronically controlled steerable beam flexibility but at significantly higher price.

As previously mention, the switched-beam smart antennas’s method is one of the simplest approaches that can be used. Here, a linear RF network, called a Fixed Beamforming Network (FBN) combines \(M\) antenna elements to form up to \(M\) directional beams. In order to obtain easily analyzed and general results we adopted the flat-top model [25], page 137. It is assumed that each FBN covers 360 degrees with \(M\) sectors selected by the MAC protocol. The horizontal antenna pattern \(A_i(\theta, s)\) for each sector \(s; s = 1 \ldots M\) is given by (3) and it is illustrated in Fig.2.3.

\[
A_i(\theta, s) = \begin{cases} 
\frac{2\pi}{\phi_h}; & (s-1)\phi_h < \theta < s\phi_h \\
\frac{1}{a_{sl}}; & Otherwise
\end{cases}
\]

(2.9)

where \(\phi_h\) is the horizontal antenna beamwidth (BW) and \(a_{sl}\) is the side lobe attenuation.

Adaptive Beam forming antennas (BFA) are evaluated using the Spatial Filtering for Interference Reduction (SFIR) processing method. In SFIR a DSP processor dynamically adapts the antenna’s beam to maximize the received signal power. In this case, the horizontal antenna pattern \(A_i(\theta, j)\) used by node \(i\) while transmitting to node \(j\) is given by (2.10). The antenna radiation pattern

\(^1\)There are many ways to implement Fixed Beamforming Networks using off the shelf components (e.g. Butler Matrix)[25], page 91.
of the receiving antenna in node $j$ is computed in the same manner.

$$A_i(\theta, j) = \begin{cases} \frac{2\pi}{\phi_i}, & \theta_{ij} - \frac{\phi_i}{2} \leq \theta \leq \theta_{ij} + \frac{\phi_i}{2} \\ \frac{1}{\sigma_{ij}}, & Otherwise \end{cases} (2.10)$$

Although more complex digital processing techniques are possible (e.g. creation of nulls in the radiation pattern to limit the interference coming from neighboring nodes even further) they are not covered in this thesis.

## 2.2 Traffic Model

The multihop ad hoc network conveys information by mean of short bit strings called packets. If a message generated by an information source attached to a node is larger than the packet size, this is broken into several packets to be transmitted through the network as individual entities. From a user perspective this messages are usually a reaction to a particular event (e.g. replying to the source after receiving an email). However, under the network perspective, messages or packets arrive as a random process [5]. For simplicity, it is assumed that packets are of constant length and arrive according to a Poisson process.

---

*We are conscious that this model does not capture the reactive property experienced by users over real networks (for instance traffics generated by http or ftp sessions). However could*
2.3 Performance Measure

with total external traffic load of \( \lambda \) packets per packet duration. Furthermore, it is assumed that the traffic load is evenly distributed (2.11).

\[
\Lambda_i = \frac{\lambda}{N} \quad i \in \{1, 2, \ldots, N\},
\]

(2.11)

\( \Lambda_i \) is the external traffic load on node \( i \).

The initial Source (\( S \)) and final Destination (\( D \)) of a packet is denoted by an \((S, D)\) pair. Due to the store-and-forward mechanism, packets between \((S, D)\) pairs may travel through intermediate nodes. Therefore, the average traffic load \( \lambda_{ij} \) going through a link \((i, j)\) is the result of external and internal traffic \([19], page 25\) (2.12).

\[
\lambda_{ij} = \sum_{\forall(S,D) \text{ routed through link } (i,j)} \frac{\lambda}{N(N-1)} = \frac{\lambda}{N(N-1)} T_{ij},
\]

(2.12)

where \( T_{ij} \) are the elements of the Relative Traffic Load matrix \( T \) given by

\[
T_{ij} = \sum_{(S, D) \text{ routed through link } (i,j)}.
\]

(2.13)

As revealed by this equation, route selections have a strong influence on the network performance. Commonly, while doing route search for a particular \((S, D)\) pair, the number of hops are used to select between different possible paths. This may result in uneven traffic distribution. Besides that the MAI is also affected by routing, for instance nodes at the center of the network are highly likely to be selected as part of the shortest path to reach other nodes, resulting in higher interference.

2.3 Performance Measure

Two primary parameters are used to evaluate performance in this thesis, the End-to-end throughput and the average End-to-end packet delay.

The End-to-end packet delay, is defined as the time between the arrival of a packet at the buffer of the source node and its successful reception at the destination node. The End-to-end packet delay allows us to evaluate quality of service (QoS) under low, moderate, and high traffic.

In general, a randomly selected packet transmitted from node \( S \) to node \( D \) experiences a random delay \( D_{SD} \) that is the sum of the delays on every link utilized to route the packet (selected path). Averaging over all the equal likely \((S, D)\) pairs in the network, the expected End-to-end delay is given by

\[
E[D] = \frac{1}{N(N-1)} \sum_{\forall(S,D)} \left[ \sum_{\forall \text{ link } (i,j) \text{ in path } \text{selected to route } (S,D)} E[D_{ij}] \right],
\]

(2.14)

be a suitable model for short messages (e.g. short e-mails among users) and help us to analyze the main network design trade-off.
\( E[D_{ij}] \) is the expected packet delay over link \((i,j)\) and is a function of the external traffic load, internal traffic load, MAC protocol, and the multiple access interference. An exact analysis for \( E[D_{ij}] \) in the wireless scenario appears to be very difficult [5, 17]. Nevertheless, the above equation can be rewritten in terms of the relative traffic load and is given by

\[
E[D] = \sum_{\forall \text{ link } (i,j)} \frac{T_{ij}}{N(N-1)} E[D_{ij}], \tag{2.15}
\]

Computer simulations are commonly used to measure \( E[D_{ij}] \), however, as the number of nodes in the network increases, the computer time required simulating multihop ad hoc networks significantly increases as well. Since coordination among nodes exists when utilizing STDMA, it is possible to estimate the relative link capacity assigned to each link. This makes possible to do a reasonable estimation of \( E[D_{ij}] \) (see section 3.3).

On the other hand, CSMA/CA in multihop ad hoc seems to be very complex and computer simulation is the only method used to estimate \( E[D_{ij}] \).

As mention before, the End-to-end packet delay is a function of the traffic generated by users in the network. The total external traffic could not be higher than the network capacity otherwise the buffer queue at some nodes grows without bound making the system unstable [[32], page 4]. To avoid unstable conditions the external traffic load, \( \lambda \), must be equal to the End-to-end throughput, i.e. the number of packets that reach their final destination per time period in the entire multihop ad hoc network which is a measure of the resources utilization. The term throughput and End-to-end throughput is used in this thesis to indicate the total external traffic under stable condition measured. We are particular interested in the maximum End-to-end throughput, \( \lambda^* \), that is here defined as the upper bound limit to the maximum total external traffic load that produces finite \( E[D_{ij}] \) : \( \forall \) existing feasible links in the network.

In STDMA this upper bound is easily estimated but not in CSMA/CA. In order to find an estimation of \( \lambda^* \) with this protocol the external traffic load \( \lambda \) is increased until a buffer overflow occurs in any node of the network.
Chapter 3

Spatial TDMA with Adaptive Beamforming Antenna Systems

In this chapter the use of Adaptive Beamforming Antennas with Spatial Time Division Multiple Access protocol is analyzed and a novel routing and scheduling strategy to create the Link Assignment schedule is introduced. The new procedure takes further advantages of the spatial filtering properties of smart antennas. In addition, the influence of terrain roughness on performance is presented.

3.1 Introduction

Spatial Time Division Multiple Access is a MAC protocol where conflicts are avoided by assigning node transmissions into a repetitive pattern of slots of finite length called schedule.

There are two frequently found slots assignment methods in STDMA called Node Assignment and Link Assignment[33]. In Node Assignment a given node $i$ is allowed to transmit on a slot $t$ to any of its neighboring nodes. Other nodes are also allowed to transmit on the same slot if they do not produce mutual conflict. For instance, on the same slot $t$ another node $k$ is allowed to transmit simultaneously to any of its neighboring nodes if does not cause conflicts with reception of $i$’s transmission to its neighbors and vice versa. Due to this mechanism, Node Assignment strategies are more suitable for multicast traffic (i.e. from one source to many destinations) management [33] using omnidirectional antennas.

On the other hand, Link Assignment is a method where smart antennas can be directly applied [24] to significantly improve the performance of STDMA. Link assignment is a link-oriented method where links are assigned to transmit
Chapter 3. Spatial TDMA with Adaptive Beamforming Antenna Systems

Figure 3.1: multihop ad hoc network example with 8 nodes.

on a given slot within the schedule. For instance, if a given link \((i, j)\) is assigned to transmit on slot \(k\), it means that node \(i\) is allowed to transmit to only its neighbor node \(j\) on slot \(k\). Other links could be allowed to transmit on the same slot if they don’t produce mutual conflicts. Clearly Link Assignment is more suitable for unicast traffic (i.e. from one source to a single destination) management. To illustrate how link assignment strategy works refer to Fig.3.1 where a simple 8 nodes network with all possible (bi-directional) radio links indicated by lines connecting the nodes is shown. In this network it would, for example, seem feasible to reuse the time slots used for communication on the links \(2 \rightarrow 3\) and \(4 \rightarrow 6\), whereas \(5 \rightarrow 4\) and \(2 \rightarrow 1\) would probably not be able to share the same slot.

As presented in section 2.2, due to the forwarding procedure in multihop ad hoc networks an uneven traffic distribution could result in a potential limiting performance factor. In general, the uneven traffic distribution could be the results of:

I. Limited network connectivity
   No other path is possible between quite few \((S, D)\) pairs;

II. Poor route selection
   This may arise for instance when more than one path exists between a \((S, D)\) pair and the one with lower capacity (or more congested) is selected.

One way to improve on this problem is to implement schedule algorithms that take traffic distribution into account. These algorithms are commonly referred as Traffic Controlled or Traffic sensitive algorithms [18, 19, 33].
3.2 Routing and STDMA Schedule

Finding an "optimum" schedule for STDMA seems to be a very difficult problem [33, 34] therefore suboptimal (heuristics) schedules are commonly used. Fig. 3.2 illustrates the simulation method utilized in [19, 33] to create the traffic controlled schedule. The procedure is an interference based methods where full knowledge of the radio propagation conditions between nodes (G matrix) is assumed. In a real system, this information can be collected when the network is started and could be periodically updated, a method to do this can be found in [34]. With this information as an input, the procedure starts by creating the network topology based on the link quality. After that the Minimum Hop Algorithm is used to select a particular path between every source (S) and final destination (D) of a packet here denoted by (S, D) pair. MHA minimize the number of hops in a multihop "connection" and is independent of the access schedule and the actual traffic flows. When setting the routing table a decision has to be made if several paths with the same minimum number of hops are found. If only the number of hops is used as decision criteria, a random selection seems to be a reasonable choice (we will refer to this as random MHA). In [30] MHA has been found to produce shorter packet delay when compared with other routing algorithms on rough terrains justifying its used. The resulting routing table then is used to compute the Relative Traffic Load matrix T given by (2.13). T, and the Path Gain Matrix G are used as input to a traffic controlled algorithm that assign to each links a number of slots proportional to its relative traffic load. From now on, we will refer to this procedure by Minimum Hop Algorithm plus Traffic Controlled Scheduling (MHA + TCS).

By defining $L_n$ as the set of links allowed to transmit in slot $n$, the schedule $S$ is defined as the sets $L_n, n = 1, 2, \ldots, N_f$; where $N_f$ is the period of the schedule in slots [33]. When using an interference based algorithm to create the schedule, all links $(i, j) \in L_n$ must satisfied (2.5).

In general, the aims of the traffic controlled schedule algorithm are:

- to compensate the uneven traffic distribution created by routing,
- maximize the network efficiency by maximizing the reuse of slots and
- minimize the schedule period $N_f$.

To provide an "optimum" solution to this problem is an NP-complete problem [33], page 12 meaning that it requires excessive computational effort for even moderately size networks.

Power Control and smart antennas (two well known methods commonly used in cellular systems) could be used directly with the schedule algorithm to improve the network efficiency. In particular, the use of adaptive beamforming antennas may result in shorter schedule periods as indicated by the following proposition.
Chapter 3. Spatial TDMA with Adaptive Beamforming Antenna Systems

Given node locations and terrain database find the G matrix and derive the network topology

Use Minimum Hop Algorithm (MHA) to find relative traffic load for all links

Assign a number of slot proportional to the relative traffic to each link

\[ \text{schedule} \]

Figure 3.2: Traditional simulation method used to construct the Traffic Controlled Schedule.

**Proposition 3.1** Let \( L_n \) be the set of links allowed to transmit in slot \( n \) using omnidirectional antennas in a S-TDMA multihop ad hoc network and let \( \Gamma_{ij}^{(\text{omni})} \) be the Signal-to-Interference plus Noise ratio for any link \((i, j) \in L_n\) using constant transmission power. Let \( \Gamma_{ij}^{(\text{SFIR})} \) be the Signal-to-Interference plus Noise ratio for any link \((i, j) \in L_n\) resulting from replacing the omnidirectional antenna system by adaptive beamforming antennas with higher antenna gain and Spatial Filtering for Interference Reduction adaptation method for all nodes in the network. Then,

\[
\Gamma_{ij}^{(\text{SFIR})} > \Gamma_{ij}^{(\text{omni})}; \forall \text{ links } (i, j) \in L_n.
\]

**Proof:** Let \( A_{\text{max}} \) be the maximum gain of the adaptive beamforming antenna,
then the antenna radiation pattern is such that

$$A_i(\theta) \leq A_{\text{max}} \forall \theta.$$  \hspace{1cm} (3.2)

If SFIR is used, in any link \((i, j) \in \mathcal{L}_n\), node \(i\) maximize its antenna gain in the direction of node \(j\) and vice versa (the beam is electronically steered), meaning that

$$A_i(\theta_{ij}) = A_j(\theta_{ji}) = A_{\text{max}}.$$  \hspace{1cm} (3.3)

For all links \((k, l) \in \mathcal{L}_n\) such that link \((k, l) \neq (i, j)\) follows from (3.2) and (3.3) that

$$A_k(\theta_{kj})A_j(\theta_{jk}) \leq \sum_{\forall \text{ link } (k, l) \in \mathcal{L}_n, \text{ link } (k, l) \neq \text{ link } (i, j)} P_kG_{kj}A_{\text{max}}^2,$$  \hspace{1cm} (3.4)

$$\sum_{\forall \text{ link } (k, l) \in \mathcal{L}_n, \text{ link } (k, l) \neq \text{ link } (i, j)} P_kG_{kj}A_k(\theta_{kj})A_j(\theta_{jk}) \leq \sum_{\forall \text{ link } (k, l) \in \mathcal{L}_n, \text{ link } (k, l) \neq \text{ link } (i, j)} P_kG_{kj}A_{\text{max}}^2,$$  \hspace{1cm} (3.5)

Therefore, since the terms in (3.5) are greater than zero,

$$\frac{P_iG_{ij}A_{\text{max}}^2}{\sum_{\forall \text{ link } (k, l) \in \mathcal{L}_n, \text{ link } (k, l) \neq \text{ link } (i, j)} P_kG_{kj}A_k(\theta_{kj})A_j(\theta_{jk}) + P_{\text{Noise}}} \geq \frac{P_iG_{ij}}{\sum_{\forall \text{ link } (k, l) \in \mathcal{L}_n, \text{ link } (k, l) \neq \text{ link } (i, j)} P_kG_{kj} + \frac{P_{\text{Noise}}}{A_{\text{max}}^2}}.$$  \hspace{1cm} (3.6)

When omnidirectional antennas are used, the right hand side of equation (3.5) gives a lower bound for SINR because \(A_{\text{max}} > A_{\text{omni}}\).

The above proof could be easily extended for different antennas beamwidth \((\phi_h)\). As the antenna beamwidth get narrower the antenna gain increases, then, if comparing two systems, system \(a\) with system \(b\), \(A_{\text{max}}^{(a)} > A_{\text{max}}^{(b)}\); if \(\phi_{h}^{(a)} < \phi_{h}^{(b)}\), hence a more general statement is that

$$\Gamma_{ij}^{(\text{SFIR}_a)} > \Gamma_{ij}^{(\text{SFIR}_b)}; \forall \text{ link } (i, j) \in \mathcal{L}_n; \text{ if } \phi_{h}^{(a)} < \phi_{h}^{(b)}.$$  \hspace{1cm} (3.7)

Note that the above statement does not necessarily hold if switch beam antenna systems are used.

As mention before, this may imply that higher reuse may be achieved as the antenna beamwidth reduces.
While creating the schedule, the problem of compensating for uneven traffic distribution by MHA + TCS is done basically assigning a number of slots proportional to the traffic load of a given link. We can see this as an optimization problem where the objective function is to maximize the maximum \( \text{End-to-end Throughput} \), \( \lambda^* \), for the whole network. To explain this, we define \( n_{ij} \) to be the number of slots within a period of the schedule, \( N_f \), allocated to link \((i, j)\); then the relative link capacity \( C_{ij} \) is

\[
C_{ij} = \frac{n_{ij}}{N_f},
\]

that constitute the elements of the network capacity matrix \( C \).

The values for \( C_{ij} \) and the relative traffic load is all we need for a good estimation of the maximum \( \text{End-to-end} \) throughput \( \lambda^* \). Assuming infinite buffer length, if the average traffic load routed through link \((i, j)\) is \( \lambda_{i,j} \), for stable condition \( \lambda_{i,j} \) must be lower than \( C_{ij} \). Consequently, the maximum \( \text{End-to-end} \) throughput over any link that produces a finite \( \text{Packet delay} \), \( D_{ij} \), is given by [33]

\[
\lambda < \lambda^* = N(N - 1) \min_{\text{link } (i,j)} \left\{ \frac{n_{ij}}{N_f T_{ij}} \right\}.
\]

Equation (3.9) reveals that assigning a number of slot proportional to the relative traffic load of a link improves \( \lambda^* \). Therefore, as previously stated, traffic controlled algorithms aim to maximize the \( \text{End-to-end throughput} \). However compensating after route selection is not an optimal solution since the frame length \( N_f \) is also function of \( n_{ij} \) which in turns is a function of the spatial reusability of slots, therefore influenced by the MAI, network topology, and routing. In addition to interference, the schedule’s period is influence also by the fact that a node can not receive from more than a single source, as illustrated by the following example.

**Example 3.2.1** Let consider the case illustrated in Fig.3.3 where all nodes select a route to transmit to node E using narrow beamforming antennas such that the MAI is effectively eliminated. If we applied the Minimum Hop Algorithm for route selection two possible relative traffic distribution may result as indicated by the number over each edge on the graph. In this example, link \((D, E)\) carries 3 times more traffic than links \((A,D), (B,D), \) and \((C,E)\) if Route selection 1 is the result of the MHA. If we use a traffic controlled schedule, link \((A,D)\) must be guaranteed 3 slots resulting in the illustrated schedule of length \( N_f = 5 \) slots with a total number of slot assignments of 7 in the frame, corresponding to \( 7/5 \) total network capacity. If Route selection 2 is used as an input to the traffic controlled algorithm then there will be a total capacity of \( 8/4 = 2 \) which is obviously more efficient. The resulting maximum throughput is \( 1/5 \) for Route selection 1 and \( 1/4 \) for Route selection 2 which correspond to 25% higher throughput.
3.2. Routing and STDMA Schedule

As the example shows, if we think in the case of being able to remove all the interference (e.g. narrow beam Smart antennas) the fact that a node can not receive from more than a single node and neither can transmit simultaneously becomes a limiting factor. In the intermediate case, both interference and route selection are important. Therefore a combine routing & scheduling strategy can improve the system performance.

3.2.1 Reuse Adaptive Minimum Hop Algorithm (RA-MHA)

In MHA + TCS routing information is used by the MAC protocol through the relative traffic load. As a way to integrate routing and schedule two way information could be used, that is from routing to the traffic schedule algorithm and from this to a routing that takes into account the resulting link capacity from the schedule. Fig.3.4 illustrate the procedure that we will refer as Reuse Adaptive Minimum Hop Algorithm (RA-MHA) utilized to further improve the performance of Spatial TDMA with smart antennas.

Similar to the previous method the algorithm starts by computing the $G$ matrix based on node locations, and the terrain database. The second step aims to spread the traffic with the objective of spreading the MAI. This was achieved by employing the routing decision for RA-MHA (Appendix A), that takes into account the set of minimum hop paths and capacity assigned to each link for route selection. In this step, it is assumed that all links have the same capacity.
Figure 3.4: Procedure to create the Link Schedule for STDMA called Reuse Adaptive Minimum Hop Algorithm RA-MHA.

Given node locations and terrain database find the G matrix and derive the network topology.

Find routing \( r_1 \) using routing decision RA-MHA (Appendix A) with \( C_{ij} = 1 \) for all feasible links in the network and compute \( T_{ij} \).

Create schedule (slot assignment) using a Traffic Controlled algorithm and compute the resulting \( C_{ij} = n_{ij}/N_f \).

Compute \( \lambda_i^r \) for \( r_1 \).

Find routing \( r_2 \) using routing decision RA-MHA with \( C_{ij} = n_{ij}/N_f \) for all feasible links in the network and compute \( T_{ij} \).

Compute \( \lambda_i^r \) for \( r_2 \).

\[
\text{routing} = \begin{cases} 
    r_1 & \lambda_i^r > \lambda_i^r \\
    r_2 & \text{otherwise}
\end{cases}
\]

From the resulting schedule the number of slots assigned to each link and the period of the schedule can be found to compute the resulting capacity of each link; i.e. \( C_{ij} = n_{ij}/N_f \). The relative traffic load matrix \( T \) and the capacity matrix \( C \) are used in the next step to find the maximum throughput achieved with the routing \( r_1 \) using (3.9).

The next step tries to improve the route selection by considering the actual resulting capacity matrix \( C \). The capacity assigned to each link by the schedule is used to find a new routing table \( r_2 \) with the routing decision for RA-MHA. Next, the maximum throughput achieved by routing \( r_2 \) and the schedule is computed. Finally, the routing to be used is the one that produces the highest throughput.

The difference between \( r_2 \) and \( r_1 \) is that \( r_2 \) utilizes the real network capacity obtained by the traffic controlled algorithm to try to maximize the throughput.

The main idea of routing decision RA-MHA is described here and a detailed step by step algorithm can be found in appendix A. The required inputs are the

\( C_{ij} = 1 \) and the generated routing table is labelled \( r_1 \) for later decision. The relative traffic load \( (T_{ij}) \) produced by \( r_1 \) for every link can be computed and it is used in the next step to find the schedule as an output by applying a Traffic controlled schedule (TCS) algorithm.
3.3. Approximate Analytical Method for Delay Calculation in STDMA

network topology and link capacity \( C_{ij} \). The algorithm could be summarized by,

I. Collect the set of paths with shortest distance between all \((S, D)\) pairs in the network. MHA can be used to find the set of paths.

II. Put \((S, D)\) pairs in ascending order according to the number of possible paths. If two \((S, D)\) pairs have equal number of possible paths, give priority to the one with higher number of hops.

III. From the set of path for each \((S, D)\) pair, select the one that produce \( \max \{ \min \{ C_{ij}/T_{ij} \} \} \) for all links within the path and update the traffic load for all links within the selected path with \( T_{ij} = T_{ij} + 1 \).

IV. Repeat III until all \((S, D)\) pairs have been considered.

Note that in step II, priority is given to the path with longer distance since this will affect a higher number of links. Every time a route is selected the relative traffic load is updated adding one to all links within the selected path to influence the next routing decision. Note that the increment by 1 in \( T_{ij} \) is the result of the assumption of even traffic load among nodes, however it could be modified to include differences in traffic between different \((S, D)\) pairs. Note also that the resulting routing table used by each node is a matrix (rather than a vector as in MHA), with row and column indexes correspond to sources and destinations respectively, and the value held is the index of the relaying node to be used to deliver the packet.

End-to-end packet delay, \( E[D] \), and maximum throughput, \( \lambda^* \), were both used to measure the performance.

3.3 Approximate Analytical Method for Delay Calculation in STDMA

As described in section 2.3, a randomly selected packet transmitted from node \( S \) to node \( D \) experiences a random delay \( D_{SD} \) that is the sum of the delays on every link utilized to route the packet. Averaging over all the equal likely \((S, D)\) pairs in the network, the expected end-to-end delay is given by

\[
E[D] = \sum_{\forall \text{ link } (i,j)} \frac{T_{ij}}{N(N-1)} E[D_{ij}],
\]

(3.10)

Although an exact analysis for \( E[D_{ij}] \) (the expected packet delay over link \((i,j)\)) appears to be difficult \([5, 17]\) an approximate model can be employed to obtain a numerical estimation. For this the following assumptions are needed:
I. each node uses a different infinite length buffer for every feasible outgoing link,

II. packets arrival time to be transmitted over each link is poisson distributed with arrival rate \( \lambda_{ij} \), and

III. the slots assigned to link \((i, j)\), \( n_{ij} \), are uniformly distributed within the schedule.

Assumption II implies that packet arrival to each link are independent from the delay and queue process over the previous relaying link. This is known as Kleinrock’s principle of independence [35]. For low traffic obviously this is not true since one packet from a Source to a Destination will find basically empty queues over each relaying node making the poisson distribution arrival process assumption to each link invalid. For medium and high traffic the queuing process makes the arrival and departure of packets much more complex and the assumption appear to be valid, see Fig.3.5. Assumption III depends on the Traffic controlled Schedule Algorithm utilized and could be difficult to be actually true. It has been suggested in [17] that assumption III is a desirable property of a good scheduling algorithm. The algorithm proposed by Grönkvist in [20] utilizing priorities to create the schedule tries to create the schedule with this property, therefore his algorithm will be used for our evaluation.

Nevertheless, if the above assumptions are used, the expected packet delay through link \((i, j)\), \( E[D_{ij}] \) could be modelled as the resulting packet delay in a TDMA system with a frame length \( N_f/n_{ij} \), with a packet transmission time of 1 Slot [[7], page 13]. Hence, equation (2.15) can be approximated by (3.11).

\[
E[D] \approx \sum_{\forall \text{link } (i,j)} \frac{\lambda_{ij}}{\lambda} \left[ \frac{1}{2\left(C_{ij} - \lambda_{ij}\right)} + 1 \right] \text{ Slot.} \tag{3.11}
\]

In our case since we are comparing MHA + TCS against RA-MHA method is very important to verify that this approximation does not gives favorable results for either of the two procedures. Hence we have evaluate this aproximation by computer simulation. Fig.3.5 shows results of simulation for network A when 60 degrees Beam Forming Antennas (BFA) are used. In the simulation, external packets arriving at each node where generated according to a Poisson process with equally likely destination among nodes. Each node had a 100 packet buffer length (FIFO) for each outgoing link where transit and local packets were placed for transmission after its reception. The model produces a relatively small underestimation for low traffic in both routing methods. For moderate and relatively high traffic, a more accurate result is achieved.

3.4 Results

Sample networks A, B, and C in Fig.2.1.3, and 2.2 have been used to evaluate the performance result with MHA + TCS and RA-MHA. We can see that network
3.4. Results

A is an sparse network with relatively weak links but reasonably connected with on average 7.5 neighbors per node and an average number of hops between any $(S, D)$ pair of 1.8 hops. On the other hand network B is more dense getting a better connected network than A, with on average 10.2 neighbors per node and an average number of hops 1.5 hops. Network C is much less connected than A with only 6.9 neighbors on average per node needing on the average 2.1 hops to send a packet between a $(S, D)$ pair. Each node transmits with constant power that produces a maximum radio range of 40 km with propagation constant $\alpha = 3$.

Fig. 3.6, 3.7, and 3.8 show the cumulative distribution function of the maximum throughput for networks A, B, and C for RA-MHA and random MHA + TCS with 100 independent trials. Furthermore, Fig.3.9 and Fig.3.10 show the end-to-end packet delay versus the external total traffic load, $\lambda$ for networks A and B (a single snapshot in random MHA was used in this case). Note that the maximum throughput using RA-MHA (indicated with *) occurs with probability one, therefore the cdf is a unitary step function $u(\lambda - \lambda^*)$.

As expected, Fig.3.6, 3.7, and 3.8 show that when narrow antenna beamwidth is used the new method (RA-MHA) may produce significant higher throughput than random MHA + TCS. For instance, the throughput improvement applying RA-MHA with 60 degrees antennas was 31.8%, 6.2% and 18.3% higher throughput for network A, B and C respectively, when compared to the mean value achieved with random MHA + TCS. The lowest improvement in network B is produced because nodes are very close to each other as revealed by its topology.

Figure 3.5: Result of approximation (3.11) versus simulation for a randomly selected network with 20 nodes. Note that the M/D/1 model describe the system performance.
Note that (in networks A and C) the same throughput is achieved with 60 and 10 degrees antennas. This indicates that interference is effectively reduced by spatial location and routing becomes the main limiting factor.

The results in Fig.3.9 and 3.10 demonstrate that the use of RA-MHA may result also in lower delays for almost all traffic conditions with respect to MHA + TCS. An interesting result is that higher maximum throughput is achieved with 120 degrees antennas beamwidth with RA-MHA than with 60 and 10 with MHA + TCS. As before, note that little improvement is achieved in network A when 10 degrees antennas are used respect to 60 degrees antennas.

Fig.3.11, 3.12, and 3.13 summarize the maximum throughput improvement obtained by RA-MHA compared with the mean value achieved with MHA + TCS. In scenarios where nodes are close to each other like in sample network B higher improvement is obtained with very narrow antenna beamwidth. The gain with omnidirectional antennas is very small suggesting that the traffic controlled schedule algorithm effectively manage the uneven traffic distribution created by the routing because interference dominates. Furthermore, the results demonstrate that smart antennas can produce a tremendous capacity improvement with respect to omnidirectional antennas with relatively simple antennas array (big improvement with only 120 degrees antenna’s beamwidth was achieved).

### 3.5 STDMA in Rough Terrain

In the rural scenario the impact of the terrain on the network performance is very important. STDMA with omni-directional antennas has been already studied by Somarriba in [19] and the results show that Rough (mountainous) terrain makes it more difficult to achieve a fully connected network, but when this is achieved, it has the advantage of "shielding" the nodes from interference yielding more efficient STDMA schedules. More recently, Grönkvist [33] has found that the network connectivity is a very important factor when using omnidirectional antennas over a realistic terrain. Therefore in this section we relax our assumption of flat terrain and distance dependent radio propagation model to observe the effect of the terrain roughness on the performance of multihop ad hoc networks with beam forming antennas as a function of the network connectivity, here defined by

\[ C = \frac{1}{N - 1} E[\text{neighbors}] \]  \quad (3.12)

Note that the value of \( C \) is an important measure of the network topology, which in turn is influenced by the terrain and nodes’ transmission power. Hence, many of the results in this section has been plot as a function of \( C \). In general, for a connected network the connectivity must satisfy (3.13).

\[ \frac{2}{N} \leq C \leq 1 \]  \quad (3.13)
3.5. STDMA in Rough Terrain

Figure 3.6: Cumulative Distribution Function of Maximum Throughput using adaptive BFAs with SFIR (Network A). On the graph, letters a, b, and c correspond to MHA + TCS with 120, 60 and 10 degrees respectively. The use of RA-MHA is indicated with a*, b*, and c*.

Figure 3.7: Cumulative Distribution Function of Maximum Throughput using adaptive BFAs with SFIR (Network B). On the graph, letters a, b, and c correspond to MHA + TCS with 120, 60 and 10 degrees respectively. The use of RA-MHA is indicated with a*, b*, and c*. 
Different terrain roughness has been simulated using the synthetic terrain model described in appendix C with height parameters $\sigma=10, 40$ and 80 meters and smoothness $\rho = 5$ km over 50x50 km. As the value of $\sigma$ increases, the terrain roughness increases as well. With $\sigma = 10, 40$ and 80 meters, the maximum height found were 69.8, 244.6, and 595.9 meters respectively. The node locations for networks A, B and C shown in Fig.2.1.3 and 2.2 have been used for the evaluation. In order to vary the connectivity over each of the different terrains the path losses are computed as described in appendix C and the transmission power was gradually increased. If the received power $P_{ij}$ for link $(i, j)$ exceeds $\gamma_0 P_{\text{Noise}}$ the link is assumed to be feasible. The receiver’s noise figure was assumed to be $F_{\text{sys}} = 15$ dB, its effective noise bandwidth 100 kHz, operating frequency 430 MHz, and $\gamma_0 = 10$ dB which correspond to a BER lower than $10^{-5}$ for BPSK modulation scheme. RA-MHA procedure was utilized as the method to create the schedule.

Fig.3.14, 3.16 and 3.18 show the maximum end-to-end throughput using this three different terrains with node distribution for network A, B and C respectively using omnidirectional antennas and adaptive BFA with $\phi_h = 10^\circ$ antennas beamwidth (narrow beam antennas). The required transmission power as function of the network connectivity $C$ is shown in Fig. 3.15, 3.17 and 3.19 for networks A, B, and C respectively. In general, it can be seen that as the terrain roughness increases, higher transmission power is needed to achieve the same connectivity. The node locations is an important factor for the network connec-
3.5. STDMA in Rough Terrain

Figure 3.9: Packet Delay vs. traffic load (Network A).
MHA + TCS : $\phi_h = 360^\circ$, $\phi_h = 120^\circ$, $\phi_h = 60^\circ$, and $\phi_h = 10^\circ$ beamwidth.
RA-MHA: $\phi_h^* = 360^\circ$, $\phi_h^* = 120^\circ$, $\phi_h^* = 60^\circ$, and $\phi_h^* = 10^\circ$ beamwidth.

Figure 3.10: Packet Delay vs. traffic load (Network B).
MHA + TCS : $\phi_h = 360^\circ$, $\phi_h = 120^\circ$, $\phi_h = 60^\circ$, and $\phi_h = 10^\circ$ beamwidth.
RA-MHA: $\phi_h^* = 360^\circ$, $\phi_h^* = 120^\circ$, $\phi_h^* = 60^\circ$, and $\phi_h^* = 10^\circ$ beamwidth.
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Figure 3.11: Maximum throughput for different antenna beamwidth (Network A).

Figure 3.12: Maximum throughput for different antenna beamwidth (Network B).
tivity, as revealed by the results for network B which is a more dense network. In this case, when compared with networks A, higher power is needed to achieve a connected network. This is caused by node 13 which is separated from the group. Note also that, in the three sample networks observed, achieving connectivity higher than 0.8 requires significant amount of power.

From Fig. 3.14, 3.16 and 3.18 it can be observed that the throughput exhibits a linearly increasing behavior as a function of the connectivity for both narrow beam forming antennas and omnidirectional antennas, in the three networks observed, this behavior is independent of the terrain roughness. As the network connectivity decreases, the throughput with adaptive BFA approaches to the omnidirectional case. The throughput achieved with adaptive BFA was 8.24, 8.4 and 8.26 times the throughput with omnidirectional antennas for $C = 1$. For the lowest connectivity the result was 5.45, 4.25, 3.3 times the throughput with omnidirectional antennas.

Fig. 3.20, 3.21 and 3.22 show the impact on the end-to-end packet delay measure at 75% the maximum throughput. As reveal by the figure, the end-to-end packet delay exhibits high variability with respect to the connectivity with omnidirectional antennas but appears to be independent of the terrain roughness. Note that the packet delay increases very much for connectivity higher than 0.8; this is a consequence of very high transmission power resulting in a lack of slot reuse. This discontinuity (jump in delay at $C = 0.8$) is also found with adaptive beamforming antennas, such a condition should therefore be avoided.
Nevertheless, the packet delay is almost constant up to $C = 0.8$ with this antenna beamwidth.

### 3.6 Summary

In this chapter we have analyzed the utilization of Smart Antennas with the conflict-free MAC protocol called Spatial Time Division Multiple Access (STDMA). As was explained in this chapter, Link Assignment is better than Node Assignment in networks with smart antennas and the scheduling may be performed by adopting existing heuristic algorithms. If during a given slot the transmitting node and the receiving node adapt their antennas to maximize the received power (referred as Spatial Filtering for Interference Reduction, SFIR), the resulting SIR is reduced as the antenna beamwidth reduces, potentially increasing the slot reuse.

Routing was found to be a very important problem limiting the potential network throughput. When interference reduction measures such as narrow antenna beamwidth are used the problem that a node can not receive and transmit at the same time becomes an important limiting factor. To improve the network performance a novel procedure to create the Link Schedule that combines routing & scheduling, called Reused Adaptive Minimum Hop Algorithm was introduced and its performance was evaluated. Both lower end-to-end packet delay and higher throughput were demonstrated through application of the new strategy.

Influence of the terrain roughness on the network connectivity and performance of STDMA was also investigated. Results show that connectivity of the network is a very important factor that influence both throughput and delay. Terrain roughness influences the connectivity in the sense that higher transmission power is needed to obtained the same connectivity. Throughput and delay results are similar for the same network connectivity appearing to be independent of the terrain roughness. It was observed that on rough terrain, the throughput linearly increases as the connectivity increases. The performance improvement of narrow antennas increases with respect to the omnidirectional case as the connectivity increases as well. Very high transmission power is required to achieve higher connectivity ($C \geq 0.8$ in the three sample network studied) which results in high transmission power since only a single hop is needed to reach any destination but it also results in high delay because of poor spatial reuse. This effect is reduced but not eliminated by the used of adaptive beamforming antennas.
3.6. Summary

Throughput vs Connectivity on Rough Terrain (Network A)

Maximum End-to-end Throughput, $l^*$

Throughput vs Connectivity on Rough Terrain (Network A)

Figure 3.14: Maximum throughput versus connectivity for Network A on rough
terrain with $\sigma=10$, 40 and 80 meters utilizing omnidirectional antennas and
adaptive BFA with $10^\circ$ antennas beamwidth.

Figure 3.15: Transmission power versus connectivity for Network A on rough
terrain with $\sigma=10$, 40 and 80 meters.
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Figure 3.16: Maximum throughput versus connectivity for Network B on rough terrain with $\sigma=10$, 40 and 80 meters utilizing omnidirectional antennas and adaptive BFA with $10^\circ$ antennas beamwidth.

Figure 3.17: Transmission power versus connectivity for Network B on rough terrains with $\sigma=10$, 40 and 80 meters.
3.6. Summary

Figure 3.18: Maximum throughput versus connectivity for Network C on rough terrain with \( \sigma = 10, 40 \) and 80 meters utilizing omnidirectional antennas and 10° antennas beamwidth.

Figure 3.19: Transmission power versus connectivity for network C on rough terrains with \( \sigma = 10, 40 \) and 80 meters.
Figure 3.20: End-to-end packet delay at 75% the maximum end-to-end throughput versus connectivity for Network A on rough terrains with $\sigma = 10$, 40 and 80 meters utilizing omnidirectional antennas and adaptive BFA with $10^\circ$ antenna beamwidth.

Figure 3.21: End-to-end packet delay at 75% the maximum end-to-end throughput versus connectivity for Network B on rough terrains with $\sigma = 10$, 40 and 80 meters utilizing omnidirectional antennas and adaptive BFA with $10^\circ$ antenna beamwidth.
Figure 3.22: End-to-end packet delay at 75% the maximum end-to-end throughput versus connectivity for Network C on rough terrains with σ=10, 40 and 80 meters utilizing omnidirectional antennas and adaptive BFA with 10° antenna beamwidth.
Chapter 4

Carrier Sensing Multiple Access with RTS/CTS and Switch Beam Antenna Systems

This chapter focuses on the utilization of smart antennas with the random access protocol Carrier Sense Multiple Access/ Collision Avoidance (CSMA/CA) with Request to Send (RTS) and Clear to Send (CTS) handshaking mechanism. The setup procedure utilized in this protocol makes it possible to use smart antennas at both the transmitter and the receiver. Although it is expected that the application of smart antennas in CSMA/CA with handshaking can provide significant improvement with respect to the omnidirectional case however, as expounded later in this chapter, the system design needs careful consideration. Since cost is of paramount importance, the study is limited to utilization of switch beam systems. Several beam selection policies controlled by the MAC-sublayer are proposed and their performance evaluated.

4.1 Introduction

A handshaking procedure for wireless multihop ad hoc networks was first proposed by Phil Karn in [11]. Several variants of this protocol have been proposed including the IEEE 802.11 standard [12–16].

A CSMA/CA node uses a simple half-duplex transceiver controlled at at the link layer to receive or to transmit. At the MAC sub-layer, transition from transmission to reception is based on the CSMA/CA protocol, which is designed to minimize the probability of collisions. This is done by transferring a data
Chapter 4. Carrier Sensing Multiple Access with RTS/CTS and Switch Beam Antenna Systems

Figure 4.1: Data transfer procedure from Node A to Node B using Carrier Sense Multiple Access Collision Avoidance with RTS and CTS.

packet in three steps as illustrated in Fig.4.1. Firstly a node that has data to transmit sends a short Request to Send (RTS) packet. All nodes hearing the RTS, excepting the target receiver node, defer their transmissions. Secondly, the target node transmits a short Clear to Send (CTS) and all nodes hearing the CTS, excepting the originating node, defer their transmission until after the end of the data packet. Finally the originating node transmits the data, now having a fair degree of confidence that the channel will be free of interference. In addition to these three steps a node inhibits its transmission if it senses another transmitter on the channel, i.e. Carrier Sense (CS). Link layer acknowledgement could follow the data packet immediately after its reception, like in IEEE 802.11 standard [12]. The type of CSMA/CA implemented for evaluation and generate the results in this chapter is very similar to FAMA described in [14] where higher layer acknowledgement solutions are assumed to be used. Details about the simulation of this protocol could be found in appendix B.

Two well known problems found in CSMA/CA are the hidden terminal and exposed terminal problem. Fig. 4.2 illustrates a packet transmission from Node A to Node B using omnidirectional antennas. The maximum range of Carrier Sensing $d_{CS}$ is greater than the range of error free reception $d_{RTS}$ of an RTS (or Data) in absence of MAI. Note that Node C can not sense the RTS yet may be close enough to Node B to interfere with RTS’s reception. Node C is said to be the hidden terminal. Carrier Sensing is important in reducing the hidden terminal problem [5][17][36]. Alternatively Node D can sense the RTS and DATA but may be able to transmit without interfering with the DATA packet’s reception. If this is so, then Node D is said to be exposed. The range of
the RTS and CTS is set by the modulation and coding while the range of carrier sensing is determined by the carrier sensing time constant and threshold.

Carrier detection can be performed at the physical layer through a power detector to produce a local estimation of the MAI. Let \( x_i \) be the \( i \)-th input sample to the power detector and \( \bar{x} \) the average output power over an M samples window; the output power estimation level is then given by

\[
\bar{x} = \frac{1}{M} \sum_{i=0}^{M-1} x_i^2
\]  

(4.1)

Let \( I_{CD} \) be a binary variable with a 1 used to indicate carrier sense and 0 otherwise. Then the value \( I_{CD} \) passed to the MAC-sublayer is given by

\[
I_{CD} = \begin{cases} 
1 & \text{if } \bar{x} > P_{Th} \\
0 & \text{otherwise} 
\end{cases}
\]  

(4.2)

\( P_{Th} \) is the carrier detection power level threshold. Since \( x_i \) is the sum of signal plus noise on the channel, setting the carrier sensing threshold too low may cause that a node falsely detects the channel busy due to background noise only. On the other hand, setting \( P_{Th} \) too high will result in a bad MAI estimation. The selected value for \( P_{Th} \) can be expressed as a function of the noise power and is given by (4.3).

\[
P_{Th} = \gamma_{cs} P_{Noise}
\]  

(4.3)

\( \gamma_{cs} \) is the signal to noise ratio for carrier sensing, \( 1 < \gamma_{cs} \leq \gamma_0 \).
The minimum value for $P_{Th}$ must be chosen to minimize false carrier detection. In absence of any node transmission (noise limited system) the white Gaussian noise dominates and the output of the power detector $\bar{x}$ is distributed as chi-square with $M$ degrees of freedom with mean $P_{\text{Noise}}$ and variance $\sigma^2 = 2P^2_{\text{Noise}}/M$ [36]. If we do a fairly large number of samples good estimation of the noise power (low variance) could be achieved. However, the use of large $M$ also produces an undesirable carrier detection delay while receiving that could result in reduction in performance [9]; therefore short $M$ is also desirable. In this work it is considered that a minimum carrier detection threshold of 3dB above the noise floor can be used. The receiver needs a minimum time to sense the carrier included within our simulations through the microslots period. By setting the microslot period to much less than the length of an RTS the probability of collision is reduced.

It has been previously stated that carrier sensing could be removed and rely only on the RTS/CTS handshaking in protocols like MACA[18]. The hidden terminal and exposed terminal problems are difficult to thoroughly analyze, however RTS collisions are considered to be critical[37]. How carrier sensing could help with RTS collisions is better understood through an example.

**Example 4.1.1** We want to illustrate the relation between carrier sensing threshold and the probability of RTS collision between two given nodes when using omnidirectional antennas.

Let’s assume for simplicity a distance dependent radio propagation model. Then, in absence of multiple access interference, the range for error free reception of the RTS
4.1. Introduction

\( d_{RTS} \) is given by (see Fig.4.2),

\[
d_{RTS} = \sqrt[\gamma_0]{\frac{P_A}{P_{Noise}}} ,
\]

(4.4)

The RTS reception area can be computed by \( A_{RTS} = \pi d_{RTS}^2 \).

In similar way, the carrier detection distance can be computed

\[
d_{CS} = \sqrt[\gamma_{cs}]{\frac{P_A}{P_{Noise}}} = \sqrt[\gamma_{cs}]{\frac{P_A}{P_{Th}}} ,
\]

(4.5)

Assume a hidden Node \( C \) lies just out of carrier sensing range as shown in Fig. 4.3 (\( d_{AC} = d_{cs} \)). The received SIR \( \Gamma_{AB} \) (ignoring background noise) is

\[
\Gamma_{AB} = \frac{P_{AB}}{P_{CB}} = \left( \frac{d_{BC}}{d_{AB}} \right)^\alpha \geq \gamma_0 ,
\]

(4.6)

where \( d_{BC}^2 = d_{AB}^2 + d_{CS}^2 - 2d_{AB}d_{CS}\cos\theta \). Hence, the distance for which \( A \)'s RTS survives is \( d_{AB} = d_{cap} \). Then

\[
\left( \frac{d_{cs}}{d_{cap}} \right)^2 - 2\left( \frac{d_{cs}}{d_{cap}} \right)\cos\theta + 1 \geq \gamma_0^{2/\alpha} .
\]

(4.7)

Hence, the capture range can be approximated by

\[
d_{cap} \approx \min \left( d_{RTS}, \frac{d_{cs}}{\cos\theta + \sqrt{(\gamma_0^{2/\alpha} - 1) + \cos^2\theta}} \right)
\]

(4.8)

Some examples of the resulting relative capture area using (4.8) are drawn in Fig.4.4 using the parameters of table I with carrier sensing thresholds of 3dB, 6dB, 9dB and 10dB (no CD zone) above the noise floor. It can be seen from the figure that the correct detection area of the RTS is shrink to 75.6%, 57.9%, 40.8%, 34.9% for 3dB, 6dB, 9dB, and 10dB carrier sensing threshold respectively. If nodes are uniform distributed over this area this correspond to the probability of successfully reception of the RTS.

Collision with short RTS packet is less costly in performance than data packet collisions. This could be true if the data packet size is much bigger than the RTS and CTS packet. To verify the impact on the end-to-end packet delay of RTS collisions we have done discrete step simulations with the simulation parameters summarized in table 4.1. We have selected RTS and CTS packet size of 25 bytes each which are small when compared with the Data packet size of 500 bytes.

The impact of different carrier sense thresholds with omnidirectional antennas in network A and B are shown in Fig. 4.5. Using the minimum carrier sense threshold of 3dB yields better performance at relatively high traffic load. However the performance improvement by selecting a low carrier detection threshold is only 7.14% for network A and 5.55% for network B.

Depending on the antenna adaptation use during RTS/CTS and Data transmission, Carrier sensing impact may not be that important when narrow beam
Figure 4.4: Reception area of A’s RTS when a hidden terminal C is located at the carrier detection boundary for different values of CS threshold. RTS reception in absence of MAI is indicated by a dotted line.

Table 4.1: Simulation Parameters used for Performance Evaluation

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Packet Size (PS)</td>
<td>500 Bytes</td>
</tr>
<tr>
<td>RTS size</td>
<td>25 Bytes (5% PS)</td>
</tr>
<tr>
<td>CTS size</td>
<td>25 Bytes</td>
</tr>
<tr>
<td>Data Rate</td>
<td>100 Kbps</td>
</tr>
<tr>
<td>Buffer Length (FIFO)</td>
<td>100 packets</td>
</tr>
<tr>
<td>Clock Step (microslot)</td>
<td>5 Bytes (1% PS)</td>
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<tr>
<td>Number of Nodes (N)</td>
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<td>Packet Transmitted per Node</td>
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<td>External Packet Arrival</td>
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</tr>
<tr>
<td>Packet Destination</td>
<td>Uniform Distributed</td>
</tr>
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<td>Routing Method</td>
<td>Minimum Hop Algorithm (MHA)</td>
</tr>
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<td>Maximum Radio Range</td>
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<td>Minimum SINR</td>
<td>$\gamma_0 = 10 dB$</td>
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<td>Equivalent Receiver</td>
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<td>Noise Bandwidth (B)</td>
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</tr>
<tr>
<td>Carrier Sensing Threshold</td>
<td>+3 dB minimum</td>
</tr>
<tr>
<td>above the Noise Floor</td>
<td>+10 dB maximum</td>
</tr>
</tbody>
</table>
antennas are utilized. In addition, the use of directional patterns for RTS and CTS transmission could help to overcome the exposed terminal problem by spatial filtering of the interference but may increase the hidden terminal problem so a careful system design is needed.

In the following, it is assumed that each node is equipped with a switch beam antenna system, then the MAC sublayer must select the type of antenna (if using omnidirectional or directional) to transmit or to receive triggered by a given event (e.g. reception of an RTS). Hence it is needed to utilize what we will called a Beam Selection Policy.

4.2 Beam Selection Policies

For each transmission from $i$ to $j$ over link $(i, j)$, node $i$ and node $j$ must select the appropriated antenna sector. Five cases have been studied

I. **Omnidirectional Antennas**: All nodes within the network use omnidirectional antennas for communications for the whole time. This is the reference case.

II. **Beam Selection Policy I (Omni-RTS)**: During the transmission of
an RTS both nodes use omnidirectional antennas while during CTS and DATA transmissions both nodes use directional beams. See Fig. 4.6.a.

III. Beam Selection Policy II (Di-RTS): This policy is the same as policy I except that the RTS is transmitted using a directional beam. See Fig. 4.6.b.

IV. Beam Selection Policy III (Di-RTS/Omni-CTS): This policy is the same as policy II except that the CTS is transmitted using an omni-directional beam. See Fig. 4.6.c

V. Beam Selection Policy IV (Omni-RTS/ Omni-Rx.CTS/Di-CTS): During the transmission of an RTS both nodes use omnidirectional antennas while during reception of the CTS the originating node uses omnidirectional antenna and the receiving node transmit the CTS directionally. See Fig. 4.6.d

In all cases a receiving node (the one to whom the data is intended) use an omnidirectional reception of the CTS since doesn’t know who is the possible transmitting node. To keep the same radio range we utilized a simple power control strategy where the transmission power of node $i$ to transmit to node $j$ is given by

$$P_i = \frac{P_{omni}}{A_i(\theta_{ij})},$$

(4.9)

where $P_{omni}$ is the transmission power when transmitting with omnidirectional antenna.

Due to the complexity of the wireless Multiple Access Interference and the MAC protocol functionality it is not clear which policy performs the best. For instance, Policy I could help preventing collisions of CTS at the originating node and may help to prevent RTS collision at the receiving node. However, Omnidirectional transmission of RTS packets may cause unwanted interference. The use of directional transmission of CTS relays on the spatial filtering capability of the selected beam to transmit the data. On the other hand, Policy II is a more aggressive beam selection policy that relays completely in the interference rejection capability provided by the directional radiation pattern of the antenna. A more conservative strategy is given by policy III where transmission of an omnidirectional CTS may prevent transmissions that may or may not affect the receiving node. This may result in an unnecessary channel reservation that does not take advantage of spatial interference reduction of smart antennas.

Policies I,II, and III are very convenient if a node has total location information of its neighboring nodes. This could be the case for static or nomadic networks with very slow mobility. For a mobile scenario Policy IV is a possible and interesting solution. In a mobile scenario the originating node may not know where exactly its neighbors are located, therefore its start sending an omnidirectional RTS. After receiving the RTS the receiving node get the location
Figure 4.6: Beam Selection Polices used by node A to communicate with node B. Circles indicates the use of omnidirectional antennas and triangles directional antennas.

Information of the originating node and therefore can transmit a directional CTS which is received by the originating node using an omnidirectional antenna pattern. After that, the data transmission could be done using directional patterns by both nodes.
Note that other selection policies are possible but they were considered to result in lower performance improvement. For instance, it is possible to use both Omni-RTS and Omni-CTS but we can expect no significant benefit of reserving the channel this way.

4.3 Numerical Results

The performance using the above selection policies was evaluated using sample networks A and B in Fig.2.1.3. A carrier sensing threshold of 3dB above the noise floor was used since it performed best in the omni-directional case.

4.3.1 Policy I (Omni-RTS)

The results for sample network A and B are shown in Fig.4.7 and 4.8 respectively. It can be noted that in both networks for very low traffic load not significant impact on packet delay is observed using this policy. This is an expected result since for low traffic the probability that two nodes attempt simultaneous transmission is rather small. For medium and high traffic lower packet delay is always achieved by using narrower antenna beamwidth.

The use of of narrower antenna beamwidth always results in higher throughput. Fig.4.9 summarize the End-to-end maximum throughput achieved using this policy.

Note that higher throughput is achieved for network B since is better connected than network A (the average number of neighbors in network A is 7.5 while in network B is 10.5). On the other hand the relative improvement respect to the omnidirectional(see table 4.2) case is higher for network A since the network is more spread allowing better filtering of interference with 90, 60, and 30 degrees antenna beamwidth that with network B. The used of narrower antenna beamwidth results in an increasing SIR achieving substantial lower delay and higher throughput.

4.3.2 Policy II (Di-RTS)

One possible problem with Policy I could be the potential data packet collision with omnidirectional RTS transmissions. If a node is unable to heard a CTS after hearing an RTS and neither detect presence of carrier on the channel, it assumes that it can transmit since its estimation of the MAI indicates that it is out of the antenna front-end of the receiving node. This estimation could be completely wrong since the transmitting node uses a directional transmission of data. This create the risk that those nodes that in the omnidirectional case where considered exposed, starts transmitting an omnidirectional RTS that may produce significant interference at the receiving node while receiving the data packet resulting in degradation of the required SIR.
4.3. Numerical Results

Figure 4.7: Performance of Policy I (Omni-RTS) for network A.

Figure 4.8: Performance of Policy I (Omni-RTS) for network B.
Policy II try to improve on this problem by implementing a more aggressive transmission strategy transmitting with directional antennas during the whole procedure. This also produce the additional benefit of hardware complexity reduction since the need of power control is eliminated.

The performance using beam selection policy II are shown in Fig. 4.10 and Fig. 4.11 for networks A and B respectively. Similar to policy I, lower delay for medium and high traffic is obtained by this strategy. As expected, higher throughput is always obtained as the antenna beamwidth is reduced.

The End-to-end throughput improvement for policy I and II is summarize in Fig. 4.12. It is clear that policy II(Di-RTS) perform better than Policy I (Omni-RTS) in all cases. This confirm our previous analysis that omnidirectional transmission of RTS packets reduces the performance colliding with data packets.

The performance improvement in End-to-end throughput using policy I respect to policy II is shown in in Fig. 4.15. A throughput improvement of 21.6%, 31.8%, 21.4%, and 18.7% for network A, and 9.1%, 12.0%, 18.8%, and 18.1% for network B was obtained. Note that the improvement for network A increases up to 60° antenna beamwidth and then decreases with 30° and 10° beamwidth. Similarly, the improvement also increases until 30° antenna beamwidth and de-
4.3. Numerical Results

Figure 4.10: Performance of Policy II (Di-RTS) for network A.

Figure 4.11: Performance of Policy II (Di-RTS) for network B.
54 Switch Beam Antenna Systems

Chapter 4. Carrier Sensing Multiple Access with RTS/CTS and Switch Beam Antenna Systems

Antenna Beamwidth, $\phi_h$ (Degrees)

Performance Comparison for Policy I (Omni-RTS) and Policy II (Di-RTS)

<table>
<thead>
<tr>
<th>Policy</th>
<th>Network A</th>
<th>Policy</th>
<th>Network A</th>
<th>Policy</th>
<th>Network B</th>
<th>Policy</th>
<th>Network B</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td></td>
<td>II</td>
<td></td>
<td>I</td>
<td></td>
<td>II</td>
<td></td>
</tr>
</tbody>
</table>

Figure 4.12: End-to-end throughput comparison for Policy I and Policy II for networks A and B.

creases for $10^0$ beamwidth for network B. This is because the omnidirectional impact of RTS transmission reduces as the antenna beamwidth reduces which also confirming our previous statement.

4.3.3 Policy III (D-RTS/Omni-CTS)

A potential problem with policy II is that does not prevent transmission toward a receiving node even if this transmission may produce significant interference. One possibility to overcome this problem is through the use of Policy III (D-RTS/Omni-CTS) where transmission of an omnidirectional CTS is utilized. This result in a more conservative strategy since prevents transmission event if they may not result in destructive interference toward other direction.

The results with this strategy evaluated on our two sample networks Fig.4.13 and 4.14 show the performance on networks A and B respectively. As can see the use of this strategy results in poorer capacity improvement. Similar results to the Policy I and II for low traffic is obtained. However a significant lower throughput was found. This is an expected result since this strategy does not fully exploit the interference reduction achieved with directional antenna patterns. The use of omnidirectional CTS prevents transmissions that may not interfered with the outgoing data transmission. This seems to be the dominant effect. This can be
confirmed by the result of network A where nodes are more spread out limiting the number of nodes that are deferred by hearing an CTS.

The reason why this protocol does not produces significant improvement is because does not consider the direction of the intended receiver of the data packet to prevent transmission in that direction only. A smarter way to improve on this problem potentially producing better results could be find in [27] where they consider that multiple beams could be combined together. Even with a single beam selection, the use of location information to prevent transmission in the direction of the receiver, may result in better performance. Due to the complexity changing our simulator to include this functionality this research will be considered in further works.

4.3.4 Policy IV (Omni-Tx.RTS/Omni-Rx.CTS/Di-CTS)

As mention in section 4.2, this policy is suitable for mobile networks where does not exist exact knowledge of the location of a given node. Since the procedure start transmitting with an omnidirectional RTS and wait with an omnidirectional antenna pattern, lower performance could be expected with this policy than with Policy I and II for static networks.

Fig. 4.16 and 4.17 shows the results obtained by implementing this policy in networks A and B respectively. As expected, similar behavior to policies I and II for low and relatively high traffic is achieved. However the throughput improvement is reduced by both RTS and data collision as well as CTS collisions under high traffic conditions.

The interesting thing with this result is that a big improvement in the overall performance is achieved by using this strategy which may justified its use in mobile scenarios. The End-to-end throughput improvement obtained respect to the omnidirectional case was 28.6\%, 50.0\%, 85.7\%, and 121.4\% for network A and 22.2\%, 38.9\%, 72.2\% and 127.8\% for network B using 90\°, 60\°, 30\°, and 10\° antennas beamwidth respectively.

4.4 Beam Selection Policies in Rough Terrain

In this section impact of terrain roughness on the performance for the different policies is analyzed. Two different rural scenarios are evaluated using the terrain model described in Appendix C with roughness parameter $\sigma = 10m$ and $\sigma = 40m$ and smoothness parameter $\rho = 5km$ over a squared area of 50km x 50km. The network was deployed using 20 nodes randomly dispersed over the terrain until a connected network was found using the same criteria described in section 3.5 but with constant transmission power $P_i = 2dB$. Fig. 4.18 shows two networks topology, network C and D, over the rough terrain used in the numerical examples below. The average number of neighbors for network C was 13.9 and 12.6 for network D.
Figure 4.13: Performance of Policy III (Di-RTS/Omni-CTS) for network A.

Figure 4.14: Performance of Policy III (Di-RTS/Omni-CTS) for network B.
4.5. Summary

In this chapter we have proposed and evaluate the performance of Carrier Sense Multiple Access/ Collision avoidance with RTS/CTS control handshaking using omnidirectional and smart antennas. Since cost is of paramount importance in civilian applications we address the problem of implementing switch beam
Figure 4.16: Performance of Policy IV (Omni-Tx.RTS/Omni-Rx.CTS/Di-CTS) for network A.

Figure 4.17: Performance of Policy IV (Omni-Tx.RTS/Omni-Rx.CTS/Di-CTS) for network B.
Figure 4.18: Topology of network C with terrain standard deviation $\sigma = 10m$ and network D over rough terrain with standard deviation $\sigma = 40m$.

Figure 4.19: Performance on networks C and D with $\phi_h = 90^\circ$ antenna beamwidth.
Figure 4.20: Performance on networks C and D with $\phi_h = 60^\circ$ antenna beamwidth.

Figure 4.21: Performance on networks C and D with $\phi_h = 30^\circ$ antenna beamwidth.
technologies as the smart antenna method to increase the end-to-end throughput.

Four different Beam selection policies were proposed and their performance evaluated by discrete step simulation. Policy I, II, and III are well applied to static or nomadic networks while policy IV could be implemented for mobile networks where neither the transmitter nor the receiver knows in advance the exact location of its neighbors.

Table 4.2 summarizes the throughput improvement with respect to the omnidirectional case for all the beam selection policies when applied to the two sample networks A and B used to evaluate the performance. From this table it is found that the most aggressive strategy, Policy II (Di-RTS), which utilize directional antenna patterns all the time performs the best. This strategy fully exploit the spatial interference reduction provided by the use of directional antennas patterns. Up to 185% in throughput respect to the omnidirectional case was achieved by using this beam selection policy. An additional advantage with this policy is that can be implemented without power control to keep the same radio range of RTS and Data transmissions which results in lower hardware cost.

The throughput improvement of beam selection policy IV may justify its implementation in mobile networks. Up to 127.8% throughput improvement was obtained in our evaluation for network B.

Finally, Policy III (Di-RTS/Omni-CTS) could be considered the more conservative strategy evaluated producing the poorest result. A possible way to improve the results of this policy is using the location information to prevent

<table>
<thead>
<tr>
<th>Antenna Beamwidth (θh)</th>
<th>90°</th>
<th>60°</th>
<th>30°</th>
<th>10°</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam Selection Policy I (Omni-RTS)</td>
<td>35.7%</td>
<td>57.1%</td>
<td>100.0%</td>
<td>142.86%</td>
</tr>
<tr>
<td>Beam Selection Policy II (Directional-RTS)</td>
<td>64.3%</td>
<td>107.15%</td>
<td>142.9%</td>
<td>185.7%</td>
</tr>
<tr>
<td>Beam Selection Policy III (Di-RTS/Omni-CTS)</td>
<td>28.5%</td>
<td>42.9%</td>
<td>-</td>
<td>57.1%</td>
</tr>
<tr>
<td>Beam Selection Policy IV</td>
<td>28.6%</td>
<td>50.0%</td>
<td>85.7%</td>
<td>121.4%</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Antenna Beamwidth (θh)</th>
<th>90°</th>
<th>60°</th>
<th>30°</th>
<th>10°</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam Selection Policy I (Omni-RTS)</td>
<td>22.2%</td>
<td>38.9%</td>
<td>77.8%</td>
<td>144.4%</td>
</tr>
<tr>
<td>Beam Selection Policy II (Directional-RTS)</td>
<td>26.3%</td>
<td>47.4%</td>
<td>100.0%</td>
<td>173.7%</td>
</tr>
<tr>
<td>Beam Selection Policy III (Di-RTS/Omni-CTS)</td>
<td>5.6%</td>
<td>16.7%</td>
<td>-</td>
<td>17.0%</td>
</tr>
<tr>
<td>Beam Selection Policy IV</td>
<td>22.2%</td>
<td>38.9%</td>
<td>72.2%</td>
<td>127.8%</td>
</tr>
</tbody>
</table>
transmission only in the direction of the intended receiver. The incorporation of such as changes could be an interesting subject for further research.
Chapter 5

Conclusions

In this thesis we have studied the design of multihop ad hoc networks using either of two MAC protocols and smart antennas at both the transmitter and the receiver. When using the MAC protocol Spatial Time Division Multiple Access (STDMA), it is possible to control the relative capacity assigned to links, estimate the packet delay, and to provide some degree of quality of service. The drawback is that it may not offer good peak rates for bursty data traffic. The Carrier Sense Multiple Access/ Collision Avoidance (CSMA/CA) with RTS and CTS handshaking protocol has the ability to provide high peak data rates. The problem with this protocol, as with any other random protocol in multihop ad hoc networks, is that it is difficult to estimate the packet delay making quality of service guarantees problematic.

Application of smart antennas to Spatial Time Division Multiple Access is relatively uncomplicated and has been found to provide substantial gain in performance with respect to the omnidirectional case. The use of Adaptive Beamforming Antennas using Spatial Filtering for Interference reduction always results in higher Signal-to-Interference plus Noise Ratio and can be used to increase the reuse of slots in link assignment scheduling.

The potential improvement of smart antennas was found to be limited by route selections. When interference reduction measures such as narrow antenna beamwidth are used the constraint that a node can not receive and transmit at the same time becomes an important limiting factor. To improve the network performance a novel procedure to create the Link Schedule called Reused Adaptive Minimum Hop Algorithm was introduced and its performance evaluated. Substantial higher End-to-end throughput and lower End-to-end packet delay were demonstrated through application of the new strategy.

The influence of the terrain roughness on the network connectivity and performance of STDMA was also investigated. It was found that the terrain roughness influence the connectivity. However, for a given connectivity similar performance was achieved with different terrain roughness with omnidirectional anten-
nas and with adaptive beamforming antennas. This revealed that the network connectivity characterizes the network performance with this MAC protocol.

On the other hand, implementation of smart antennas with CSMA/CA with RTS and CTS is not straightforward. The use of smart antennas reduces the overall MAI thus reducing the exposed terminal problem, but their use may increase the hidden terminal problem. The problem of designing networks of this type using Switch Beam antenna Systems was addressed. Four different beam selection policies where proposed and their performance evaluated by discrete step simulation. Three of these policies (Policy I, II, and III) are well applied to static or nomadic networks while policy IV could be implemented for mobile networks where neither the transmitter nor the receiver knows in advance the exact location of its neighbors.

It was found that the most aggressive policy referred as Policy II (Di-RTS) which utilize directional antenna patterns whenever possible performs the best. This strategy fully exploits the spatial interference reduction provided by the use of directional antennas patterns. An additional advantage of this policy is that it can be implemented without power control to keep the same radio range of RTS and Data transmissions which results in lower hardware cost. This result was independent of the terrain roughness. If mobile networks are being considered then policy IV is recommended.

In general, CSMA/CA is a very complex MAC protocol with many parameters and it has been designed by considering that omnidirectional antennas are employed. Therefore, to fully exploit the potential improvement of smart antennas, further modifications to this MAC protocol need to be researched.
References


REFERENCES


Appendix A

Routing Decision for Reuse
Adaptive Minimum Hop
Algorithm

In the following the *relative capacity* of the network $C$ and the network topology are input parameters for routing decision. Each element in $C$ denoted by $C_{ij}$ represents the relative capacity assigned to link $(i,j)$ and it is given by (3.8).

A.1 Algorithm

I. Using the network topology, collect the set of paths with shortest distance between all $(S,D)$ pairs in the network.

II. Put the list of $(S,D)$ pairs in ascending order according to the number of possible paths; i.e. $(S,D)$ pairs with less number of choices are considered first. If several $(S,D)$ pairs have equal number of possible paths, order then according to the number of hops in descending order.

III. Set the relative traffic load $T_{ij} = 0; \forall$ links $(i,j)$.

IV. While there are elements in the list of $(S,D)$ pairs:
   
   A. Take the first $(S,D)$ pair in the list and take the first path as the best one.
   
   B. Store relative traffic load: $BestT_{ij} = T_{ij}; \forall$ links $(i,j)$
   
   C. Update the relative traffic load:

   $$BestT_{ij} = (T_{ij} + 1); \forall \text{ links } (i,j) \text{ in the selected path.}$$  \hfill (A.1)
Appendix A. Routing Decision for Reuse Adaptive Minimum Hop Algorithm

D. Compute the relative flow vector:

\[ \text{BestFlow} = \frac{C_{ij}}{\text{BestT}_{ij}} ; \forall \text{ links } (i, j) \text{in the selected path} \]  \hspace{1cm} (A.2)

E. While there are paths not considered for this \((S, D)\) pair:

1) Take the next path and store the relative traffic load:

\[ \text{NewT}_{ij} = T_{ij} \forall \text{ links } (i, j) \]  \hspace{1cm} (A.3)

2) Update traffic load:

\[ \text{NewT}_{ij} = (T_{ij} + 1) \forall \text{ links } (i, j) \text{ in the new path}. \]  \hspace{1cm} (A.4)

3) Compute the relative flow vector if we select this path:

\[ \text{NewFlow} = \frac{C_{ij}}{\text{NewT}_{ij}} ; \forall \text{ links } (i, j) \text{ in the selected path}. \]  \hspace{1cm} (A.5)

4) If Better( NewFlow, BestFlow) /* See Fig A.1 */ then

- \( \text{BestT}_{ij} = \text{NewT}_{ij} ; \forall \text{ links } (i, j) \)
- \( \text{BestFlow} = \text{NewFlow} \)

F. Update Traffic load and routing tables

1) \( T_{ij} = \text{BestT}_{ij} ; \forall \text{ links } (i, j) \)

2) Update table of relaying nodes:

- put in routing table of node \( i, (S,D)=j \), \( \forall \) nodes \( i \) in lins \((i, j)\) in the selected path.

G. Remove this \((S, D)\) pair from the list.
**Boolean Function Better(NewFlow, BestFlow)**

Better = False  
MinFlow = min(BestFlow)  
NewMinFlow = min(NewFlow)

```
Better = True
```

```
Yes
```

```
NewMinFlow > MinFlow
```

```
Better = True
```

```
No
```

```
NewMinFlow = MinFlow
```

```
Return (Better)
```

```
Yes
```

```
Sum(NewFlow = MinFlow) < Sum(BestFlow = MinFlow)
```

```
Better = True
```

```
No
```

```
Sum(NewFlow = MinFlow) == Sum(BestFlow = MinFlow)
```

```
/* Eval. Next Minimum */
BestFlow(BestFlow == MinFlow) = inf;
BestFlow(NewFlow == MinFlow) = inf;
```

```
Return (Better)
```

```
Yes
```

```
All elements of BestFlow== inf ?
```

Figure A.1: Function to decide if the traffic flow over a selected path is better that the previously selected.
Appendix B

Simulation of CSMA/CA with RTS and CTS

In our implementation of CSMA/CA a node could be in one of 5 stages: PASSIVE, RECEIVE, HANDSHAKE, BACKOFF, and TxDATA. A TIMER control the time the node will be within a stage before changing to another stage. Transition between states is triggered by the occurrence of different events (e.g. packet arrival, carrier sensing, TIMER expired etc.).

A node is in the stage PASSIVE while do not has packets to transmit and no carrier sense is detected. During this state the MAC sublayer order to the physical layer to utilize omnidirectional antennas. If while in this stage a packet arrives to the queue of the node, it transits to the HANDSHAKE stage and start transmitting an RTS packet to the relaying node (defined in its routing table) used to deliver the packet to its final destination, previous to start transmitting the packet the MAC sublayer order to the physical layer to use either omnidirectional antenna or select the sector with best signal quality for the relaying node depending of the beam selection policy been used. Within this stage, after transmitting the RTS, the node waits for a CTS from the relaying node using the antenna type defined by the beam selection policy being used. If no CTS is received a collision is assumed and the node deferred its transmission switching to use omnidirectional antenna and passing to the RECEIVE stage for the period required to transmit a maximum size data packet aiming to prevent destroying an outgoing communication. On the other hand, if a CTS with the address field to this node is received, it is assumed that the channel is acquired passing to the TxDATA state initiating the data transmission utilizing the sector with best signal quality for the relaying node.

After transmitting the data packet the node order to the physical layer to switch to omnidirectional antennas and defers any other transmission for at least the period required to hear a CTS passing to the RECEIVE stage. If while in PASSIVE a carrier is detected, the node changes to the RECEIVE stage to...
receive the information coming into the receiver (using omnidirectional antenna). A node remains in RECEIVE stage if no carrier is detected and if the TIMER set by any other stage does not expire. If carrier is detected the node starts receiving the packet from the physical layer and depending of the type of data received (RTS, CTS, DATA, or ERROR) it responds in different ways. If in this stage an RTS address to the node is received and the TIMER has not expired it does not answer to the RTS and remains in the RECEIVE stage. However, if the TIMER has expired it answers with a CTS to the requesting node using the antenna type defined by the beam selection policy being used and remaining in the RECEIVE stage afterwards using the sector with the best signal quality received from the transmitting node and setting the TIMER to the period of a packet. On the other hand, if a CTS is received while in RECEIVE stage, the node sets the TIMER in this stage for at least the period of a packet to avoid a possible collision with a data packet from any other node.

If in RECEIVE stage a Data packet is received with the address field the local node ID, this is passed to the network layer setting the TIMER to the period required to hear a CTS using omnidirectional antenna. Finally, if a data ERROR occurs, the node sets the TIMER in this stage for at least the period required to receive a data packet and using omnidirectional antenna. If the waiting time in RECEIVE expired while not carrier sense is detected and the node does not have packets in queue to be transmitted, it passes to the PASSIVE stage, otherwise it passes to the BACKOFF stage where omnidirectional antennas are used for carrier sensing.

In the BACKOFF stage an uniform distributed waiting time between 0 and 10 times the CTS period (contention windows) is generated. If the waiting time expire while not carrier is detected the node passes to the HANDSHAKE stage, otherwise it passes to the RECEIVE stage.

To simulate the interaction with other nodes and the channel perceived at each node, we used discrete step simulation where at an instance of time $t_i$ the channel state is passed to the node and its influence on the channel over the next time instants $t_{i+1}$ is returned as illustrated in Fig. B.1. Each node was simulated as a state machine following the MAC-protocol described before. The channel radio propagation conditions between nodes were computed using the channel models described in chapter 2. The received power level in a given instance of time is modified to include the antenna radiation pattern utilized by the node within the current state.

Further it is assumed that:

- To hold a reliable link, the minimum required SNR is 10 dB.
- All nodes are assumed to know the location of their neighbors (nodes within its radio range).
- Each node uses the Minimum Hop Algorithm (MHA) to route packets through the network.
Figure B.1: The channel perceived by a node is given in time $t_i$ and the node returns its influence on the channel at time instant $t_{i+1}$.

- Nodes use half-duplex transceivers with negligible turn around time from reception to transmission and vice versa.
- The packet processing time is negligible.
- An SINR of at least 10 dB is required during the whole packet transmission period for correct reception.
- The channel radio propagation conditions do not change with time but the Multiple Access Interference does.
- No multipath arrival signals are considered.

The minimum value for SNR of 10 dB correspond to the use of the Binary Phase Shift Keying (BPSK) modulation scheme and a BER below $10^{-5}$ in the presence of White Additive Gaussian Noise (AWGN) [38].

In practice, the transmitter turn around time, the round-trip radio propagation delay, and packet processing time are critical parameters that have to be considered at the MAC sublayer. For instance, while sending an RTS packet, the MAC sublayer switches the transmitter to ON and has to wait the transceiver turn around time before starting to transmit the packet. The same is true while
replying to an RTS packet or sending the DATA packet. On the other hand, the selection of the waiting time for an answer before assuming that a conflict has occurred is a critical design parameter. The waiting time for an answer after sending an RTS or a CTS must be the sum of the transmitter turn around time, the round-trip radio propagation delay, and the packet processing time delay. The packet processing time delay must include the time required to detect (carrier sensing delay), receive, and decode the packet. For instance, after transmitting an RTS, the packet processing time is the time needed for the receiving node to detect the RTS, decode the RTS and start to answer with a CTS. In the rural scenario, the radio range could be of several kilometers and the round-trip delay becomes significant. For instance, for a maximum radio range of 1km the round trip delay corresponds to $2(3.333) \approx 6.67 \mu s$, while for 40 km corresponds to $266.67 \mu s$ (0.267 ms). With 100 kbps the transmission time for a 500 Bytes packet is 40 ms, for 25 bytes RTS and CTS it is 2 ms. Therefore, with 100 kbps the round trip delay is negligible but is significant for 40 km (corresponding to 13\% $T_{RTS}$). In our simulation $t_{i+1} - t_i$ corresponds to a microslot and it was used to include the effect of the round trip delay selected to be 10\%$T_{RTS}$. 
Appendix C

Rough Terrain and Radio Propagation

To analyze influence of mountains in a rural environment we use a (synthetic) terrain which is a modification to the one introduced in [30]. In this model, the terrain height variations are modelled by a stationary two-dimensional random process, $H(x,y)$, in the locations $(x,y)$ given by

$$H(x,y) = \frac{1}{\sqrt{c}} \sum_{k=-\rho}^{\rho} \sum_{l=-\rho}^{\rho} |H^*(x-k, y-l)| p(k,l), \quad (C.1)$$

where $H^*(x,y)$ is a two dimensional white Gaussian process with zero mean and variance $\sigma^2$, and $p(k,l)$ is the impulse response of a filter given by

$$p(x,y) = \begin{cases} 
1 + \cos(\pi \sqrt{\frac{(x^2+y^2)}{\rho}}) & |x| \leq \rho, |y| \leq \rho \\
0 & \text{otherwise}, 
\end{cases} \quad (C.2)$$

and

$$c = \sum_{k=-\rho}^{\rho} \sum_{l=-\rho}^{\rho} p^2(k,l). \quad (C.3)$$

The parameters $\sigma(m)$ correspond to the standard deviation of the terrain height and $\rho(m)$ is an smoothness parameter that determines over which distance there exist correlation between heights. Fig. C.1 shows a typical terrain realization with $\sigma = 40$ m and $\rho = 5$ km used to simulate a hilly terrain. The maximum difference in terrain height was 70 m. In general, the terrain could be varied from relatively flat ($\sigma \approx 0$) to very mountainous terrain (high $\sigma > 40$).

The radio propagation properties of multihop ad hoc networks where analyzed using the diffraction model according to Epstein-Peterson refined by Ladell [31].
Appendix C. Rough Terrain and Radio Propagation

Figure C.1: Rough terrain realization with parameters $\sigma = 10\text{m}$ and $\rho = 5\text{km}$.

Figure C.2: Dominant (strongest) received power over rough terrain in Fig. C.1 with 20 nodes.

Using this model the overall propagation loss, $L_T$ is a combination of the diffraction loss produced by mountains, $L_{\text{diff}}$, the flat-earth propagation loss, $L_f$ and the free space propagation loss, $L_{fs}$, given by

$$L_T = L_{fs} + \sqrt{L_{\text{diff}}^2 + L_f^2} \text{ (dB)} , \quad (C.4)$$

These losses are calculated using the terrain model as described in [19]. Fig. C.2 shows the dominant received power level for a sample network deployed on the terrain of Fig. C.1.
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