Ad Hoc Network Capacity utilizing MIMO-techniques

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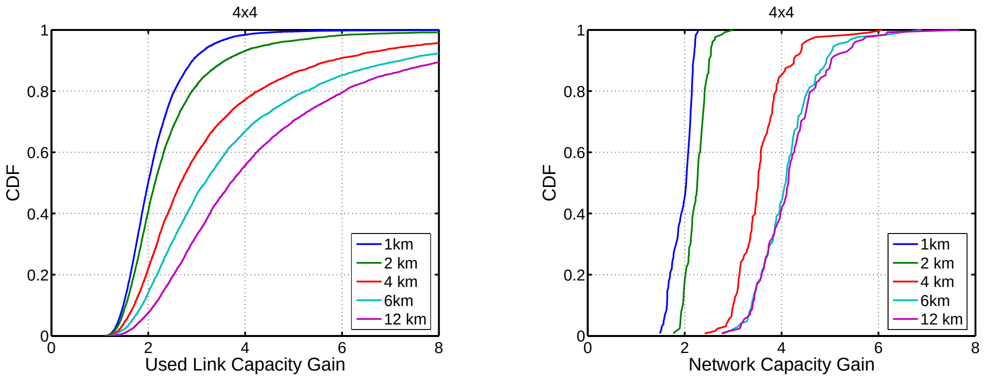

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Report title

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Abstract

Multiple-Input Multiple-Output (MIMO) antenna systems is a promising technique for achieving substantially increased capacities and robustness in future tactical wireless networks.

The purpose of this work has been to investigate the maximum network capacity gains that can be achieved by employing MIMO-techniques in wireless ad hoc networks. We study these gains from a theoretical viewpoint and derive a close formed expression of the network capacity. Furthermore, the network capacity is also examined in urban environments, using two different channel models. The results show that, the MIMO link capacity gains for links carrying traffic translate into similar network capacity gains. The network topology impacts the achievable network capacity gains, since for the examined dense networks the MIMO link capacity gains are on average significantly smaller than for sparse networks.

Keywords

Ad Hoc Networks, MIMO, Link capacity, Network Capacity

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Kapacitet hos ad hoc-nät vid användande av MIMO-teknik

Sammanfattning

Flerantennsystem (MIMO) är en lovande teknik när det gäller möjligheten att avsevärt kunna öka kapaciteten och robustheten i trådlösa taktiska kommunikationssystem.

Syftet med arbetet har varit att undersöka de möjliga nätvinsterna för trådlösa ad hoc-nät vid användande av MIMO-tekniker. Vi har studerat vinsterna utifrån ett teoretisk perspektiv och härlett ett slutet uttryck för nätkapaciteten. Dessutom har nätkapaciteten också undersökts, med hjälp av två olika kanalmodeller avsedda för stadsmiljöer. Resultaten visar på att MIMO länkkapacitetsvinsterna, för de länkar som används, överförs till liknande nätkapacitetsvinster. Nättopologin påverkar dock kraftigt den möjliga nätkapacitetsvinsten. För de undersökta kompakta näten är MIMO länkkapacitetsvinsten i medel avsevärt mindre än för de glesa näten.

Nyckelord

Ad hoc-nät, MIMO, länkkapacitet, nätkapacitet

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Contents

Chapter 1

Introduction

In order to achieve the desired high level of situation awareness, and a common operational picture for the Network Based Defence, a robust communication system with high capacity is of paramount importance. The use of sensor networks in future operations is expected to lead to an increased information flow in the radio network. Also, the use of video conferencing applications will further stress the communication network in terms of capacity and quality-of-service (QoS) guarantees. Furthermore, the concept of distributed databases is important in the development of future command and control systems. In this approach each unit regularly synchronizes the contents of its database with the other units in the network. Clearly, unless care is taken in the choice of what information should be regularly distributed to the units, this approach may require extremely high data rates on each communication link as well as an efficient utilization of the network resources.

Furthermore, the communication network must be able to handle dynamic scenarios where communication links appear and vanish frequently. Therefore, ad hoc radio networks are of particular interest in the military context since they can potentially be robust, self-forming and self-healing.

In conclusion, the dependence on the command and control system is destined to increase dramatically in future military operations, which in turn leads to increased demands on a high-capacity, low-latency radio network, with sufficient robustness towards jamming and other interfering sources.

Currently, software-defined radios, called GTRS Demo, are being developed for use in military vehicles. It is expected to be a very capable software-defined radio with unique ad hoc network capabilities, which is an essential feature for the intended users. GTRS Demo is also intended as an experimental platform for research and development on tactical ad hoc networks. Continued development, in both hardware and software (i.e. the radio waveform), is expected to take place after the procurement. Currently, several international programs are active, or underway, that focus on new broadband high-capacity waveforms for software-defined radios, e.g. the US JTRS program. The Swedish development in this area are performed within the GTRS (Common Tactical Radio System) program.

GTRS Demo is a general IP-radio that enables the distribution of various types of information, e.g. orders, unit positions, fire control and other command and control messages, if they are in the form of IP-packets. The GTRS Demo radios are, to some extent, designed to fulfill requirements that stems from a position distribution application (service). Thus, it is expected to enable the timely distribution of unit positions to other units that need/desire this information, thereby enabling efficient command and control as well as increasing the safety of the individual units (e.g. through supervision of indirect fire and/or improved blue force tracking). However, in the future it is anticipated that the amount of traffic that the users want to transmit through the network will supersede the capacities that will be provided by this first GTRS generation. Thus, continued research efforts are required in order to develop link-level techniques and network protocols that give the means to boost up the performance of future generations of GTRS radio waveforms.

Cross-layer considerations in ad hoc networks

It is widely accepted in the research community that various types of cross-layer approaches are required in order to achieve the desired large improvements in wireless network performance [1]. However, it is essential that a large level of modularity is kept in the protocol structure of the waveform in order to enable efficient maintenance and continued development [2]. Now, there are many different definitions of the term cross-layer, and a large amount of the research on ad hoc networks can be labeled as cross-layer approaches.

The main principal reasons for introducing cross-layering in wireless networks (as compared to wired networks) are the [1,2]:

- unique problems created by wireless links (e.g. high error rates and varying network topologies),

- possibility of opportunistic communication on wireless links (e.g. exploiting the time-varying link for opportunistic use of the channel through dynamic adaptation of transmission parameters),
- new modalities of communication offered by the wireless medium (e.g. that the physical layer can receive multiple packets at the same time, and the broadcast nature of the wireless channel as opposed to the point-to-point channel for wired communications).

Multiple-Input Multiple-Output (MIMO) antenna systems has the potential to yield very large link capacity gains [3,4] for frequencies that are of interest for future tactical radio systems (i.e. around 300 MHz), in particular for urban peer-to-peer scenarios. Furthermore, the use of MIMO-systems enables an increased robustness of tactical radio systems in difficult electromagnetic environments. A vehicle-mounted antenna array for the frequency range 240-380 MHz may possibly be designed by using four to eight quarter-wavelength monopole antennas, which are about 20-30 centimeters in length and perhaps a few centimeters in diameter. The antennas can for instance be placed (approximately) circularly on the turret of a fighting vehicle or main battle tank. From a cross-layer perspective, in this work we mainly focus on cross-layer issues between the two lower levels in the well-known OSI reference model, the physical-layer and the data link layer.

Motivation

In particular, the purpose of this work has been to examine the theoretical capacity gains that can be achieved in a reservation-based ad hoc network when employing MIMO-systems. If this study indicates that there is a potential for significant network capacity gains, then this may motivate further studies on what gains can be achieved in practice. We will also discuss how the use of different MIMO-techniques affects the medium access control (MAC) and routing algorithms (network layer).

Report outline

The outline of the report is as follows. Chapter 2 presents the basic MIMO-theory. Issues about how to introduce MIMO-techniques in an ad hoc network from a network protocol perspective are discussed in Chapter 3. The topic of Chapter 4 is how to calculate network capacity, and the related prerequisites and assumptions. Chapter 5 describes the two different urban environment channel models, and the scenarios, that are used to investigate link and network capacities. The results from the investigations are presented in Chapter 6. Finally, Chapter 7 summarizes the work and the main results.

Chapter 2

Basic MIMO-theory

Communication systems where both the transmitter and receiver are equipped with multiple antennas are commonly known as MIMO-systems (Multiple-Input-Multiple-Output). There exist a large variety of different MIMO-algorithms, which all have different performance gains and complexity attached to them [5]. MIMO-techniques are often grouped into three different classes depending on the principal gains they provide to the system (see Figure 2.1):

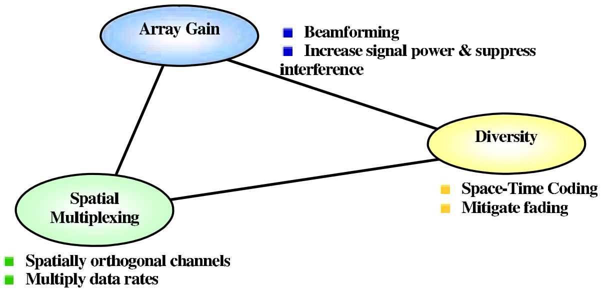


Figure 2.1: Different MIMO-techniques and associated principal gains.

- Array, or beamforming, gain, where the goal is to increase the signal power and/or suppress interference.
- Space diversity, whereby fading can be effectively mitigated.
- Spatial multiplexing, which makes it possible to multiply the data rates.

Depending on the scenario at hand different MIMO-techniques should be used. For example, in line-of-sight (LOS) scenarios, adaptive beamforming is the preferred technique. In most urban scenarios, with strong multipath propagation, combined transmit and receive space diversity can effectively minimize the detrimental effects due to signal fading. Furthermore, in these scenarios spatial multiplexing may yield dramatic improvements in the achievable data rates.

2.1 Beamforming

Beamforming can be performed in both the transmitter and receiver, thereby yielding an enhanced SNR, which for example can be used to increase the radio systems data rate, range, coverage, or to reduce the error rate. Also, adaptive interference suppression can be performed in the receiver, thereby substantially increasing the radio systems robustness in challenging electromagnetic environments. By employing adaptive interference suppression in the receiver it is possible to increase the number of transmissions in a given area. Also, this gives the opportunity to simultaneously receive different messages from multiple transmitters by using the spatial domain to separate them. This has important implications on higher-level protocols as will be discussed later.

The beamforming discussed in the MIMO context may differ from the traditional view of beamforming. In traditional transmit beamforming, where the transmitted energy is to be concentrated in certain specified directions in space, the antennas should have a spacing that is below $1/2$-wavelength in order to achieve a controlled side lobe pattern. In contrast, when performing ”MIMO-beamforming”, using accurate Channel State Information (CSI) it is possible to achieve array gain with larger antenna spacing by using the multipath structure of the channel to calculate beamforming weights (both the transmitter and receiver weights simultaneously) so that the link SNR is maximized. In traditional beamforming, which is normally used in LOS scenarios, the main lobe of the antenna is usually directed towards the receiver. In MIMO-beamforming that is performed in non-LOS scenarios the resulting ”beams” can be completely different, with a very weak relationship to the LOS direction.

2.2 Space Diversity

Space diversity is a bandwidth efficient method for mitigating the negative effects of fading. The principle is simple; if two or more antennas are spaced sufficiently apart the received signals in the antenna elements will fade differently. Thus, by using the signal from the antenna that for the moment experiences the best channel conditions, or by combining the signals from the antennas intelligently, the fading can be significantly reduced. Also, it can result in an enhanced average SNR. By increasing the signal quality it is possible to increase the data rate (through adaptive modulation), communication range or coverage.

Space diversity can also be achieved by using multiple transmit antennas and by coding the signal over both space and time (or frequency), through e.g. Alamouti's proposed Space-Time Block Coding (STBC) scheme [6].

Although space diversity can be an effective and relatively simple technique, the performance gains may become limited under certain conditions. If the signal levels in the antennas are not sufficiently uncorrelated the diversity gain can be reduced. This can occur for closely spaced antennas, on for instance fighting vehicles or tanks where the platform limits the possible antenna separations. However, on these platforms the antennas are positioned relatively close to ground and in many environments the multipath structure will be sufficient to yield satisfactory diversity gains.

2.3 Spatial Multiplexing

Spatial multiplexing is a relatively new technique that can be used to increase the spectrum efficiency (transmitted bits per second per Hertz) of radio systems in environments with substantial multipath. In spatial multiplexing, the multipath is exploited instead of being suppressed. The idea is to transmit separate data streams that are differently encoded, on different transmit antennas, thereby increasing the capacity. In multipath-rich scenarios the separate data streams can all be detected in the receiver. In theory, a maximum capacity gain proportional to the number of transmit antennas can be achieved in multipath-rich environments, provided the receive antennas are at least as many as the transmit antennas. However, the channel will limit the obtainable capacity gains for our applications. Channel state information (CSI) is required in the receiver in order to separate the parallel data streams. If CSI is available also in the transmitter, then the capacity may be increased even further, through water-filling principles, compared to the case where CSI is only available in the receiver [5]. For frequencies around 300 MHz, spatial multiplexing is a technique that enables enhanced data rates mainly for vehicle mounted radio systems in dense urban, and for sub-urban, environments. To a smaller extent, we believe that increased data rates may be achieved even in forest areas. It may also be an interesting technique for soldier-worn communication systems operating at higher frequencies (above 1 GHz), where e.g. uniform-integrated textile MIMO-antennas may become a viable option in the future.

2.4 Channel Estimation

In most MIMO-techniques, channel estimation is required in the receiver. Furthermore, if the transmitter has channel state information, (e.g. SNR) increased performance gains are usually possible to obtain. However, the channel quality estimation can be a difficult task, especially for mobile urban scenarios where the wireless channel varies rapidly. Accurate CSI is often possible to achieve at the receiver by transmitting known training symbols. It is usually more difficult to obtain accurate CSI at the transmitter, at least for mobile scenarios. For example, if the CSI is estimated during transmissions in an earlier time slot, or sent in an earlier data packet, it may be outdated when a new transmission time slot to the same receiver occurs. In contrast, for a random based CSMA/CA MAC protocol, accurate CSI may be estimated from the RTS/CTS packets. The quality of the channel estimates is likely to be the limiting factor for how large gains can be obtained in practice with different MIMO- techniques.

2.5 Theoretical MIMO Capacity Gains

The theoretical capacity that is obtainable for a Single-Input Single-Output (SISO) communication system in additive white Gaussian noise, C_{SISO}, was shown by Shannon to be

$$C_{SISO} = \log_2(1 + E_s/N_o) = \log_2(1 + \rho) \ [\text{bps/Hz}] \,, \tag{2.1}$$

where E_s is the symbol energy, N_0 is the noise energy in the receiver, and ρ denotes the average SNR.

The average capacity when using multiple antennas at the receiver, C_{SIMO}, is given by [7]

$$C_{SIMO} = \log_2(1 + \rho \mathbf{h}\mathbf{h}^H) \; [\text{bps/Hz}] , \tag{2.2}$$

where $\mathbf{h}$ is a (row) vector containing the (time-varying) complex channel responses from the single transmit antenna to all of the receiving antennas, and $(\cdot)^H$ denotes the Hermitian transpose. Henceforth, for MIMO-systems ρ denotes the average SNR per receive antenna. For a MISO-system, the capacity is equivalent.

By increasing the number of transmit (or receive) antennas, the SNR can be increased linearly, i.e. using two or four transmit (or receive) antennas may increase the SNR with 3-dB or 6-dB, respectively, compared to the SISO case. Hence, for MISO- and SIMO- systems the capacity can, in theory, be increased logarithmically with the number of transmit antennas (receive antennas for the SIMO case). However, the main purpose of performing transmit or receive diversity is normally to combat the adverse effects of fading, thereby improving the transmission quality.

The theoretical capacity for a MIMO-system is [7],

$$C_{MIMO} = \log_2 \left(\det \left[\mathbf{I} + \frac{\rho}{n_{Tx}} \mathbf{H}\mathbf{H}^H \right] \right) \; [\text{bps/Hz}] , \tag{2.3}$$

where $\det[\cdot]$ denotes the determinant operator, n_{Tx} is the number of transmit antennas, and $\mathbf{I}$ is the identity matrix. For a MIMO-system with two transmit and two receive antennas the capacity expression reduces to

$$C_{2\times 2} = \log_2 \left(1 + \frac{\rho}{2}\lambda_1 \right) + \log_2 \left(1 + \frac{\rho}{2}\lambda_2 \right) . \tag{2.4}$$

Here, λ_1 and λ_2 are the eigenvalues of the matrix $\mathbf{H}\mathbf{H}^H$, where the MIMO-channel matrix for this case is defined as

$$\mathbf{H} = \begin{bmatrix} h_{1,1} & h_{1,2} \\ h_{2,1} & h_{2,2} \end{bmatrix} \tag{2.5}$$

The complex channel responses between the antennas are defined in Figure 2.2.

Hence, from the theoretical capacity expression for a MIMO-system we can see that the capacity may be increased linearly with the number of transmit antennas, provided that we have at least as many receive antennas. Thus, the

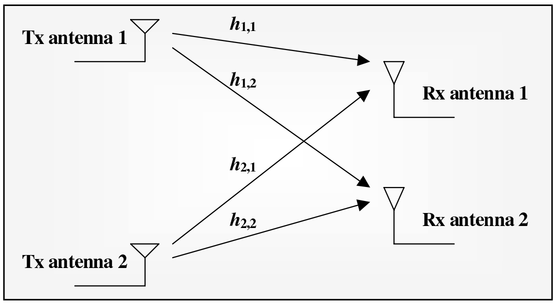


Figure 2.2: The channels between the antennas for a 2 × 2 MIMO-system.

potential capacity for a MIMO-system is dramatically increased, in comparison to MISO- and SIMO-systems where the capacity increases logarithmically with the SNR. Also, this requires that enough eigenvalues of $\mathbf{H}\mathbf{H}^H$, which corresponds to the strength of the so-called eigenmodes of the channel, are of similar strength. Thus, for a 2×2 MIMO-system there must be at least two strong eigenvalues in order to double the capacity through spatial multiplexing. The desired channel matrix only exist in environments with strong multipath. The strong multipath is required, otherwise the separate data streams may not be resolved in the receiver. For instance, a LOS channel will yield a single strong eigenvalue; hence, spatial multiplexing will yield no capacity gain.

Finally, it is worth mentioning that many (but not all) of the existing MIMO-algorithms assume flat fading channels, which make the combination of MIMO and OFDM-systems (will be described in a later section) particularly appealing. When calculating the corresponding theoretical capacities of an OFDM-system we begin by calculating the individual capacities of each (orthogonal) sub-carrier, and thereafter sum up these capacities to get the total capacity for the whole bandwith. The capacity for each sub-carrier is calculated as,

$$C_{f,MIMO} = \mathrm{BW}\log_2\left(\det\left[\mathbf{I} + \frac{\rho_f}{n_{Tx}}\mathbf{H}_f\mathbf{H}_f^H\right]\right)\ [\mathrm{bps}]\,, \tag{2.6}$$

where BW is the sub-carrier bandwidth and ρ_f is the mean SNR for sub-carrier f. Now, for channels where the mean SNR of the different antennas differ, the mean value of the SNR is calculated for the antennas and used instead. Finally, assuming a total of F sub-carriers the total capacity is then calculated as

$$C_{MIMO} = \sum_{f=0}^{F-1} C_{f,MIMO} \text{ [bps]}, \tag{2.7}$$

Also, following the work in [3], the MIMO-channel matrix is normalized such that

$$\|\mathbf{H}_f\|_F^2 = n_{Tx} n_{Rx}. \tag{2.8}$$

2.6 Theoretical MIMO and SISO capacities for measured radio channels

MIMO-channel measurements have been performed at 285 MHz outside FOI in Linköping, for a peer-to-peer scenario, with a MIMO radio channel sounder. The measurements are described in more detail in [3, 4]. The maximum obtainable capacities have been calculated for these measured channels (according to Eq. (2.3)). Over the measured scenario, a circular vertically polarized 7×7 MIMO-system typically supported an increased capacity of 3-7 times compared to a SISO-system. The estimated theoretical SISO and MIMO capacities over two measurement routes are shown in Figure 2.3. Also, in [3] the capacity gains obtainable with MISO- and SIMO-systems are calculated.

The measurements were performed over relatively short distances (from 200 to 450 meters), in a semi-rural and sub-urban environment, and it is believed that the MIMO capacity gain will increase further for larger measurement distances as well as in dense urban areas. Thus, these measurements clearly suggest that MIMO-systems around 300 MHz has the potential to yield substantial capacity gains for vehicle mounted antenna systems in urban environments.

2.7 Discussion

A multitude of combinations of the earlier discussed MIMO-techniques can be used. For instance, transmit beamforming may readily be used in conjunction with receive diversity or combined beamforming and adaptive interference suppression. Also, by combining transmit and receive diversity, a multiplicative

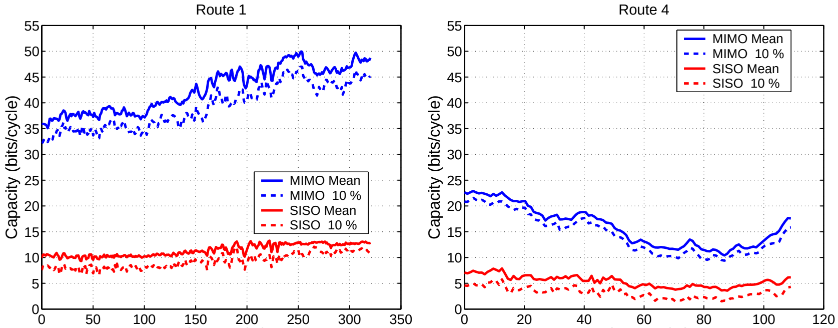


Figure 2.3: Capacity vs. distance at a fixed output power for the 7x7 MIMO system compared with a SISO system. Solid lines are mean capacities and the dashed lines are the capacities at an outage level of 10% (For detailed explenation see [3]).

diversity order is achieved; hence, using three transmit and three receive antennas a diversity order of nine can be achieved. Spatial multiplexing can be combined with adaptive interference suppression techniques in the receiver. To some extent, the different MIMO methods complement each other.

The choice between different MIMO-techniques is heavily dependent upon the number of antennas in the MIMO-systems. For a radio system operating around 300 MHz it may be possible to use up to six, or perhaps eight, antennas (that are sufficiently separated) at typical military vehicles. At higher frequencies more antennas may be possible. Space diversity methods are generally preferred if only two antennas exist at each side, the potential capacity increase that can be obtained with spatial multiplexing can then be exceeded by the benefits using space diversity. For systems employing four or more antennas both spatial multiplexing and beamforming are very interesting options.

The choice of which technique should be used depends on the scenario at hand. Beamforming methods are preferred in line-of-sight scenarios. In other scenarios beamforming can be readily utilized at the receiver; however, transmission array gain is more difficult to obtain under non-LOS conditions since accurate CSI is required. Spatial multiplexing can yield very large capacity gains in scenarios with severe multipath. Space diversity is an attractive option in non-LOS situations with few antenna elements or if the processing power is limited.

Chapter 3

MIMO in Ad Hoc Networks

MIMO and smart antenna systems have the potential to substantially increase the link performance and reduce interference, as discussed in the previous chapter. The link performance gains can be expressed in several ways, e.g. as increased data rates, increased robustness or increased communication distances. However, there are many open issues regarding how to exploit those link performance gains, and the possibilities to reduce interference, in wireless networking.

3.1 Networking Aspects

By utilizing MIMO-systems we can switch link modes, from spatial multiplexing or diversity, to beamforming. In the beamforming case we sectorize the space and make use of the spatial domain. Through beamforming an array gain can be achieved and interference can be suppressed. However, whenever we chose to utilize the spatial domain we have to carefully look over the network protocol design. Most protocols are designed with the assumption of omnidirectional antennas at the transmitter and the receiver. Whenever beamforming is used, protocols for scheduling, node/neighbour discovery, network initialization and configuration may need to include mechanisms to deal with the spatial domain. Routing, flow control, and possibly other higher layer protocols, may also benefit from taking the spatial domain into account, but this may also require protocol modifications.

The traffic, whether it is point-to-point or broadcast traffic, is another factor that will influence the choice of appropriate MIMO technique. On a point-to-point link the three principle gains can be utilized, as discussed earlier. On the other hand, in a broadcast transmission from one node to many receiving nodes, the array gain is normally restricted to the receiving side. The diversity gain from MIMO is useful in a broadcast situation. There is a tradeoff to consider in broadcast transmissions, between either reaching many nodes over a large area at a low data rate, or reaching few nodes at a small area at a high data rate. Spatial multiplexing using several omni-directional antennas is possible, but how to most efficiently utilize the potential spatial multiplexing gain for broadcasting over the entire network is an open issue. A similar tradeoff as in the diversity case should be considered. Letting the data rate to different nodes be different is a possibility, but such an approach requires new broadcast protocols. Unequal error protection coding and modulation make it possible to detect different amounts of information from a received packet dependent on the SNR at the receiver.

Another issue is how to utilize the possible link performance gains that are enabled by MIMO-systems. In a high density network the right strategy could be to focus on increasing the data rates on the links by spatial multiplexing. In a low density network the strategy could instead be to first increase the communication distance on some critical links to get a reasonably connected network, and therafter increase the data rate on the remaining links [8, 9]. An alternative is to use some redundancy for interference cancellation to increase the spatial reuse, thereby enabling more simultaneous transmissions in the network.

3.2 Cross-layer Design for MIMO-Techniques

Next, let us briefly consider the MIMO-techniques from a protocol-layer perspective and the need for protocol modifications, or new protocols, when introducing the various MIMO-techniques.

If spatial multiplexing or diversity, assuming fairly omni-directional antennas, is used it is likely that no major protocol modifications are necessary. However, in order to take full advantage of the increased data rates we should be able to handle variable data rates on the different links. This can be done by the routing, e.g. base the routing metric on the data rate. To do this is feasible in most proactive routing protocols, but it can be a problem in some of the reactive protocols [10]. Furthermore, in a time slotted system we should make sure that the slot sizes match the set of data rates for the given packet size, or else allow for packet fragmentation. Moreover, a traffic adaptive reservation based MAC protocol will need information about the link data rates in the scheduling.

As soon as we introduce beamforming most MAC protocols will be affected [11, 12]. An exception is a simple TDMA protocol with unicast traffic, but such a protocol does not take advantage of the reduced interference situation. By Spatial reuse TDMA (STDMA) we can use beamforming on the point-to-point links without too much modifications. Adaptive beamforming at the receiver can give a significantly increased spatial-reuse [11]. However, to be able to take advantage of the reduced interference situation we need either a network model including the interferences, or actual interference measurements. Thereafter, this information is used in the scheduling in order to increase the spatial-reuse. In a static scenario, and assuming a centralized scheduler, this is a feasible extension, but it will be much more troublesome to include it in a highly mobile scenario. Also, time slots need to be left for the control traffic, and for new nodes so they can join the network. For those slots omni-directional transmissions should be used, e.g. using transmit diversity.

For random access based MAC like CSMA the situation is different since it is based on carrier sensing [12]. For example, a node A might not detect a neighbouring node B if it transmits to another neighbouring node C by beamforming, even if A is within omni-directional sensing range from B and C. Node A may therefore start a transmission to B (or C) with a collision as a result. Anyway, there are many issues to consider in random access protocol design when incorporating MIMO-systems at the link level. Most work on MIMO MAC is for CSMA based protocols, e.g. the popular 802.11 protocol that uses a request to send and clear to send (RTS/CTS) handshake [13].

Beamforming will influence the node/neighbour discovery phase. This can of course be avoided, if the part of the time frame allocated to discovery phase uses omni-directional transmissions. Unfortunately, then we do not get a complete picture of the network and its connectivity, e.g. a node may only be connected to the network in the beamforming mode. It is clear that obtaining the complete picture about how the network can be connected considering all the different MIMO modes, will be complicated.

Routing may benefit from beamforming. By far the greater part of the papers in that area, e.g. [8], consider MIMO together with reactive routing. In the route search procedure the possibility to switch between different MIMO modes is useful. Furthermore, a spatial domain term, e.g. the area inhibited by a routing path, can be introduced in the route metric. Such a term may also be useful in the SISO case. In conclusion, there is a need for new routing protocols, in particular for reactive routing, taking the MIMO aspects into account.

Beamforming with multiple antennas open up the possibility to simultaneously transmit different data streams to different receiving nodes. Also, at the receiving side simultaneous streams from different transmitting nodes can be separated. Such simultaneous reception is normally less costly, in terms of power usage, than simultaneous transmissions [13]. Notice that reception of multiple streams can be done either in the spatial domain by beamforming, or with normal multiple-access methods. Hence, we have, besides the modes discussed earlier, also the choice to introduce MIMO multiple access into ad hoc networks. With multiple access we then mean that a node can simultaneously receive (or transmit) different data streams from several different nodes. Most existing network protocols are not equipped to handle MIMO multiple access.

The great flexibility offered by MIMO, the different modes including the multiple access option, gives us the posibility to employ a very capable adaptive link layer in an ad hoc network. However, a very large link level adaptivity may be difficult to exploit in a network. A large, and still mostly unexplored, research area is how networks through resource optimization and cross-layer design can handle and exploit such an adaptive and variable data link layer effectively.

Chapter 4

Network Capacity

In this Chapter we will derive a closed form expression for the network capacity in a wireless network, with a reservation based MAC protocol that utilizes adaptive link data rate. Adaptive link data rate is a prerequisite to fully utilize the full potential of MIMO-techniques. In Section 4.1 we establish a few needed definitions and describe the network model. The actual derivation of the network capacity is performed in Section 4.2.

4.1 Network Model

To ease the formulation of our network model we need two definitions. First let $\mathcal{N}$ denote the set of nodes in the network, i.e.

$$\mathcal{N} = \{i : i \in [0, N-1]\}. \tag{4.1}$$

Secondly, we let $\mathcal{L}$ denote the set of links in the network, i.e.

$$\mathcal{L} = \{(i, j) : i \in \mathcal{N}, j \in \mathcal{N}, i \neq j\}. \tag{4.2}$$

4.1.1 Link Model

Orthogonal Frequency Division Multiplexing (OFDM) is a flexible multi-carrier technique that can achieve high capacity with a feasible complexity. In an OFDM-system, a frequency selective channel is transformed into multiple flat fading sub-channels by transmitting data on multiple orthogonal narrowband sub-carriers. Thus, instead of transmitting data symbols over a large bandwidth for a very short time, the symbols are transmitted on multiple narrowband sub-carriers where the length of each symbol is much larger than the delay spread of the channel. Different modulation-levels may be assigned to the sub-carriers, depending on their signal-to-noise-ratios, in order to increase the data rates.

4.1.2 Medium Access Control

CSMA is one of the most frequently used MAC protocols in ad hoc networks. Like most contention-based protocols, it inherently has problems with providing QoS guarantees. Another MAC protocol that is more suitable from a QoS perspective is TDMA. TDMA is a static collision-free protocol where the channel sharing is done in the time domain, i.e. time is divided into time slots, with duration T_s, and each node is assigned one or several time slots where it is allowed to use the channel. In our study, the protocol is node-oriented. Since each node has a fixed resource allocation, it is possible to make delay bound guarantees for bounded, i.e. finite, network loads.

Traffic adaptivity in reservation based protocols

To increase the maximum network throughput, we use traffic adaptivity in the MAC-layer, i.e. bottleneck nodes in the network are assigned more time slots than other nodes, see for example [14].

Let Λ_{ij} denote the number of routes that includes link (i, j). We then define the slot requirement, s_i, for node i as the sum of the quotient between Λ_{ij} and the capacity , C_{ij}, for all outgoing links from the node,

$$s_i = \sum_{\forall j \in \mathcal{N} : C_{ij} > 0} \frac{\Lambda_{ij}}{C_{ij}} \,. \tag{4.3}$$

If we assign node i

$$t_i = \frac{s_i}{\sum\limits_{\forall j \in \mathcal{N}} s_j}, \tag{4.4}$$

time units we assure perfect traffic adaptivity. This is of course not realistic, in a real system we would have to use discrete values for the time slots. Furthermore, a discretization of the time slot length can lead to very large frame lengths. We want to avoid that since large frame lengths leads to large network delays. In order to avoid that it is often necessary to trunkate the frame so in practice we would not achive perfect traffic adaptivity.

4.1.3 Routing

We use minimum cost routing which is solved with Dijkstra's algorithm described in [15]. Due to the variable link data rate we do not use the common number-of-hops cost metric. Instead we use the more suitable inverse of link data rate ($1/C_{ij}$) as cost metric [16]. This creates a routing table that minimizes the channel utilization needed to transport a packet to its destination node.

4.1.4 Traffic Model

We assume unicast traffic, i.e. a packet has a single source and single destination. Unicast traffic can be modelled as a stream of packets where each packet enters the network at a source node v_i according to a probability function $p_s(i)$, and leaves the network at a destination node v_j. The choice of destination node for a packet can be modelled by a conditional probability, i.e. given that the source node is v_i the probability that the destination node is v_j is $p_d(j|i)$.

We use a traffic model where packets of equal size, 1 bit, arrive to the network according to a Poisson process, with arrival rate λ. That is, on average λ bits per second arrive to the network.

Furthermore, we assume that the traffic is uniformly distributed over the nodes, i.e. each node is equally probable as source node and each node except the source node is equally probable as destination node. Hence, $p_s(i) = 1/N$ and $p_d(j) = 1/(N-1)$, where N is the number of nodes in the network.

4.2 Network Capacity

The network capacity is often measured as the maximum load that the network can sustain while still having a finite network delay. We define the network delay as the expected value of the average end-to-end packet delay over all routes. With that we define the network capacity, λ^*, as the largest input traffic arrival rate for which the network delay is finite. Hence, the network is considered stable when the following condition holds for all links (i, j)

$$\lambda_{ij} \leq \mu_{ij}, \tag{4.5}$$

where λ_{ij} is the traffic load on link (i, j) and μ_{ij} is the capacity of link (i, j). The maximum throughput is reached when the condition is met with equality for at least one link.

In order to calculate the network capacity we make the following assumptions

- Fully connected network (via multi-hop).
- Possible to assign arbitrary time unit to each node and the node is able to fully utilize that time for transmissions (no guard times etc.)
- There is always data to transmit and we have uniform unicast traffic.
- Traffic adaptive TDMA.
- We only assume that a routing table exists (no specific metric) that gives us a the link load Λ_{ij}.
- We do not consider mobility, only instantaneous capacity.

To calculate the traffic load, λ_{ij}, on link (i, j) we note that the network is connected and therefore there are a total of $N(N-1)$ point-to-point connections in the network. If there are Λ_{ij} routes that traverses link (i, j) and we have uniform traffic, we can write λ_{ij} as

$$\lambda_{ij} = \lambda \frac{\Lambda_{ij}}{N(N-1)}\,, \tag{4.6}$$

where N is the number of nodes.

Returning to Eq. (4.5), the maximum number of bits/s that can be transmitted by link (i, j) is

$$\mu_{ij} = t_{ij} C_{ij}\,, \tag{4.7}$$

where t_{ij} is the time units that are allocated to link (i, j) and C_{ij} is the capacity in bits/s given by Eq. (2.3). Since we use a node oriented protocol, we need an expression for the fraction of time, denoted α_{ij}, that node i uses link (i,j) when it transmits. We can write α_{ij} as the quotient between the slot requirement for link (i,j) and the total slot requirement for node i

$$\alpha_{ij} = \frac{\dfrac{\Lambda_{ij}}{C_{ij}}}{\displaystyle\sum_{\forall n \in \mathcal{N}: C_{in} > 0} \frac{\Lambda_{in}}{C_{in}}}. \tag{4.8}$$

The time unit t_{ij} is then given by

$$t_{ij} = \alpha_{ij} t_i. \tag{4.9}$$

With Eqs. (4.6), (4.7) and (4.9) we can rewrite Eq. (4.5) as

$$\lambda \frac{\Lambda_{ij}}{N(N-1)} \leq \alpha_{ij} t_i C_{ij}. \tag{4.10}$$

Solving for λ and searching for the maximum λ for which Eq. (4.5) holds for all links we get

$$\lambda^* = \min_{(i,j) \in \mathcal{L}} \left(t_i \alpha_{ij} C_{ij} \cdot \frac{N(N-1)}{\Lambda_{ij}} \right). \tag{4.11}$$

With Eqs. (4.4), (4.8) and (4.11) we get

$$\lambda^* = \frac{N(N-1)}{\displaystyle\sum_{(n,k) \in \mathcal{L}} \Lambda_{nk}} \cdot \frac{\displaystyle\sum_{(n,k) \in \mathcal{L}} \Lambda_{nk}}{\displaystyle\sum_{(n,k) \in \mathcal{L}} \frac{\Lambda_{nk}}{C_{nk}}}. \tag{4.12}$$

We can identify the left term as the inverse of the mean route length, $\bar{L}$, in terms of number of hops. The right term is the weighted harmonic mean with weights Λ_{nk}. Hence, we can write the network capacity as

$$\lambda^* = \frac{1}{\bar{L}} \cdot \frac{\displaystyle\sum_{(n,k) \in \mathcal{L}} \Lambda_{nk}}{\displaystyle\sum_{(n,k) \in \mathcal{L}} \frac{\Lambda_{nk}}{C_{nk}}}. \tag{4.13}$$

This equation gives us the means to calculate the capacity in a TDMA network with traffic adaptivity. It will be used further on to explain the results in Ch. 6. The weighted harmonic mean implicates that the capacity of bottleneck nodes, nodes with large Λ_{ij}, will have a greater impact on total network capacity than other nodes.

We can make two additional observations of special cases. First, if all links that are used have equal capacity C, then Eq. (4.13) reduces to

$$\lambda^* = \frac{C}{\bar{L}}. \tag{4.14}$$

The second observation is that if the network is a single hop network, i.e. we have $\Lambda_{nk} = 1$, Eq. (4.13) reduces to

$$\lambda^* = \frac{N(N-1)}{\displaystyle\sum_{(n,k)\in\mathcal{L}} \frac{1}{C_{nk}}}, \tag{4.15}$$

which we can identify as the harmonic mean of the link capacity.

Chapter 5

Simulation Scenarios and Parameters

In this work we have examined the theoretical performance gains that can be achieved with MIMO-systems for two different channel models for urban environments. An essential part of modelling an on-ground or near-ground radio network is the electromagnetic propagation characteristics due to the terrain variations.

5.1 SCME - A Geometry Based Stochastic Channel Model

The WINNER project [17] developed a channel model called Spatial Channel Model Extended (SCME) [18], [19] based on the 3GPP Spatial Channel Model (SCM) [20]. The 3GPP SCM is a geometry based stochastic channel model for macro- and microcells in 3G mobile systems. The SCME as an extension of the 3GPP SCM adds the following features:

- Intra-cluster delay-spread.
- 5 GHz path-loss model.
- Line-of-sight (LOS) and K-factor model for all scenarios.
- Time-variant shadow fading.

- Time-variant angles and delays.
- Reduced-variability TDL model.

A modification of the standard SCME has been performed to more accurately model the behavior of the radio channel at 300 MHz. This modification consists of a different path loss model in order to achieve more realistic low frequency channels. The changes has been described in more detail in [21]. Furthermore, we are interested in a peer-to-peer communications scenario, but the SCME model is designed for a base station cell scenario, with one elevated node. Thus, the resulting multi-path distributions will differ.

For scenario generation with SCME we use the options listed in Table 5.1, all options not listed there are left at their default values. The networks generated with SCME consists of 32 nodes randomly scattered in square shaped area. To get an indication on what impact the node density has on MIMO capacity we vary the length of the square's sides over 1 km, 2 km, 4 km, 6 km and 12 km. Also, we evaluate the following antenna configurations 1×1, 2×2, 4×4 and 8×8, all in the form of a uniform linear array (ULA) with an element spacing of $\lambda/2$. For each set of parameters we have generated 128 random network topologies.

Table 5.1: For scenario generation with SCME the following options were used. For all other options the default values were used.

Option	**Value**	**Description**
CenterFrequency	300 MHz	The center frequency.
Scenario	urban_macro	The SCME channel scenario.
ShadowingModelUsed	yes	Include shadow fading.
BsHeight	1.5	Base station height.
MsHeight	1.5	Mobile station height.

5.2 RPS - A Ray-Tracing Based Channel Model for Urban Environments

We have also used a commercial ray-tracing based channel model, named RPS (Radiowave Propagation Simulator), in order to simulate more realistic sitespecific MIMO-channels in urban terrain [22]. RPS simulates the wireless channel impulse response by using a building-layout of a city, transmitting rays in different directions, and following the rays until their energy is below a specified threshold. Hence, it can calculate the rays that arrive at the receiver taking signal reflections, diffractions, and penetration (through walls) into account. It is mainly designed for mobile telephony frequencies, but it can also be used at lower frequencies such as 300 MHz with a reduced accuracy.

We simulated the channel impulse responses for all links in a 23 node (static) network, consisting of 11 node pairs and a single node, distributed over an area of approximately 8-by-6 kilometres, see Figure 5.1. The node pairs were positioned a few hundred meters from each other, typically with one node positioned in a street crossing and the other node in a potentially more malign position. We wanted to examine if these relatively small differences in positions would have a significant effect on the achievable MIMO link capacities.

In these simulations, one ray was transmitted for every degree. Also, a first-order diffraction model was used, where rays were traced only for diffraction components that occurred into shadow regions. The reason for these choices was to keep the computational complexity of the simulation on a manageable level. Also, the transmit power was set to 1 W, and the threshold for when the rays were cut off from the simulation was set to -130 dBm. Due to the lack of detailed information concerning the buldings (e.g. windows, wall thickness and materiel, etc), no penetration of the radio wave was allowed in the simulations.

We examined the capacity gains for 2×2, 4×4 and 8×8 MIMO-systems. The antennas were positioned uniformly on a circle with 1 m radius, i.e. using a UCA geometry.

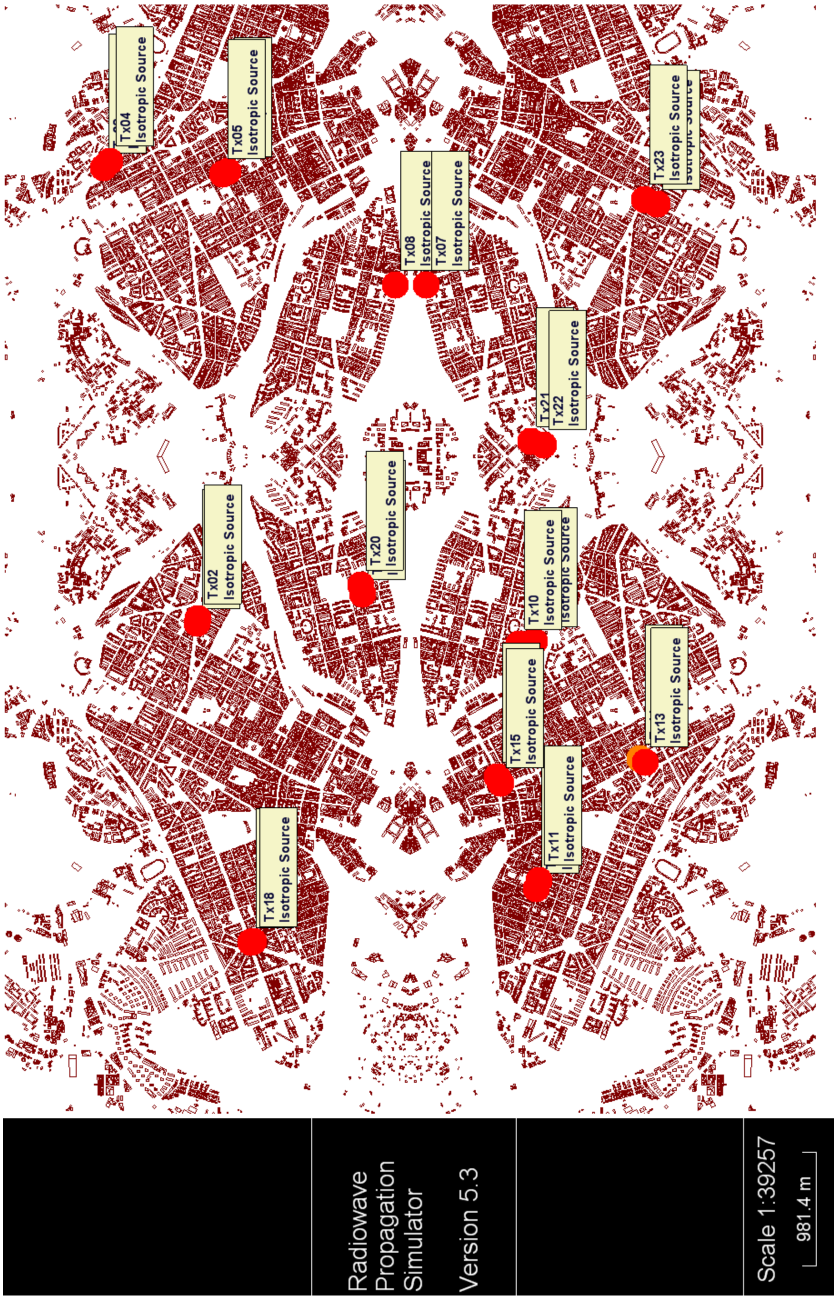


Figure 5.1: The urban network scenario, RPS enables scenario based evaluation of MIMO-performance gains on both link and network levels.

Chapter 6

Results

In this chapter we present the results from the investigations about the theoretical link and network capacity gains when utilizing MIMO-systems. The first section contains the results for the geometry based stochastic channel model (SCME), and the second section the results for the ray-tracing based channel model.

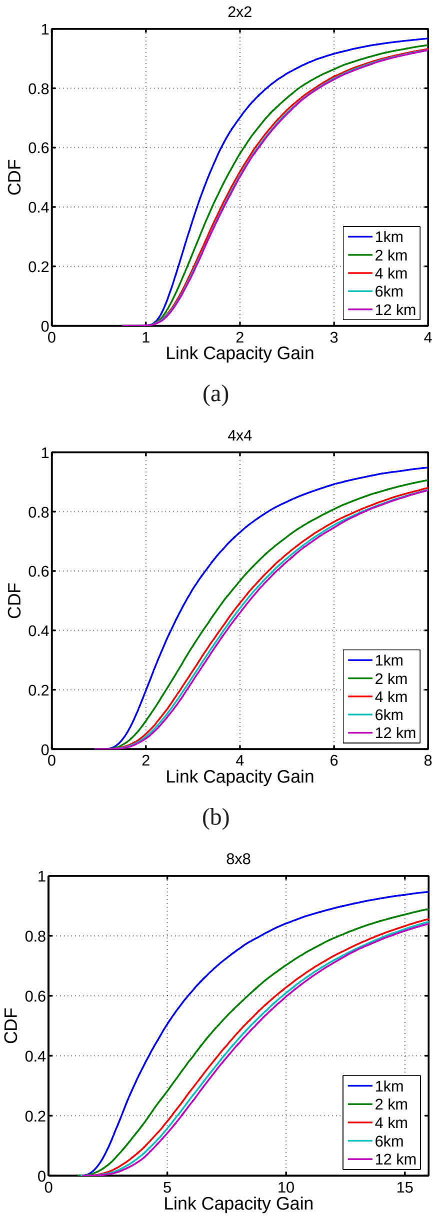
6.1 Link and network capacity gains for the SCME channel model

Theoretically, the maximum mean link gain achievable with spatial multiplexing is, assuming independent Rayleigh-fading channels, given by

$$\min(n_{Tx}, n_{Rx}), \tag{6.1}$$

where n_{Tx} and n_{Rx} are the number of antenna elements at the transmitter and receiver, respectively. As discussed earlier, this capacity can only be achieved if sufficient multipath is present. Note that the link capacity gains shown here are the maximum theoretically achievable gains in average (comparable to Shannons well known capacity formula for single antenna systems). Thus, the full potential of these capacity gains will not be achieved in practice.

Figure 6.1 shows the Cumulative Distribution Function (CDF) for link capacity gains with different antenna configurations. The link capacities are calculated as the theoretical capacities according to Eq. (2.7). For the examined

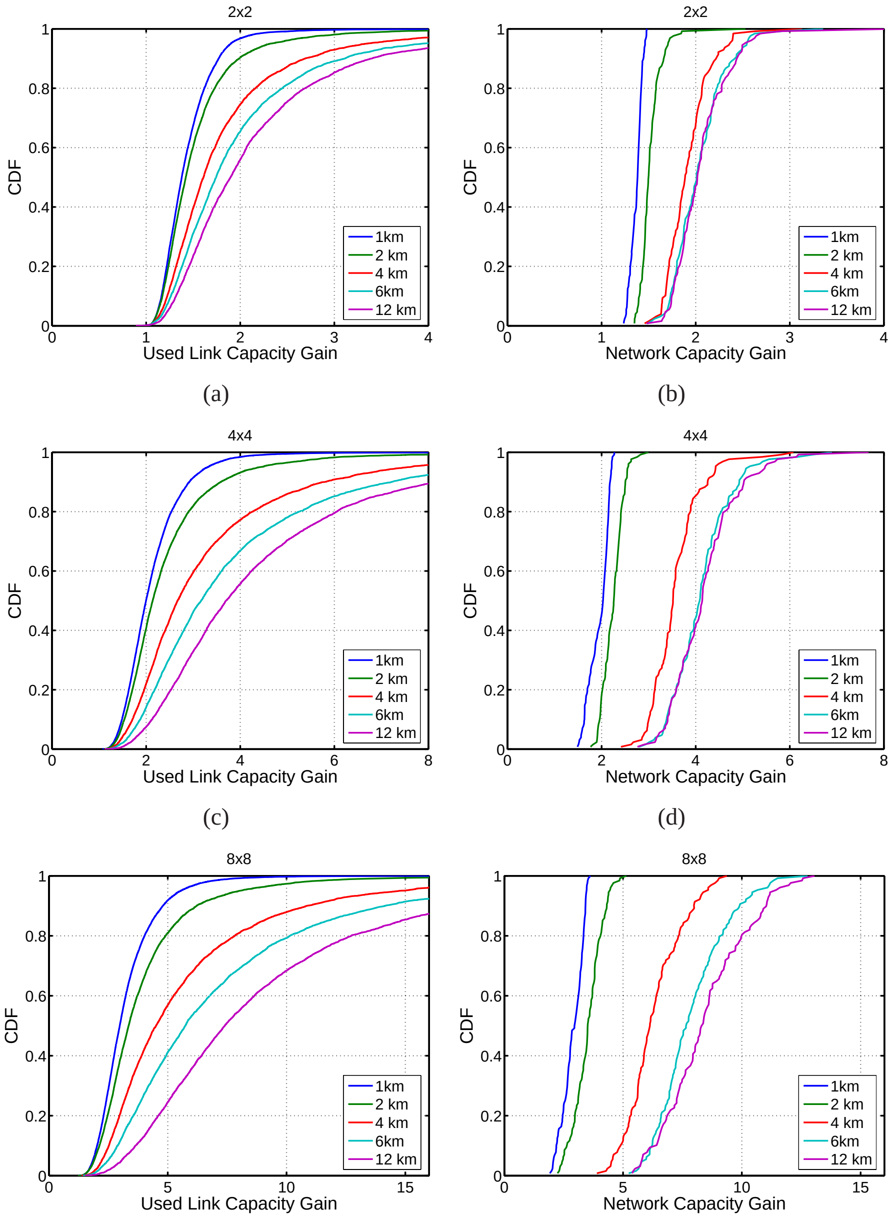


(a)

(b)

(c)

Figure 6.1: Link capacity gains for 2×2-, 4×4- and 8×8-MIMO.



(a) (b)

(c) (d)

(e) (f)

Figure 6.2: Network and link capacity gain for different antenna configurations.

channels the median value of the link capacity gain is comparable to those predicted by Eq. (6.1). We can also note that the gain depends on the node density of the network. A larger MIMO gain is obtained in the sparse networks. The length of the links will increase for these networks, resulting in reduced correlation in the different receiving antennas. Furthermore, we see that for the 8×8 antenna case the median link capacity gain is almost twice as large for the sparse (12 km) network as compared to the dense (1 km) network.

The CDF of the link capacity gains show surprisingly large gains. For a few of the channel realizations the gain in link capacity was over 100 times. The reason is that, for this channel model, in particular cases the whole 5 MHz bandwidth fades in the SISO case. Of course, for these links the SISO capacity was very small due to a very low SNR, and by employing several antenna elements it is likely that at least one of the receiving antenna elements experiences a reasonable SNR. However, in practice these large capacity gains will not be obtained for a time-varying channel since the small scale fading normally is handled by error-correcting coding. Moreover, the small scale fading behaviour obtained with this channel model is not expected to occur in real-world wideband peer-to-peer radio channels.

The network capacity gain is affected by the distribution of MIMO link capacities. Naturally, if all links experience similar MIMO gains, then the network capacity will increase by the same amount. The network capacities were calculated according to Eq. (4.13). Note however, that *only* the links that are chosen by the routing protocol affects the network capacity. The CDF of the link capacity gains for these links, with different antenna configurations, are shown in Figures 6.2(a), 6.2(c), and 6.2(e). The number of such used links is much smaller than the total number of links and the long and weak low capacity links are only used in particular cases, e.g. when they are needed to connect the network. In the route selection the good links with high capacity are preferred. Thus, such links dominates as used links in a dense network, but when the network get sparser, more and more weak links will be used. Correspondingly, since the network capacity is obtained from the capacities of used links (and their traffic), it is in a sparse network to a larger extent obtained based on capacities of weak links. However, the SISO and MIMO capacity difference is larger for weak than for good links, this is further illustrated in the next section in Figure 6.5.

In the Figures 6.2(b), 6.2(d), and 6.2(f) we can see how the link capacity gains are transformed into network capacity gains. The network capacity gains are largest for the sparse and large area networks. Thus, it is in sparse networks that MIMO is most effective in terms of median network capacity gain as compared to median link capacity gain (as shown in Figure 6.1). However, note that the (absolute) network capacity decreases with an increased network area. The large and sparse networks contain long and low capacity links as well as long routes with many hops.

When examining Figure 6.2, we see that the median value of the network capacity gains is comparable to the corresponding median value of the link capacity gains (for the used links) for a given network area. However, for the sparse networks the median network capacity gain is somewhat larger than the corresponding median link capacity gain. One reason is that in the sparse networks we have more links with, compared to the median value, high link capacity gains.

When considering the CDFs of the network capacity gains (Figure 6.2) we can notice a steeper function than for the link capacity gains, i.e. there are much fewer networks having a capacity gain that deviates significantly from the median network capacity gain. This can be explained by the formulas derived in Section 4.2, where we concluded that the network capacity can be expressed as the weighted harmonic mean of the link capacities. There, the weight for a link is given by the number of paths (traffic) crossing that link. Note also that a small link capacity has a larger contribution to the harmonic mean than a large link capacity, see Eq. (4.13). Consider a case where we have two specific links in the network, with the same link capacity but with different amounts of traffic. Assuming no re-routing occurs, then more is gained in network capacity if the link carrying more traffic gets an increased link capacity compared to the link carrying less traffic. This can also be intuitively explained as follows: the network capacity gain will be somewhere between the largest and smallest link capacity gains in that particular network; thus, the CDF of the network capacity gain will become steeper than the corresponding link capacity gains.

With MIMO, as compared to SISO, the mean route length (i.e. average number of hops) is reduced, as can be seen in Figure 6.3. How much shorter the route length becomes depends on the network area. For the dense network (1 km) the route length is hardly reduced. This is probably because the average route lengths are short and the used routes already contains high capacity links in the SISO case. The largest reduction in route length occurs for the 2 km and

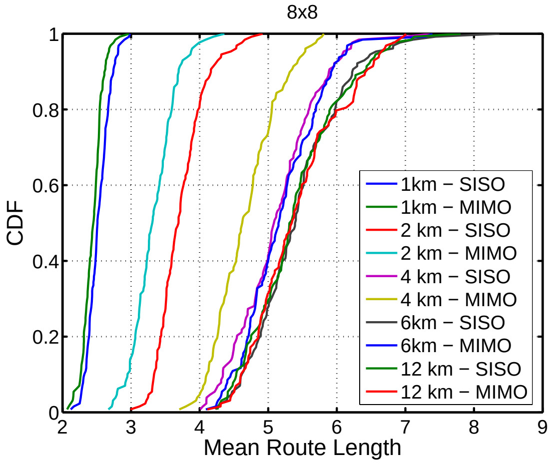


Figure 6.3: Mean route length for 8×8-MIMO.

the 4 km networks. However, for the examined sparse networks (long links), utilizing MIMO hardly affects the route lengths. A probable explanation in this case is that when selecting a route the path loss is the dominating factor. For sparse networks the difference in path loss between alternative routes exceeds the difference in MIMO gains that the alternative routes may experience.

Table 6.1: The median number of links that are used (i.e. traffic carrying links) in the network for various network densities and antenna configurations.

	1 km	**2 km**	**4 km**	**6 km**	**12 km**
SISO	95	54	39	37	36
2×2	98	58	40	37	36
4×4	101	61	41	37	36
8×8	102	64	43	38	36

In Table 6.1 we present the median number of links that carries traffic in the network for various network densities and antenna configurations. There we see that employing MIMO-techniques can increase the number of traffic carrying links. If we use more links the length of the TDMA schedule will increase, if we have a link-based schedule, with the consequence of increased network delay. However, the mean route length decreases when using MIMO-systems, as can be seen in Figure 6.3, and this decreases the network delay. The total impact on network delay is therefore still somewhat unclear.

6.2 Link and network capacity gains for the RPS channel model

In Figure 6.4 the link capacity gain with MIMO is shown for the channels obtained with RPS. For this scenario, with relatively large distances between the nodes, only about 100 links are available. For the remaining links, no rays received the intended receivers with sufficient energy.

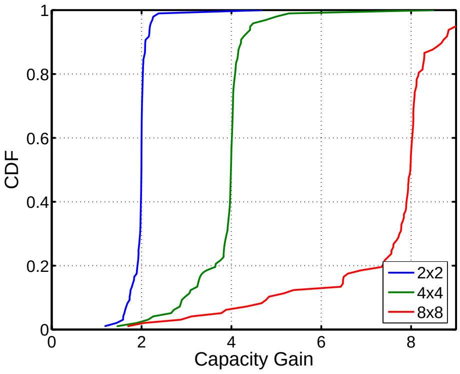
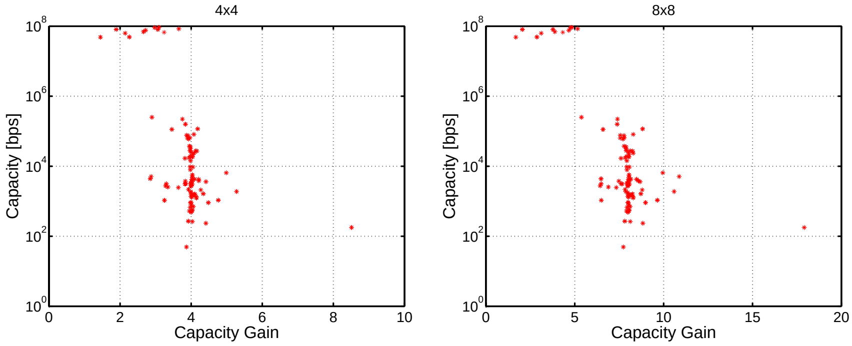


Figure 6.4: Link capacity gain (for all available links).

The CDF of the link capacity gains are steeper for these channels compared to the examined stochastic channel model. We can see that the median value of the link capacity gain is in the order given by Eq. (6.1). A fraction of the links (about 20 percent) does not get such a link capacity gain for this scenario. A closer examination shows that it is mainly the short, high capacity links between the nodes in the node pairs that yield the low link capacity gain, see Section 5.2. The SISO capacities over these links are however very high. In Figure 6.5 we illustrate the SISO link capacity versus link capacity gain with MIMO for the different links in the scenario, where the dots in the upper left corner represent the short links. It is also interesting to see that the link capacity gain increases less for these links when using 8 instead of 4 antennas, thereby indicating that these channels do not support the full use of spatial multiplexing techniques. Roughly, we can see that the long links achieve the expected link capacity gain with MIMO, but they have lower absolute link capacities compared to the short links.



(a) 4×4-MIMO (b) 8×8-MIMO

Figure 6.5: SISO Capacity vs. capacity gain.

The network capacity gains, as well as the average number of hops, are shown in Table 6.2 for different antenna configurations. The distances between the nodes are large which implies large path losses and the difference in MIMO gains for the links is relatively small. Hence, the same routes, with an average of 3.94 hops, are used for all examined antenna configurations. The network capacity gains equal the median link capacity gains, with capacity gains of 2, 4 and 7.99 for the different antenna configurations.

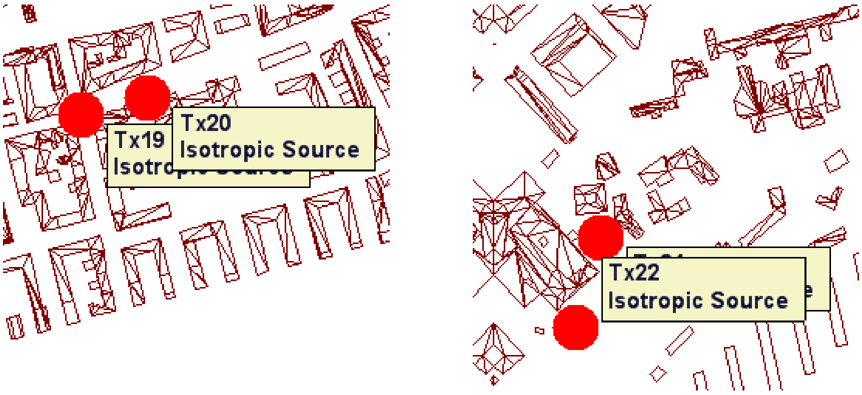
Table 6.2: Network capacity gain and mean number of hops.

	$\mathbf{2 \times 2}$	$\mathbf{4 \times 4}$	$\mathbf{8 \times 8}$
Network Capacity gain	2.00	4.00	7.99
Mean hops	3.94	3.94	3.94

Finally, in Table 6.3 we show the differences in link capacities for the links between two specific node pairs. The two short links between neighboring nodes have (SISO) capacities of about 80 and 49 Mbit/s, while the longer links can support capacities from about 4 kbit/s up to 116 kbit/s. The MIMO capacity gain for the short links (2.8 and 3.8 times) is well below the capacity gains for the longer links (between 6.3 and 8.8 times). Furthermore, detailed examination revealed that the link between node 19 and 21 had a smaller angular spread for the incoming rays compared to the link between 19 and 22. This results in a higher capacity gain for the latter link. Also, we see that the MIMO capacities varies significantly for the long links despite of the relatively short differences in distance; hence, the local positions of the nodes has a large impact on link capacities. However, it is not certain that the nodes placed in street crossings yield higher capacities compared to somewhat more "hidden" nodes (positioned along streets).

Table 6.3: The link capacity between the two node pairs 19,20 and 21,22.

Link	**SISO**	**2×2**	**4×4**	**8×8**
19-20	80.19 Mbit/s	127.35 Mbit/s	245.66 Mbit/s	302.87 Mbit/s
19-21	4.38 kbit/s	6.33 kbit/s	12.50 kbit/s	28.42 kbit/s
19-22	31.82 kbit/s	63.44 kbit/s	126.58 kbit/s	251.07 kbit/s
20-21	116.44 kbit/s	223.92 kbit/s	487.12 kbit/s	1.03 Mbit/s
20-22	27.06 kbit/s	56.52 kbit/s	112.51 kbit/s	223.45 kbit/s
21-22	48.93 Mbit/s	80.05 Mbit/s	110.65 Mbit/s	140.57 Mbit/s



(a) Node 19 and 20

(b) Node 21 and 22

Figure 6.6: Detailed view of the positions of nodes 19-22.

Chapter 7

Conclusions

In order to achieve the desired high level of situation awareness, and a common operational picture for the Network Based Defence, a robust communication system with high capacity is essential. Multiple-Input Multiple-Output (MIMO) antenna systems is a promising technique for achieving significantly increased capacities and robustness in future tactical wireless networks. However, there is still a need for new protocols to fully utilize the capabilities of such advanced radio link techniques.

In this report, we have discussed how MIMO-techniques affects network protocols, primarily focused on MAC and routing protocols. In summary, the effect on network protocols from introducing spatial multiplexing and diversity are less compared to introducing beamforming approaches. Also, in order to achieve increased network capacities we need to use protocols that can handle adaptive data rates.

We have derived a closed form expression of the network capacity for a reservation based MAC protocol, utilizing traffic adaptivity. The network capacity then becomes the weighted harmonic mean of the capacities of the links that carry traffic, divided by the mean route length (see Eq. (4.13)).

The theoretical maximum MIMO link capacity gains has been examined for two different urban environment channel models, a geometry-based stochastic channel model and a ray-tracing based model. Large MIMO link capacity gains could be observed over the examined channels. The theoretical MIMO gains were mainly affected by the distance between the nodes. The high MIMO gains can only be achieved if sufficient multipath is present. Furthermore, the local position of the nodes significantly affects the link capacities.

We have also examined how link capacity gains translates into network capacity gains. The results show that the MIMO link capacity gains for links carrying traffic translate into similar network capacity gains. The network topology determines the achievable network capacity gains. For instance, for the examined sparse networks the median network capacity gain was close to the number of antenna elements. However, for the dense networks the median network capacity gain was significantly smaller, in some cases reduced with about 50%. The reason is that, for the examined dense networks the MIMO link capacity gains are on average significantly smaller than for sparse networks. For the dense networks the links are shorter on average and these links yields lower MIMO link capacity gains. Moreover, MIMO-techniques led to reduced mean route lengths, but the reduction depends on network topology.

In summary, the purpose of this work has been to investigate the maximum network capacity gains that can be achieved by employing MIMO-techniques, and the examinations show that the network capacity gains are substantial. Hence, these results merit further research on how well existing protocols achieves these gains, and how new protocols should be designed to efficiently exploit the possibilities with MIMO-systems.

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