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High capacity techniques for mobile radio networks

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Sammanfattning

Huvudmålen med rapporten är att

- beskriva tekniker som har potentialen att avsevärt förbättra kapaciteten i taktiska ad hoc nät,
- ge läsaren en förståelse för återstående utmaningar som behöver lösas för att kunna införa kapacitetsförbättrande länktekniker i framtida militära radiovågformer.

De mest intressanta teknikerna för att förbättra kapaciteten inkluderar adaptiv modulation och kodning, MIMO-tekniker och algoritmer för kontroll av vem/vilka som vid en given tidpunkt får utnyttja kanalen (MAC-algoritmer). Adaptiv modulation/kodning och MIMO-tekniker används sedan flera år i civila radiosystem. Vilken prestanda som kan erhållas med dessa tekniker i urbana *peer-to-peer* scenarion vid 240-400 MHz är dock fortfarande okänd under realistiska antaganden angående tillgångänglig-heten av aktuell kanalinformation, samt för icke-ideala kanalestimatorer.

Ett stort antal forskningsfrågeställningar angående adaptiv kodning och modulation och MIMO presenters och rekommendationer ges för vilka av dessa som projektet ska försöka lösa.

Slutligen så identifieras och diskuteras de viktigaste krav och begränsningar som resulterar från de högre lagren på högkapacitetsteknikerna på länknivå. Några av de mest centrala aspekterna gällande samdesignen av de undersökta länkalgoritmerna och MAC-algoritmen har identifierats. Det är sannolikt att betydande modifikationer av vågformen är nödvändiga för att effektivt kunna utnyttja de föreslagna högkapacitetsteknikerna i mobila ad hoc nät. Idag är dock kunskapen om hur dessa tekniker ska samdesignas rudimentär och för att lösa uppgiften kommer betydande forsknings- och utvecklingsinsatser krävas.

Nyckelord:

Adaptiv modulation och kodning, MIMO, ad hoc network, kapacitet, cross-layer

Summary

The main objectives with this report is to:

- present and describe techniques that have the potential to significantly increase the capacity of tactical ad hoc networks,
- give the reader an understanding for the remaining challenges that need to be solved before incorporating these techniques in future military radio waveforms.

The most interesting techniques for increasing the capacity of future military waveforms include: adaptive modulation and coding (ACM) schemes, MIMO-techniques (which uses multiple antennas at both transmitter and receiver), and multiples access control (MAC) schemes utilizing elaborate traffic adaptivity and spatial-reuse techniques. Adaptive modulation/coding and MIMO-techniques are commonly used in civilian systems and standards. However, the achievable capacity gains for typical military peer-to-peer scenarios at 240-400 MHz is still unknown considering realistic conditions, e.g. on real-world urban peer-to-peer communication channels, and with imperfect channel information and channel estimators.

Several outstanding research questions regarding adaptive coding and modulation and MIMO are described, and recommendations are given concerning which of these should be targeted by the project.

Furthermore, we have identified and discussed the most crucial requirements and restrictions stemming from the higher layers on the high capacity techniques. Also, some of the most crucial aspects concerning the co-design of ACM, MIMO and MAC algorithms have been identified. It is believed that major protocol modifications are needed in order to efficiently utilize the proposed techniques in mobile ad hoc networks. However, the knowledge of how to co-design MAC together with MIMO and ACM algorithms for tactical ad hoc networks is rudimentary at this point and this task will require substantial research and development efforts to solve.

Keywords:

MIMO, adaptive coding and modulation, cross-layer design, ad hoc network, capacity

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1 Introduction

1.1 Project background

In the project "High capacity techniques for mobile radio networks"[1], our main objectives are to

- evaluate and demonstrate the capacity gains achievable under realistic conditions with capacity enhancing (i.e. increasing the spectral efficiency) signal-in-space (SiS) techniques,
- examine the effects on network performance when incorporating the above techniques.

One of our ambitions is that we at the end of the project will be able to either recommend the incorporation of these technique in future military radio waveforms, or to tell that the probable performance enhancements obtainable with these techniques may not suffice to make up for the increased cost in implementing these techniques. A detailed cost-benefit analysis is out of the scope of the project; however, we should be able to tell what level of performance could be expected in realistic environments (i.e. the benefit-side of the above equation).

This report documents the work that has been performed within one of the project activities, namely "High capacity techniques". The work within this activity has, so far, been focused on deciding what SiS-techniques to study during the remainder of the project, and to identify the remaining difficulties and challenges associated with the incorporation of these techniques in future military ad hoc networks.

During the remainder of this activity, we will isolate in more detail what algorithms will be studied during the next two years. For instance, considering adaptive coding and modulation schemes numerous different approaches exist depending on e.g. traffic types (unicast or multicast) and on channel information delays in the transmitter for TDMA-based (Time Division Multiple Access) networks. We recognise that a future waveform may need to implement multiple adaptive approaches, but we will only be able to develop algorithms and examine their performance for a limited sub-set of all possible, relevant implementations. Hence, we need to choose this sub-set of algorithms to be examined carefully.

Other project activities has targeted the development of suitable channel models for urban, peer-to-peer scenarios, with support for MIMO-systems (utilizing multiple antennas at both transmitter and receiver) at frequencies around 300MHz. Furthermore, combined channel-link models, with low complexity, for use in simulations of ad hoc network performance are under development. These are necessary tools for the evaluation of Signal-in-Space (SiS) techniques and network-level performance. This first year of the project is to a large extent focused on developing these models, while we during the second year will shift our main focus towards implementation and evaluation

[1] Kapacitetshöjande tekniker för mobila radionät, E53053

of adaptive coding and modulation, and MIMO-techniques. The final year the focus will again shift towards higher levels, with co-design and implementations of medium access schemes, and network performance evaluations. A hardware demonstrator will also be developed during year two and three of the project.

1.2 Objective

This report is meant to serve as the foundation for the upcoming work within the project. We attempt to give a description of relevant techniques and open research issues, so that military personnel can understand what we are doing and why we are doing it.

Hence, the main objectives with this report is to:

- present and describe the techniques that have the potential to significantly increase the capacity of tactical ad hoc networks,
- give the reader a feeling for the remaining challenges that need to be solved before attempting to incorporate these techniques in future military radio waveforms.

The most promising SiS techniques are adaptive coding and modulation (ACM) and MIMO-systems. Evaluations of ACM and MIMO-systems will partly be based upon measurements in realistic scenarios, while the consequences on network performance (as perceived by the user) will be studied through simulations. A hardware demonstrator for the SiS techniques will be developed. Finally, studies on the effects on network performance implies that current MAC-schemes be modified in order to efficiently utilize adaptive data rates on the links. TDMA-based schemes, such as spatial-reuse TDMA, could be developed to accomplish this.

1.3 Motivation

In summary, the most interesting high capacity SiS techniques for future military waveforms include

- adaptive modulation and coding schemes,
- MIMO-techniques using multiple antennas at both transmitter and receiver,
- multiples access control (MAC) schemes utilizing elaborate spatial-reuse techniques.

ACM and MIMO-techniques are commonly utilized in civilian radio systems, and the resulting performance gains in these systems are fairly well documented. However, the radio channel characteristics at the military interesting frequency band around 240-400 MHz are different in many important aspects. Hence, our view is that the achievable capacity gains for typical military peer-to-peer scenarios have not yet been examined thoroughly.

Extensive work has been conducted during the past years at FOI concerning characterization of the MIMO radio channel for urban environments. This cutting-edge research has shown that the channel itself supports high MIMO theoretical capacities in this scenario, about the same order as has been reported from other measurements performed at higher frequencies. However, we still need to examine the performance of different algorithms under realistic conditions, e.g. with imperfect channel information and channel estimators. The same reasoning holds true for ACM, but with special emphasis on examining the effects of typical delays in channel information in the transmitter. ACM techniques require channel knowledge in the transmitter, or a feedback channel where the intended receiver tells the transmitter what to transmit. MIMO-techniques on the other hand can improve their performance if accurate, timely channel information is available in the transmitter, but we will focus on algorithms that do not require information in the transmitter. Accurate channel estimation in the receiver is however crucial for the performance of all MIMO-techniques.

Furthermore, the higher layers, e.g. the choice of multiple access control scheduler and the traffic types (unicast vs. multicast), will limit the possible implementations with ACM and MIMO-techniques. One example of this is that the possibilities for achieving accurate and timely channel state information (CSI) in the transmitter differs between MAC protocols. A successful adaptation scheme is dependent on accurate channel information in the transmitter - adaptivity is all about adapting the transmission to the prevailing channel conditions. Since the channel is highly time-variant, any delay in the channel estimation can lead to the need for excessively large margins in the adaptation process thereby reducing the resulting data rates. Therefore, it is important to identify and discuss the requirements and restrictions stemming from the higher layers in any evaluation of the potential performance of high capacity enabling techniques in tactical radio systems.

Finally, it may at first seem as a not too daunting task to implement these techniques in future military radio systems; however, due to the complex interactions between the physical and higher layers in ad hoc networks, even the efficient incorporation of adaptive data rates in future software defined radio waveforms is a demanding task. Our intention is to clarify these challenges, and also to show at the end of this research project that there are possible ways to handle these challenges. It is likely that substantial modifications in state-of-the-art waveforms are required in order to efficiently utilize high capacity physical layer techniques; thus, we must first determine if substantial gains can be obtained on individual links before any recommendation can be made about whether or not incorporate these techniques in future waveforms.

1.4 Document structure

In Chapter 2, the pros and cons with two different carrier techniques, which are of interest for military applications, are described. Thereafter, adaptive modulation and coding techniques are described in Chapter 3, while MIMO-techniques are discussed in Chapter 4. The importance of accurate channel information is stressed in particular, for both ACM and MIMO-systems. A large number of open research issues exist when it comes to efficiently incorporating adaptive data rates, and MIMO-techniques, into tactical ad hoc networks. These are identified and discussed in Chapter 5. Finally, a recapitulation of the report, and concluding remarks, are given in Chapter 6.

Chapters 2-4 all begin with basic descriptions of the associated techniques and the experienced reader may readily jump directly to the discussion sub-chapters. There, recommendations are given concerning research tracks that should be followed during the remainder of the project.

2 Multi-carrier and single carrier systems

Numerous different carrier techniques exist, including combinations, but we have chosen to restrict our discussions to two interesting approaches, namely Single Carrier (SC) and Orthogonal Frequency Division Multiplex (OFDM) techniques. The reasons for this are mainly two-fold, we have ample experience with these techniques and they are commonly favoured in the standardization of future military and civilian radio systems.

In a SC-system the transmitted symbols are short and thus occupies a broad frequency band. In multi-carrier systems like OFDM long symbols are used, occupying a small and narrow frequency band. Instead, we can stack a large number of sub-carriers to allow the transmission of several data symbols simultaneously. The bandwidth, W, of a symbol is inversely proportional to the length of the symbol, $W=1/T$. We can stack K OFDM symbols in the same bandwidth as a symbol of length of T/K. Also, the signal and noise energy scale the same way. From a theoretical point of view the performance should therefore be equal for OFDM and SC in an additive white Gaussian noise (AWGN) channel. The difference between the two systems will appear when we discuss multi-path properties, as well as implementation and synchronization issues.

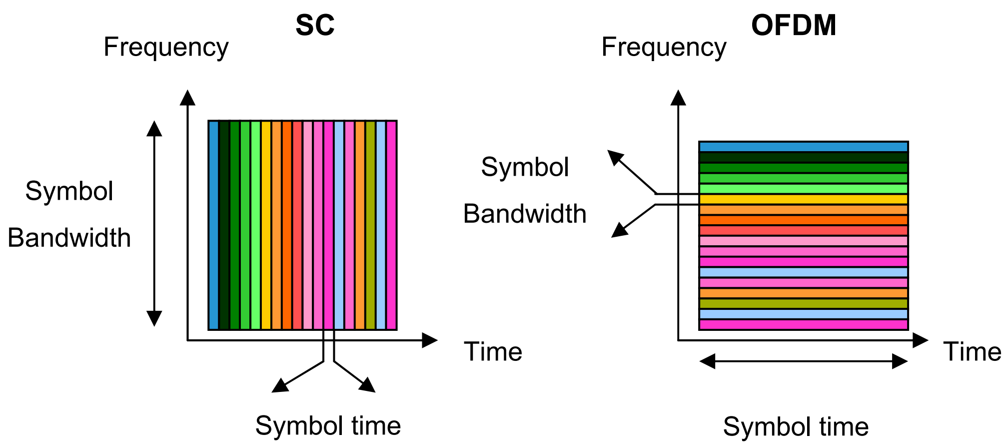

Figure 2.1: Illustration of the conceptual difference between single carrier and multi-carrier (OFDM) systems.

2.1 Multi-carrier system (OFDM)

OFDM has received a lot of attention during the last decade and it has been included in several international standards. It is a highly flexible multi-carrier technique that can achieve high capacity with a feasible complexity. In an OFDM-system, the frequency selective channel is transformed into multiple flat fading sub-channels by transmitting data on multiple orthogonal narrow-band sub-carriers. Hence, instead of transmitting the data symbols over a large bandwidth for a very short time, the symbols are transmitted on multiple narrowband sub-carriers for longer time periods.

There are both pros and cons with an OFDM-system when compared to other systems, for instance:

Pros

- Bandwidth efficient – allows high data rates
- No equalizer is needed
- Transmit diversity – combination with MIMO with feasible complexity
- Flexible frequency resource allocation

Cons

- High Peak to Average Power Ratio (PAPR)
- Sensitive to high Doppler spreads
- The cyclic prefix may have to be long in certain channel conditions
- LPD/LPI

Perhaps the main advantage with OFDM is the flexibility it offers and that it is fairly easy to adapt the power and data rates, as well as the frequency resources, after the prevailing channel conditions and service needs. Moreover, by implementing an IFFT at the transmitter and an FFT at the receiver, and by adding an cyclic prefix, OFDM converts an intersymbol interference (ISI)-channel with additive white Gaussian noise (AWGN) into parallel ISI-free subchannels. This means that no equalizer is needed at the receiver. ISI occurs when delayed multipath components of previous data symbols overlap the current symbol in the received signal, thereby making it more difficult to detect the current symbol. On the other hand, a cyclic prefix with a length correspon-ding to the delay spread has to be inserted. The cyclix prefix repeats parts of the OFDM signal and introduces redundancy. This is the cost of not needing an equalizer. The cyclic prefix can also be used by an interceptor to simplify the signal detection; thus, worsening the LPD/LPI (stealth) properties of the system.

However, the main disadvantage that normally is mentioned together with OFDM is its high peak to average power ratio (PAPR). This requires linear transmitter circuitry, which suffers from poor power efficiency. In situations where power efficiency is important, e.g., in small handheld terminals, the high PAPR requirements have so far limited the use of OFDM. Finally, OFDM is sensitive in cases with large Doppler spreads and in such cases a frequency equalizer may be needed. In military pedestrian and vehicular applications (with relative low speeds up to 20 m/s) Doppler spread is not expected to be a problem.

To summarize, OFDM is an attractive option in many different situations, and it enables the use of high-capacity techniques such as adaptive coding and modulation and MIMO-schemes. However, OFDM may not be the right choice in cases with; high Doppler spread, LPI/LPD requirements, and for small terminals where power efficiency during transmission is very important.

2.2 Single-carrier system

In a single carrier system the symbols are transmitted consecutively. Each symbol is comparatively short. Therefore, coherent processing is easy to maintain in the receiver. However, the duration of the symbols is short compared to the difference in delay over different propagation paths. Therefore, upon reception of a given symbol, other delayed symbols that have traveled other paths will arrive simultaneously, which will cause ISI. This is no problem from a signal processing view since with a good channel estimation and an equalizing filter in the receiver, the ISI can be cancelled. The multipath will then be turned into an advantage in a way that it introduces diversity through the fact that the probability of at least one path being strong increases. This can be seen as a richness of the multipath channel which is exploited by a SC-system.

Pros
- Bandwidth efficient – allows for high data rates
- Using an equalizer, the diversity offered by the channel can be used
- Transmit diversity – combination with MIMO
- Small peak to average ratio in transmitted signal simplifies power amplifier
- Low sensitivity to Doppler spread and phase instabilities

Cons
- Requires a complex channel estimator and equalizer in the receiver
- Is not as flexible as OFDM for obtaining different data rates in a given bandwidth

2.3 Discussion

If we have a communication system with mobiles and base stations we usually require less complex hand-held mobiles and allow the base stations, which belong to the infrastructure, to be more complex. Since OFDM tends to make the transmitter more complex and SC makes the receiver more complex one approach could be to use SC in uplink and OFDM in downlink. This is an approach that has been adopted by the LTE (Long Term Evolution) standard for next generation mobile telephony. However, it is uncertain if a similar approach is cost efficient when considering future software-defined radios with soldier and vehicle "waveforms". The development cost of a separate waveform is often high and relatively few radios will be fielded, yielding potentially high development costs per radio for each waveform to be implemented.

The system choice between SC and OFDM will strongly influence the remaining work within the project. The specific techniques and strategies for implementing high-capacity techniques such as adaptive coding and modulation, as well as MIMO, will differ between these approaches. One important aspect is of course what capacities can be achieved with the different systems during channel conditions encountered in military tactical radios at the frequency band 240-400 MHz. However, other important aspects are the computational complexity and power efficiency of the systems, especially when considering hand-held radios, when employing adaptive techniques and

MIMO-algorithms in conjunction with channel estimation algorithms and metrics, and so on. A more thorough study is required in order to answer these questions.

FOI has for several years developed SC-based acoustic communication systems, especially considering advanced channel estimation and equalization techniques based on turbo-codes. These algorithms can be converted and tested in the planned hardware demonstrator, but they need to be amended by specific algorithms for ACM and MIMO. Furthermore, OFDM has been the basis for FOIs research in tactical communications for the last five years and algorithms for ACM (for unicast traffic) have previously been developed and examined. A related project at FOI is currently pursuing the development of a hardware demonstrator for dynamic spectrum allocation algorithms based upon OFDM.

Recommendation

Due to synergies with related projects concerning implementation of OFDM-schemes in a hardware platform, in combination with an OFDM-systems flexibility and potential high capacity, we recommend that OFDM is used as the primary technique in the remaining work.

SC-based may be of particular interest for hand-held radios and we recommend that a study is initiated concerning a comparison of complexity and performance for SC and OFDM when utilizing MIMO and ACM. Also, the amount of work required for implementing SC techniques, based on algorithms and code previously developed for acoustical communications, in the hardware platform should be examined.

3 Adaptive Coding and Modulation

3.1 Modulation and coding techniques

Modulation

Before transmission over the channel, the digital information needs to be converted to an analogue continuous signal. The frequency, amplitude or phase, or combinations of these, of one or several sine signals is modulated in accordance to the digital information. The receiver is then interpreting digital information from the frequency (FM), amplitude (AM) or phase (PSK) of the received signal. If the receiver misinterprets the received signal, errors are introduced in the received digital information.

Before the transmission, one or several information bits are grouped into symbols, which are then mapped into different signal alternatives. One symbol consists of m bits. The different signal alternatives can be shown in a vector diagram, where the number of symbols $M=2^m$ and their locations are displayed. Examples of signal constellations are shown in Figure 3.1.

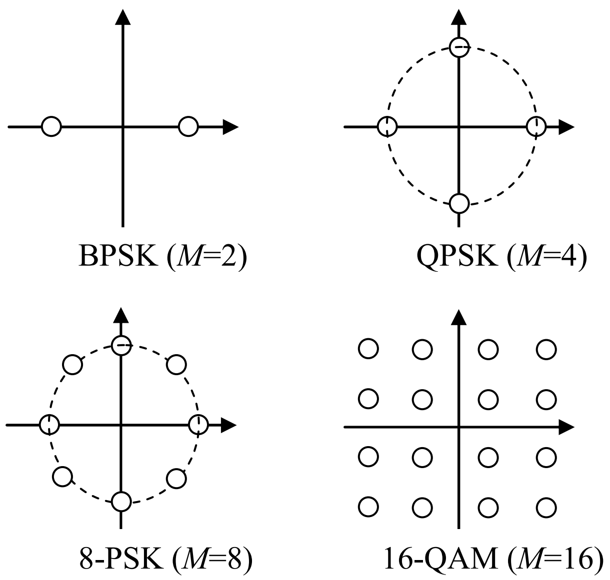

Figure 3.1: Examples of signal constellations with different number of signal alternatives.

The larger the signal constellation is, the more information is transmitted for every use of the channel, thereby resulting in higher spectrum efficiency. Communication systems have limited energy, which is why the signal constellation will have a limited size. Consequently, more signal alternatives in the signal constellation yield smaller Euclidean distances, which in turn causes a larger probability of error. The choice of signal constellation size is a trade-off between high spectrum efficiency and low error probability.

For scenarios with high signal-to-noise ratio (SNR), it is suitable to choose a signal constellation with many signal alternatives (large M), while a low M is suitable for low SNR scenarios in order to achieve an acceptably low error probability. Thus, knowledge of instantaneous SNR is beneficial in order to be able to make a good choice of the constellation size.

Error-Correcting Coding

The purpose of Error-Correcting Coding (ECC), a.k.a. Channel coding or Forward Error Correction (FEC), is to protect information (a sequence of data bits) against errors that arise during transmission, or storage. This is performed by adding a controlled amount of redundancy in such a way that the original information can be recreated by the receiver with high probability as long as the number of errors introduced by the channel does not exceed a certain limit. The new longer bit sequence is referred to as a code word. An ECC can be characterized by the code rate and error correcting capability. The code rate r is the ratio between the number of information bits k and the length of the code word n, $r=k/n$. Thus, the larger the number of check bits, the lower the code rate. The error correcting capability determines how many (randomly placed) errors the code can correct. The more redundancy we add, the better error correcting capability we get. When designing an ECC we must know, or estimate, the expected fraction of errors to occur during transmission over the particular channel. Thereafter, the radio designer needs to decide upon the trade-off between the conflicting requirements on high code rate (low redundancy) and powerful error correcting abilities. In high-capacity systems we of course strive for as high code rate as possible.

For modern codes, e.g., turbo codes and low-density parity-check (LDPC) codes, the error correcting ability increases with code word length n but the delay increases. In addition to the aforementioned requirements on code rate and error correcting ability we will also have to consider the acceptable delay. For instance, an irregular LDPC code with $r=1/2$ (i.e., one extra control bit for each information bit) and $n=10^7$ practically reaches the theoretical limit [1, 2]. However, the delay may be unacceptable. If the data rate over the channel is low, the delay before we have received the entire code word will be significant. Furthermore, the source may not generate data at a sufficient rate. Assume for instance that we use a speech codec that generates 2500 bits per second. It would then take a good half hour to collect data to generate a single code word! Hence, there are reasons to design short, efficient codes with good error correcting capability.

Coded Modulation

In Coded Modulation, or Trellis Coded Modulation (TCM) [3], we combine channel coding and modulation such that the encoder generates a symbol sequence from the signal constellation instead of a bit sequence. TCM increases the spectral efficiency by increasing the constellation size and compensates for the increased noise susceptibility by protecting the transmitted information using the ECC.

3.2 Adaptive coding and modulation (ACM)

For a non-varying channel, a certain modulation and coding scheme can be chosen in the initial design of the system. However, for a time-varying channel, the optimal choice of constellation size and code parameters will change as the channel conditions (e.g. SNR) changes. Hence, we can not choose a certain combination of modulation and code parameters once and for all. If the system is designed for a low SNR, the channel will be inefficiently used under the periods of high SNR. On the other hand, if the system is designed for high SNR conditions, an unacceptable amount of errors will appear for periods with low SNR.

The motivation of ACM is to maximize the capacity with information of e.g. the instantaneous SNR while maintaining an acceptable level of error rate. The advantage of ACM is an increased capacity on a time-varying channel compared to a certain choice of modulation and coding method for a guaranteed average error rate. The drawback is the complexity associated with the necessary channel state information (CSI) and the increased ability of the transmitter and receiver to change between different modulation and coding schemes.

Channel state information

One of the key issues for the system is to achieve knowledge of the CSI. This information can either be estimated or predicted. The channel predictor works on received channel symbols received in the past. The channel estimator, however, may use channel symbols received both in the past and in the future to estimate the fading envelope [4]. As the estimation or prediction of CSI introduces some amount of delay, the CSI for a certain time instant will be based on partly old information. Furthermore, the CSI will also consist of prediction or estimation error, which will result in a non-perfect CSI.

There are different solutions to obtain the CSI. Predetermined information can be inserted to the ordinary information (pilot symbols) or placed on an adjacent sub carrier (pilot tones). The receiver can then perform channel estimation and prediction based on the received pilot symbols or pilot tones.

One common solution is to let the receiver determine the CSI and use a separate channel (back channel) for transmission of the choice of modulation and coding parameters to the transmitter. The receiver can make this decision based on e.g. the quality of its received information, estimate of BER or measurement of the channel SNR.

For ad hoc networks a similar method is possible for retrieving CSI. In these sorts of networks, there is often a procedure where the nodes now and then inform other nodes, which nodes they can hear and what quality they experience. This information can be used in order to obtain CSI between different nodes.

With use of a back channel, a part of the link capacity needs to be used for control information consisting of modulation and coding parameters to be used in the next transmission. The accuracy of this information, the rate it is updated and the delay of this information are of great importance of the potential ACM gain. Also, insertion of pilot symbols or pilot tones need to use some of the total link capacity. Furthermore, all these factors will affect the reduction of the total capacity due to the control information in the back (return) channel.

In summary, in order to enable accurate evaluations of the potential performance gains achievable with ACM in tactical ad hoc networks it is of crucial importance to find out what restrictions the network puts on e.g. CSI delays and other parameters, and implement algorithms in hardware platforms and perform tests in realistic channel conditions.

Adaptive Coding and Modulation in OFDM

In [5] we consider an OFDM transmission in a multiple-access system using Time Division Multiple Access (TDMA). Each OFDM symbol consists of N subcarriers, spanning a total bandwidth of B_T Hz. In this and related work [6, 7], we assume $N \approx 1000$. The OFDM symbol is transmitted over a channel with coherence bandwidth B_C Hz, resulting in $n_C = B_T / B_C$ sub-channels. The sub-channels are assumed to be independently Rayleigh fading channels of equal bandwidth. The OFDM symbol is divided into $n_B \geq n_C$ blocks of equal size. In each block we use n_P subcarriers for pilot symbols and the remaining subcarriers in a block are modulated using the same code-rate and signal constellation size. The frequency domain structure of the OFDM symbol is illustrated in Figure 3.2. The choice of code-rate and constellation size depends on the instantaneous SNR in the block. In the adaptive Coding and Modulation (ACM) scheme, the instantaneous SNR of each sub-channel is estimated at the receiver. Based on this side information, or Channel State Information (CSI), and Bit Error Rate (BER) requirements, the receiver decides on which transmission rate to use in the next transmission. This information is then fed back to the transmitter which then uses the appropriate code-rate and constellation size.

We assume that the forward and feedback channels share resources, i.e. the more feedback a system require, the less information can be transmitted in the forward direction. Hence, a higher resolution of the feedback information (time between updates, number of sub-channels in OFDM systems, number of ACM levels) does not necessarily result in higher system throughput.

In [5] we used Serial Concatenated Trellis -Coded Modulation (SCTCM) consisting of a Serial Concatenated Convolutional Code (SCCC) mapped to a Gray-labeled signal constellation We used seven code rates between r=1/4 and r=5/6, and six signal constellations carrying 1 – 6 bits per symbol, resulting in 42 possible combinations. In Figure 3.3 we show the information rate as a function of the SNR required to achieve a BER of 10^{-5}. Some combinations of code and constellation yield the same spectral efficiency. In those cases, we select the combination that requires the lowest SNR to achieve a BER of 10^{-5}. In the figure those points are indicated by red circles. We also show the Shannon limit for an AWGN channel for comparison.

We summarize our investigation of how the selection of rates impacts the performance and efficiency in a set of design rules for rate selection:

- The lowest available rate will determine the minimum SNR for transmission
- The highest available rate will determine the maximum throughput at high SNR
- The granularity (difference between rates) will determine how close to the theoretical capacity the system can perform
- Approximately equal spacing between available rates yields best performance over the “active” SNR range

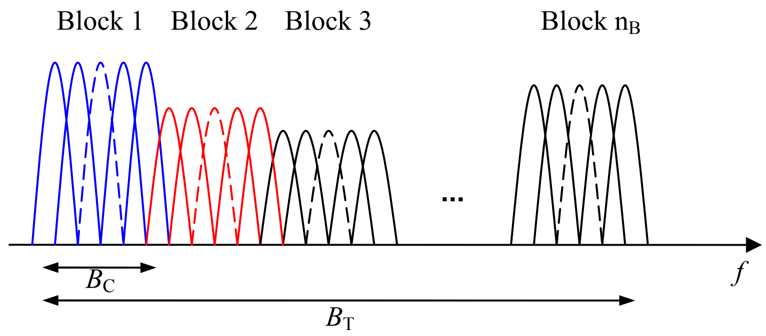

Figure 3.2: OFDM frequency block structure. The total bandwidth B_T is divided into a number of sub-channels of bandwidth B_C. In each block we have one pilot, $n_P = 1$, indicated with dashed lines. The blocks experience different SNRs which is indicated by the height of the sub-carriers.

- Due to the increase in feedback volume, there are diminishing returns on further increase of the rate vector sizes

A small number of rates, probably between 4 – 8, selected such that their required SNRs are evenly spread over the expected SNR range, will give substantial performance gains compared to a single-rate system.

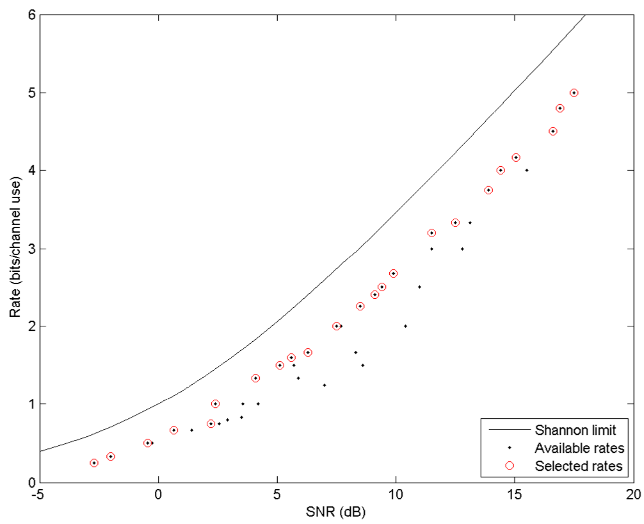

Figure 3.3: The simulated code-constellation combinations compared to the Shannon limit for AWGN channels.

3.3 Discussion

Potential capacity enhancement with ACM

Earlier work ([5, 8] among several) has shown large capacity improvements with ACM compared to a certain, fix modulation and coding scheme. The information rate can, with properly chosen modulation and code parameters, approach the Shannon limit of capacity for AWGN channels. The Turbo code and the constellations studied in [5] give approximately only 1 dB higher SNR than what the Shannon limit yield. Low-Density Parity-Check (LDPC) codes might give even better performance than Turbo codes.

In general, ACM is usually designed to optimize the capacity in order to give a high information rate. The adaptivity could instead be used to increase the robustness and the adaptation metric could be designed to make sure that the system fulfils a certain level of quality of service. The increased level of robustness is necessary for certain applications, like transmission of time-sensitive information.

There may also be a trade-off between the increase in capacity obtained at the link-level, and the amount of extra retransmissions that are caused by an increased number of packet-losses for an ACM-scheme.

Suitable modulation and coding schemes for ACM

The more available combinations that are available in the ACM system, the closer to the Shannon limit the ACM system gets. It is important that there are ACM parameter combinations suitable for all average SNR levels the system is supposed to assume, in order to achieve a good performance of the system. Suitable error correcting codes are Turbo codes, LDPC or Ungerboeck codes. The introduced delay has to be considered as well.

In [5], an information data rate from ¼ bit/s/Hz (r=1/4, m=1) at a SNR of -2.7 dB up to 5 bits/s/Hz (r=5/6, m=6) at a SNR of 17.5 dB can be obtained, while maintaining an average bit error rate BER of 10^{-5}. For this case, the SNR region is between -2.7 dB and 17.5 dB. This region can be extended upwards by using larger signal constellations and higher coding rate for high data rate applications. For extreme applications with stealth requirements or high robustness, the SNR region can be extended downwards.

CSI and necessary rate to update

A key issue in order to achieve a good performance of the ACM system is to have relevant information of the channel in the transmitter. Algorithms for CSI prediction and estimation are crucial. A suitable solution will be dependent on channel characteristics, applications or services, MAC protocol, coding schemes, among others. Furthermore, the updating rate of the CSI and the delay of the information are two important factors that need to be investigated. From our earlier work, concerning channel measurements performed in Linköping city for a peer-to-peer scenario with a moving receiver at 300 MHz [9], we can receive information of important channel parameters like mean and variance of the slow fading. For a wideband radio system equipped with MIMO-diversity, the effects of the fast fading may in many situations turn out to be negligible.

The CSI itself can be obtained through prediction of future values of one or several channel metrics. The system can use pilot symbol assisted modulation (PSAM) or pilot tones. For ACM in an OFDM system pilot tones are very suitable.

The rate of which the CSI needs to be updated is dependent on how rapidly the channel changes and the dynamics or statistics of the channel. However, in [5] it is shown that you will loose only marginally with information of average SNR instead of instantaneous SNR when utilizing powerful error correcting codes like Turbo codes. A long Turbo code will have an averaging effect on the time-varying SNR. On the other hand, long Turbo codes, combined with a high number of decoding iterations at the detector, will introduce long delays. The use of a powerful code and estimation of CSI of the slowly fading parameters can be suitable as a first approach. Average SNR is the most important information, but other parameters can also be of interest. Another factor that will affect the CSI update rate is the choice of MAC protocol.

Recommendations for future work

The most important issue to examine when attempting to evaluate the performance of ACM in military applications is to assess the reduction in performance stemming from limited, somewhat erroneous, and delayed channel information in the transmitter. This will be an integral part of our future work.

When designing ECCs for high capacity systems we encounter conflicting requirements on high code rate, good error-correcting capability, the ability to handle varying block lengths, low delay and low complexity/energy consumption. A promising technique to meet these requirements is LDPC codes based on protographs [10]. It is recommended that this approach is considered in the following work concerning ACM schemes. Although the improvement over turbo codes in terms of spectral efficiency are not expected to be dramatic, their potential flexibility are appealing.

4 MIMO-techniques

Multiple-input-multiple-output (MIMO) systems, where both transmitter and receiver are equipped with multiple antennas, is a technique that has the potential to significantly improve the spectral efficiency (and robustness) of tactical radio systems.

4.1 Different MIMO-techniques

MIMO-techniques are often divided into three principal strategies, namely

- space diversity,
- spatial multiplexing,
- array gain, or beamforming.

Furthermore, interference cancellation schemes can be incorporated into the above techniques, yielding different trade-offs between robustness and capacity. In military applications, the ability to change between high capacity and robustness is of particular interest. More thorough descriptions of different MIMO-techniques can be found in e.g. [11-14], and a brief summary is given below.

Space diversity

If several antennas are spaced apart, it is unlikely that all antennas will experience fading minima simultaneously. Thus, space diversity has the potential to eliminate the detrimental effects of fading, which in turn for a ACM-scheme may enable large improvements in data rates.

MIMO-diversity, where transmit and receive diversity schemes are utilized, can achieve a multiplicative diversity order, i.e. the diversity order for a system with one transmit antenna and nine receive antennas is similar to that for a MIMO-system with three transmit and three receive antennas. Thus, a very high degree of diversity is obtainable with even a limited MIMO-system. For a radio operating at 300 MHz with a bandwidth of a few MHz it is probable that a MIMO-diversity system using 3-by-3 antennas has the potential to virtually eliminate the small-scale fading.

Spatial multiplexing

In order for a spatial multiplexing scheme to be effective, it requires that substantial multipath is available. In spatial multiplexing, multipath is exploited instead of being suppressed. Separate data streams are encoded and transmitted simultaneously on different antennas, and provided that the multipath is sufficiently strong these data streams can be detected through use of the (different) spatial characteristics of the incoming signals. Hence, for each additional transmit antenna that is available, another data stream is possible, thereby increasing the capacity. However, in order to decode these streams the number of receive antennas must be at least as many as the transmit antennas. Also, the so-called rank of the channel matrix must not be lower than the number of transmit antennas, and this requires that substantial multipath propagation is available.

Beamforming

Through beamforming, the SNR in the receiver can be increased. This increase in SNR can be utilized by the radio to increase the data rate if ACM is implemented, or to increase system robustness and/or range.

Beamforming techniques can also be combined with adaptive interference suppression mechanisms, which may be important for interference-limited radio systems.

4.2 Potential MIMO capacity gains in urban peer-to-peer scenarios

Extensive channel measurements have been performed in earlier projects, see e.g. [15-17]. MIMO-channel impulse responses, for 8×8 antennas, were collected for a large number of routes in Linköping and Malmö. All transmit sites mimics a peer-to-peer scenario, see e.g. the Linköping measurements sites in Figure 4.2, except for Tx1 in Malmö where the transmitter was positioned approximately 18 meters above ground, on the top-level of a parking garage.

The measurements have been crucial in our attempt to develop state-of-the-art channel models for urban peer-to-peer scenarios around 300 MHz. Furthermore, the measurements have revealed that the channel supports very high spectral efficiencies [16], as shown in Figure 4.1 and summarized in Table 4.1. Approximately 65-70 % of the corresponding capacities for an ideal independent, identically distributed (i.i.d.) Rayleigh-fading channel were obtained. These results are close to what has been reported at higher frequencies. Somewhat lower capacity gains were obtained for the scenario with an elevated transmitter, which is to be expected.

In summary, previous work has shown that large capacity gains are supported by the channel. However, the performance of MIMO-algorithms during realistic channel conditions with an imperfect channel estimation and under channel state information delays remains to be demonstrated for mobile scenarios.

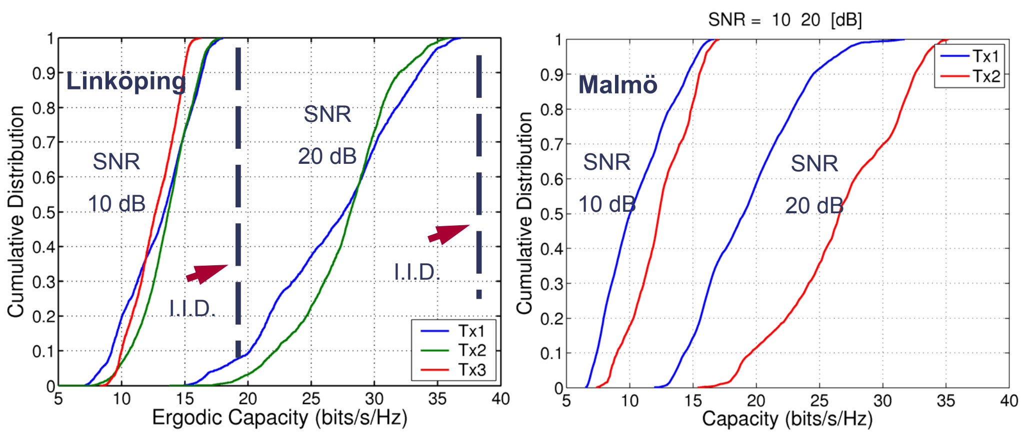

Figure 4.2: Ergodic capacity, evaluated at SNR of 10 and 20 dB, for measurements performed in Linköping (left) and Malmö (right) city centers. All transmit sites mimics a

peer-to-peer scenario, except for Tx2 in Malmö where the transmitter was positioned approximately 18 meters above ground, on a parking garage.

Table 4.1: Mean ergodic capacities for Linköping and Malmö measurements.

Mean erg. Cap.	**bits/s/Hz**		**Rel. to i.i.d. Rayleigh**	
SNR	10 dB	20 dB	10 dB	20 dB
Linköping (All)	13.2	27.2	69%	71%
Malmö (Tx1)	10.6	19.4	56%	50%
Malmö (Tx2)	12.5	26.7	65%	69%

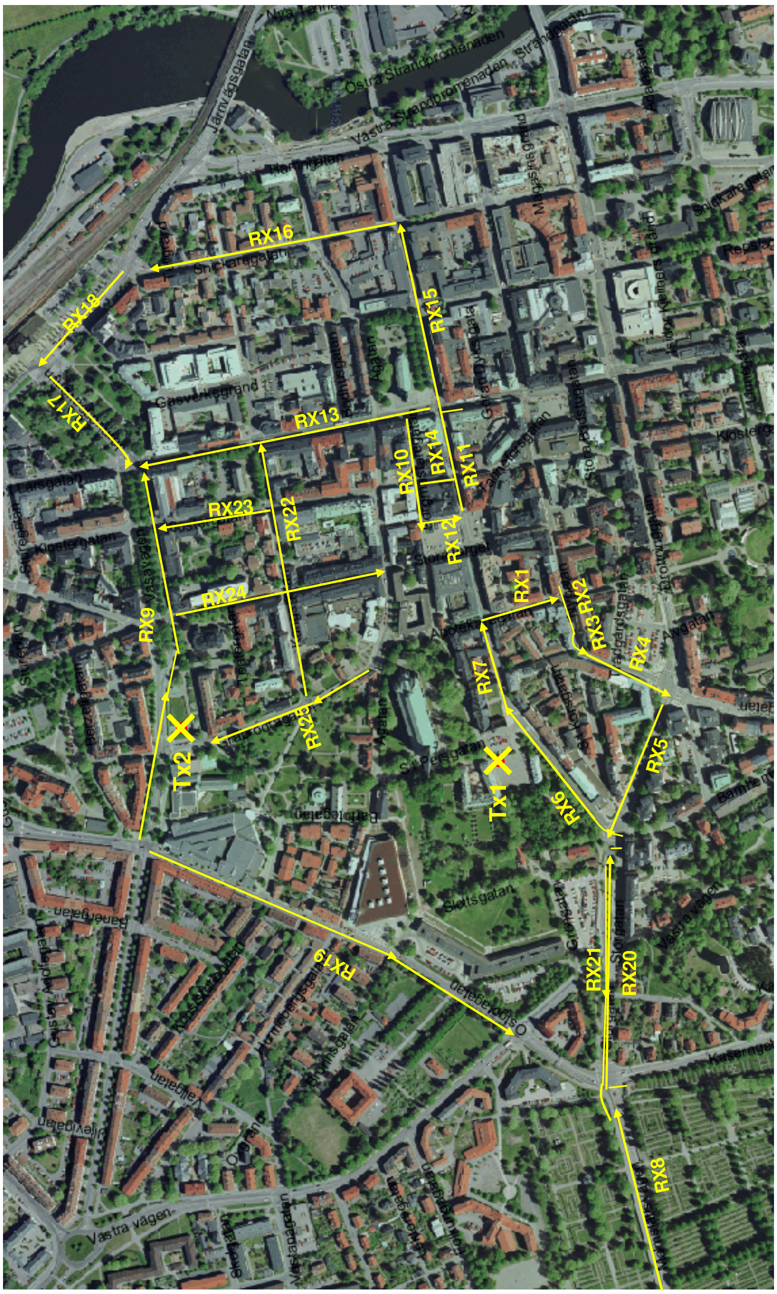

Figure 4.2: Part of the measurement area in Linköping city center [16].

4.3 Discussion

Channel estimation

Most MIMO-techniques require channel estimation in the receiver. This can be obtained through the insertion of known training sequences (SC) or pilot sub-carriers (OFDM). In theory, improved spectral efficiencies can be achieved in situations with accurate channel information in the transmitter. However, for mobile ad hoc networks it is difficult to obtain the desired level of information in the transmitter due to channel estimation delays, and a reasonable restriction at this stage is to examine algorithms that only requires channel information in the receiver.

Space diversity vs. spatial multiplexing vs. beamforming vs. interference cancellation

The choice of algorithm depends on the scenario, e.g. on the multipath properties of the channel, the quality of the link (SNR), and the number of available antennas. To some extent, the MIMO-strategies have complementary performance and they perform most efficiently during different conditions.

Space diversity and spatial multiplexing schemes are generally considered of particular interest in multipath-rich radio channels. Spatial multiplexing then has the potential to yield an increased capacity that grows proportionally to the number of transmit and receive antennas. Spatial multiplexing is interesting for high SNR scenarios, while diversity schemes may be the preferred choice for low SNR situations. A motivation can be formulated as follows: the outage capacity is often more important than mean capacities, in particular for ad hoc networks where re-transmissions are costly. Space diversity schemes can yield large improvements in outage capacity at low SNR.

Beamforming approaches are of interest in (preferrably line-of-sight) radio channels with limited multipath propagation, and where the SNR (or SIR) is high. In time-variant channels with severe multipath, transmit beamforming is difficult since channel information is normally required in the transmitter. As a consequence, our hypothesis is that in dense urban environments we would normally be using space diversity or spatial multiplexing, but rarely beamforming.

Space diversity algorithms

In recent years, spherical decoding approaches has received substantial interest. A trade-off between diversity and spherical decoding approximates the maximum-likelihood decoding, but with reduced complexity. However, the complexity for spherical decoding strategies is still high. Traditional space-time-block-codes (STBC) utilizing e.g. Alamouti's scheme [14] has very low complexity and it yields a good trade-off between diversity and complexity.

Antenna aspects

On fighting vehicles it may be possible to utilize up to four, or possibly six, antennas at the examined frequencies around 300 MHz. The number of antennas, and their placements, may however be strictly limited due to practical considerations. Note that, compared to traditional beamforming approaches where approximately half-wavelength separations are desired, no restrictions on the antennas are applied for MIMO-systems. However, the larger the antenna spacing, the less correlated the signals becomes, and a low correlation implies potential for MIMO-gains.

Recommendations of future work

Practical antenna placements for military vehicles should be examined and discussed with user representatives.

An interesting research topic is to examine during what channel conditions spatial multiplexing, space diversity and beamforming techniques are preferred. In order to evaluate the performance of these MIMO-algorithms, field measurements are required.

In any evaluation between different MIMO-diversity algorithms it is recommended that Alamouti's simple scheme is implemented and compared against.

Furthermore, algorithms that yields various different trade-offs between space diversity, spatial multiplexing and interference suppression is an active research field. This area should be followed and interesting algorithms, especially combining interference suppression techniques, should be evaluated.

5 High capacity link technologies in ad hoc networks

To fully utilize the introduction of capacity-enhancing link technologies in ad hoc networks, adaptations of the entire waveform towards topology and traffic changes are key components. Such adaptation of the waveform can be performed in many different ways, at different layers and at different time scales. To quantify which adaptations that are most important is difficult. The following are some of the more important features of adaptation for enhancing capacity, which involves both the physical layer and some of the layers above.

Interaction between the layers is required to obtain the desired network performance when incorporating physical layer techniques that results in adaptive data rates. There are some fundamental differences, related to waveform adaptation, between the higher and lower layers. Adaptation at lower layers can normally be performed at a faster pace than at the higher layers. For example, the packet data rate on a link can be changed on a packet-by-packet basis; however, a new route is selected much more seldom, normally when the current route fails. The reason for applying conservative route change strategies is that every route change requires transmission of substantial overhead data, for route discovery and route notifications. Lower layers only need local information for adaptation, while the higher layers often need to combine information from links in the whole network. These and other differences between the layers make the design of adaptive schemes involving several layers difficult.

We will here look at the problem from two different views. First we will look at the problem from a network oriented view, and thereafter we will look at the problem from a link oriented view.

5.1 Network view

In this section we will discuss in more detail what impact networking protocols may have on the possibility of adding high capacity techniques such as adaptive coding and modulation, and MIMO-techniques. Depending on protocol choices and properties in a mobile ad hoc network, not all forms of technologies will be as efficient as could be seen on a point-to-point link; they might even not be possible to implement at all.

Applications

The characteristics of the traffic in the network will affect the result of introducing advanced link technologies. We assume here that all the information sent between applications will be sent as packets. If the network should be able to deliver the packets to its destinations it is crucial that the probability of errors in packet headers is sufficiently low. Furthermore, most of the used applications in military ad hoc networks will assume that delivered packets are error free (after decoding). A normal assumption in ad hoc networks is therefore that a packet with uncorrected bit errors should be thrown away, i.e. always result in a packet loss.

Another property of the applications that in many cases will influence lower layer is the fact that military applications produce both unicast and multicast traffic. Unicast traffic has one source and one destination, while multicast on the other hand has many destinations for a generated packet. Unicast and multicast traffic may require different strategies for incorporating MIMO and ACM.

Routing

In general, the purpose of a routing algorithm is to find the best path between source and destination, although technically this is often performed on a node-per-node basis finding the best next hop. This is done by choosing a metric that gives a cost for each link, and thereafter finding routes that minimize the total cost for the examined links to the destination. However, most existing routing algorithms for ad hoc networks apply shortest path routing where the metric used is equal on all links; clearly, this approach is unsuitable when incorporating links with adaptive data rates. Using shortest path routing in conjunction with adaptive data rate links can in some cases even lead to a reduced network performance compared to fixed data rate systems.

Routing for ad hoc networks can be divided into two types, proactive and reactive. Reactive routing only finds paths whenever they are needed, and this is usually done by flooding a route request through the network. An alternative is to use proactive routing; in this case information about all routes is constantly kept updated. For further in formation see e.g. [18].

In order for routing to take adaptive links into consideration, the used metric needs to correspond to the actual link quality. For reactive routing, such information could be added to the route search, giving fairly updated information when the route is found. However, normally the route is not changed until it fails which means that better routes may exist. More route searches could be added regularly but this would add much overhead and make it more like proactive routing. Proactive routing would easier detect if better routes have appeared, but information is only updated at certain intervals (to reduce overhead). It is important to use a metric so that the paths don’t change too often, since this will create other problems such as resource management problems for the MAC layer.

Medium Access Control

An important design issue for ad hoc networks is the MAC-protocol, i.e. how to avoid or resolve conflicts at the radio channel due to simultaneously transmitting nodes. This can be performed in different ways and different classifications can be used to differentiate between the methods and algorithms. One easy differentiation is the division in conflict-free and conflict resolution MAC-algorithms, but many algorithms can be seen as hybrids to some degree.

Conflict-free MAC

Conflict-free MAC is based on dividing the available channel resources among the users so that conflicts are avoided. This can be achieved in different ways, and time division (TDMA), frequency division (FDMA), code division (CDMA) multiple access are traditional methods in radio communication.

For multihop networks, TDMA is the preferred medium access method. FDMA usually requires further coordination since a single node will have difficulties with receiving multiple transmissions simultaneously even if they are all on different frequencies (especially if it is transmitting at the same time). Frequency hopping has the same problems of course. Direct sequence spread spectrum methods also need extra coordination, since power control as in cellular network is not possible, in general, for multi-hop networks.

Spatial-reuse TDMA, combined with traffic adaptive time-slot allocations, can be an efficient means to increase the capacity in TDMA-based networks. Spatial-reuse TDMA is a reservation-based time-slotted MAC protocol which can achieve an increased capacity by letting time-slots be spatially reused, i.e. a time-slot can be shared by radio transmitters that are geographically separated if they cause sufficiently small interference to each other.

Conflict resolution MAC

Conflict resolution algorithms are based on handling problems such as collisions when they occur. Normally, collision avoidance techniques are also added. Carrier Sense Multiple Access (CSMA) is the most used such protocol and it is simply described as the principle of listening for other users before sending a message. CSMA works well if all users can hear each other and if the delay is small between when a node starts to transmit and when the other nodes have determined that the channel is busy.

Collisions still occur in the receiver though, which creates problem if all nodes cannot hear each other directly. To avoid the so called hidden-terminal problem caused by this, a technique called collision avoidance (CA) has been added to the basic CSMA protocol. Here, a short request-to-send (RTS) is transmitted whenever a node has something to send, and the receiver answers with a short clear-to-send (CTS) if the channel is clear. CSMA/CA is the basis for the different IEEE 802.11 standards which are the most used protocol for ad hoc networks (in civilian research) [18].

Collecting CSI – a challenge for both spatial-reuse TDMA and CSMA

For adaptive data rate links, the RTS-CTS sequences allow the nodes to estimate the channel conditions over the link. The drawback is that CA cannot easily be used for broadcast traffic and that CSMA/CA tends to perform badly (causing long delays) if the network gets highly loaded.

For conflict-free schedules such as TDMA, current information about the channel will not be automatically available in the transmitter. In theory, time-slots can be scheduled so that the link can be turned around in the first part of the time-slot, thereby allowing for instantaneous channel estimation. Part of the time-slot will then be allocated for overhead traffic and it is unclear if these approaches will actually increase network throughput. Another problem with this approach is broadcast traffic, since responses from all receivers usually aren't available. Thus, channel information in the transmitter will not be perfect for TDMA-schedules, but how large impact this will have on the performance is dependent on both how fast the channel is varying as well as how the scheduling is done. In fast changing channel conditions we probably want a responsive scheduler as well.

The introduction of variable data rates and MIMO in spatial-reuse TDMA-based networks will affect many parts of the protocol. If the data rate changes on a link the number of time-slots the link needs will also change. Thus, the information about data rates of the links must be spread to other nodes together with the traffic estimates. However, since the cost of making changes to the time-slot allocation might be high it is important that only long term changes, that a node can not handle internally or at link level, affects the time-slot allocation. Furthermore, if MIMO is used for beamforming the algorithm that is estimating the interferences when creating the spatial-reuse TDMA schedule must take the varying “antenna patterns” into account.

5.2 Link view

In this section we will discuss more in detail what impact some specific link technologies may have on the network protocols. We will primarily focus on techniques to achieve variable data rates and MIMO.

Link knowledge

As discussed above, one of the fundamental problems with adding link adaptivity in an ad hoc network is how to know the quality of the links, this includes even the existence of links. Which nodes can be reached at the moment and which data rates can be used? In a network setting, we cannot keep the exact information about all links simultaneously. In practice, we can only achieve information about links when they are used, and this information is gathered in the receiver, not transmitter. However, decisions about transmissions, link parameters as well as decisions on which node to transmit to, is normally made in the transmitter. Since the channel resource is shared between the users and nodes normally cannot transmit and receive at the same time (at least not in similar frequency bands) each link will be unused more than it is used. Information about their properties is therefore fundamentally limited.

This is a problem that does not only exist in a network with adaptive links, it also occurs for systems with fixed data rates on the links. Is the link still useful or did the other node just pass around the corner of a building? If the link quality changes slowly it may be possible to use old estimates, but link adaptivity techniques complicates the problem even further.

Variable Data Rate

Having the possibility to use several data rates in an ad hoc network is beneficial. However, how to perform the data rate adaptation, in order to obtain the gains that are possible, is not straightforward. Firstly, there is a difference between unicast and broadcast. In the first case only one link, a sender and a receiver, is involved. In the second case, several receiving nodes and links have to be considered. The data rate has to be chosen so that all the nodes that are selected as receiving nodes can be reached. That is, the lowest of the data rates on the involved links have to be chosen unless sophisticated modulation techniques allowing for graceful degradation are applied. Strategies for selecting the data rate in broadcast situations have previously been investigated in [19].

In the following we consider unicast traffic, i.e., data rate adaption on a single link. Fast adaptation on a packet-by-packet basis can be a problem, i.e., a feedback channel from the receiver is needed to obtain sufficiently accurate channel estimates for such an adaptation. This then has to be controlled by the MAC layer. Slower rate adaptation, on the other hand, with several time frames (several seconds) between changes in data rate can probably be incorporated using channel estimates from previous time slots. These estimates can be improved by applying channel prediction algorithms.

Another issue concerns how many data rates that should be supported. To use very different rates, e.g., 1 kbps and 1Mbps in a similar region of the network is seldom useful, see [20,21]. Furthermore, using very different data rates complicates the MAC solution. In particular for TDMA the data rate is one important parameter when selecting the size of a time slot and the frame structure. On the other hand, in particular cases a very low data rate to one remote node can be motivated in order to avoid fragmentation of the network.

Packet fragmentation is another topic that needs to be handled efficiently if several data rates are used. For example, it will probably be better to reduce the data rate, and thereby increase the quality, if not the whole allocated time slot is needed to transmit the assigned data in a high data rate mode.

The introduction of advanced link technologies introduces the possibility of decreasing the data rate in order to increase the robustness of a link. The increased robustness of a link means that the link can handle more interference which can be used to increase the spatial reuse in the network.

MIMO

MIMO and smart antenna systems have the potential to substantially increase the link performance and reduce interference, thereby increasing the performance of an ad hoc network, see [13]. By utilizing MIMO-systems we can switch link modes, from spatial multiplexing or diversity, to beamforming. If spatial multiplexing or diversity 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.

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 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 omni-directional antennas at the transmitter and the receiver. Whenever beamforming is used, protocols for scheduling, node and 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 however useful in a broadcast situation. There is a trade-off to consider in broadcast transmissions, between 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.

Another issue concerns how to utilize the possible link performance gains that are enabled by MIMO-systems. In a high density network the 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 thereafter increase the data rate on the remaining links. Another alternative is to use some redundancy for interference cancellation to increase the spatial reuse, thereby enabling more simultaneous transmissions in the network.

Another consequence of using different techniques for adaptivity on the link layer is that it may affect the range of the links. Data rate and power adaptation are two ways to increase the communication range. Using adaptive antennas is another method that can be used. This can be done in both transmitter and receiver. One problem that arises is that all MAC algorithms do not specify which of a node's neighbour are going to transmit to it, which either means that the node needs to detect new transmissions with omni-directional reception (before switching to directional reception).

5.3 Discussion

In order to achieve the full benefit with adaptive data rates the SiS and upper layers need to be co-designed. This is a difficult task that thus far has prevented the use of adaptive coding and modulation even in state-of-the-art tactical mobile ad hoc networks.

As is apparent from the above discussion, there exists numerous choices and trade-offs that need to be dealt with when incorporating adaptive data rate links into an ad hoc network. Herein we have tried to bring up the most important issues that need to be considered in the future development and analysis of high capacity radio networks. At this stage, the number of open research questions shows the complexity of the work that lies ahead of us.

A short summary gives that e.g. handling multicast and broadcast traffic in general, and in combination with adaptive link data rates, lacks good solutions. Cross-layer design of ad hoc networks has been discussed in numerous research papers, but they are usually limited in scope and very few are implemented. Introducing adaptive link data rates may seem trivial but poses several challenges.

We do not have the solutions to all these questions at this point; however, we intend to develop and examine approaches that will show whether or not it is feasible to efficiently incorporating intelligent link layer techniques in mobile ad hoc networks.

Recommendations of future work

The first task should be to describe the different approaches possible for applying adaptive techniques when considering the different choices such as traffic type, etc.

A study should be initiated concerning the possibilities of obtaining up-to-date channel information in the transmitter for TDMA-based networks. This will yield necessary input to the link evaluations of adaptive coding and modulation techniques.

The work should continue concerning the development of a traffic-adaptive spatial-reuse TDMA network capable of utilizing links with adaptive data rates.

6 Recapitulation and concluding remarks

The use of single- and multi-carrier technology was briefly examined. The used carrier technique will significantly influence the specific algorithm implementations, computational complexity and also what performance can be achieved.

Thereafter, we discussed the use of high capacity techniques, ACM and MIMO, in the context of mobile ad hoc networks. The techniques are commonly used in civilian systems and standards; however, the achievable capacity gains for typical military peer-to-peer scenarios have not yet been examined thoroughly at the frequency band around 240-400 MHz under realistic conditions, e.g. on real-world urban peer-to-peer communication channels, and with imperfect channel information and channel estimators.

A hardware platform will be assembled, for research and demonstration purposes, which will enable the evaluation of these techniques during realistic channel conditions.

Several outstanding research questions regarding adaptive coding and modulation and MIMO were put on the table, and recommendations were given concerning which ones should be targeted by the project.

Furthermore, we have identified and discussed some of the most crucial requirements and restrictions stemming from the higher layers on the high capacity techniques. Also, some of the most crucial aspects concerning the co-design of ACM, MIMO and MAC algorithms was identified. It is believed that major protocol modifications are needed in order to efficiently utilize the proposed techniques in mobile ad hoc networks. However, the knowledge of how to co-design MAC together with MIMO and ACM algorithms for tactical ad hoc networks is rudimentary at this point and this task will require substantial research efforts to solve. Our ambition within this project is not to design a complete waveform with co-designed layers that efficiently utilizes high capacity techniques; however, we should show that there are feasible approaches to be pursued further that can solve these issues.

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