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Performance studies of an adaptive air-interface for a tactical waveform

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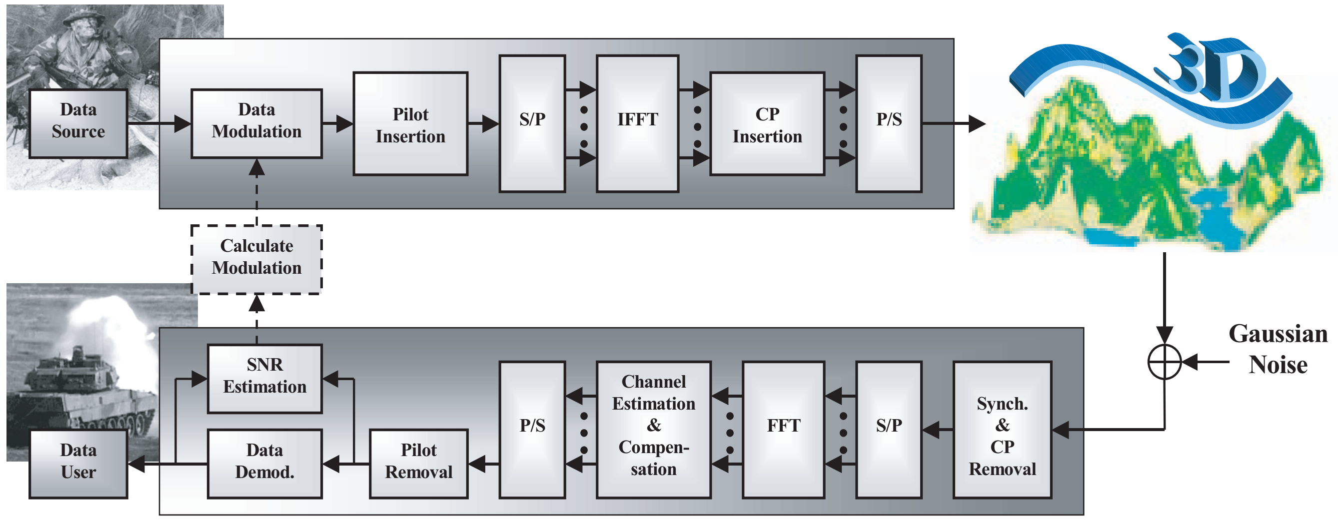

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Report title

Performance studies of an adaptive air-interface for a tactical waveform

Abstract

In this work some adaptive techniques of an air-interface for a tactical waveform are studied. The techniques are simulated in a mobile scenario with a map-based channel model. The communication system simulator is based on OFDM. The effects of space diversity, both transmit and receive, adaptive modulation and feedback delay have been investigated.

Results show that space diversity in combination with adaptive modulation enables a higher system throughput compared to a system with no space diversity. Furthermore, the usage of space diversity reduces the sensitivity to delays of the feedback information.

Keywords

Adaptive radio, tactical waveform, OFDM, MIMO, adaptive modulation

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Prestandaundersökningar för ett adaptivt luftgränssnitt för en taktisk vågform

Sammanfattning

Några adaptive tekniker för luftgränssnittet av en taktisk vågform har undersökts. Med data från en kartbaserad kanalmodell har teknikerna simulerats i mobilt scenario. Kommunikationssystemet som simuleras bygger på OFDM. Sändnings- och mottagningsdiversitet, adaptiv modulation och effekter från fördröjningar har undersökts.

Resultaten visar att genomströmningen i systemet blir högre för ett system med rumsdiversitet och adaptiv modulation än för ett system utan diversitet. När rumsdiversitet används minskar även känsligheten för fördröjningar i av feedback information.

Nyckelord

Adaptiv radio, taktisk vågform, OFDM, MIMO, adaptiv modulation

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1 Introduction

The vision of today's military radio development today is seamless real-time communications among warfighters through voice, data and video, across military services and coalition forces. Flexibility and interoperability are to be obtained by using reprogrammable radios, that are designed around a common software communications architecture (SCA), to carry information the "last tactical mile".

In the concept of software defined radio all radio functionality, i.e. waveforms[1], will be implemented in software. The vision is that a software defined radio can, in the matter of minutes, be reprogrammed with new waveforms. A single radio box may house a number of different waveforms. By either running the waveforms in parallel or by switching between the waveforms, the radio can act as a gateway and tie radio networks, with different air interfaces and protocols, together. These features facilitate interoperability with legacy radio systems as well as with allied forces for specific missions.

The software radio approach also enables individual waveforms to be adaptive, i.e. the parameters of the waveform may be tuned to optimize its performance. The waveform may be implemented to adapt to requirements on bandwidth and power usage, capacity, error rate, delay etc.

However, even if the concept of software radio is an interesting development, there are a number of radio related issues that have to be solved, for example how a large span in frequency range is going to be handled by an antenna system. Of course, an adaptive radio node can also be built in a more traditional way.

In this report we focus on the air interface of an interesting candidate for future software defined radio waveforms. The air interface of the waveform is Multiple-Input Multiple-Output Orthogonal Frequency Division Multiplexing (MIMO-OFDM), which is flexible and offers high spectrum efficiency and capacity.

1.1 Adaptive radio nodes

The goal with an adaptive radio node is to be able to adjust the parameters of the radio transmitter and receiver, when changes in the tactical scenario, radio channel conditions, signal environment or service demands have occurred, so that the best possible performance is obtained. The radio should be capable of automatic adaptation to continuously maximize one (or several) given performance measure(s), for instance capacity, while closely tracking variations in the service demands on error rates, delays, availability, robustness, stealth, etc. For a node in a military ad hoc network the ability to adapt to users' requirements on robustness, stealth and capacity yields improved possibilities for the military user to perform its tasks, see Figure 1.

[1] In today's tactical radio system development the word "waveform" is often used to describe the entire set of radio functions occurring from the user input to the RF output and vice versa. A waveform includes everything from encryption, QoS routing and security to transport protocol, Mutiple Access Protocol (MAC) and air interface.

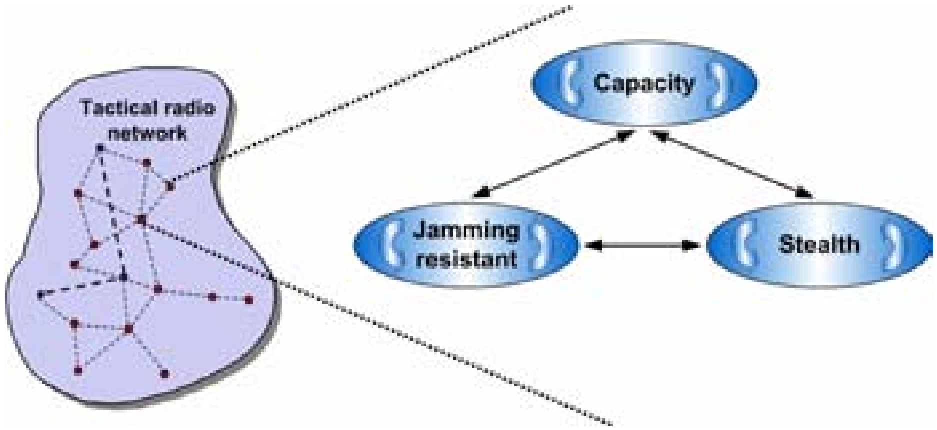

Figure 1: In a tactical ad hoc network, an adaptive radio node that can automatically change between user requirements on capacity, jamming resistance and stealth, yields improved possibilities for the military user to perform its tasks.

The number of different services to be provided by communication systems, e.g., speech, video, database replication, situation awareness and file transfers, increases. As a consequence higher capacity is required in the communication systems and to meet these requirements larger bandwidths must be used. When increasing the bandwidth the problem of frequency selective fading arises. A promising technique for handling the frequency selective fading in broadband systems is Orthogonal Frequency Division Multiplexing (OFDM).

An OFDM system is flexible and offers high spectrum efficiency and capacity. A multiple antenna system in both the transmitter and receiver, a so-called Multiple-Input Multiple-Output (MIMO) system, is expected to give substantial performance benefits. For example, depending on the scenario at hand, diversity gains can be achieved through transmit and receive space diversity, increased capacity through spatial multiplexing, or increased robustness through adaptive beam-forming approaches. However, the number of antenna elements that it is reasonable to use, especially at lower frequencies, can be limited by their physical size or the size of the platform. Furthermore, adaptive modulation, where the modulation level is adapted according to the perceived channel quality, may yield substantial capacity gains. Naturally, these capacity gains can also be used to increase the amount of channel coding and thereby enhance the quality and robustness of the given service.

In order to accurately track changes in the channel or service requirements adaptation will, for many techniques, be performed on a short time scale, packets or OFDM-symbols. However, some types of adaptation, for example towards the network conditions or slowly changing channel conditions, will be performed on a longer time scale.

In the civilian domain, the research on MIMO- and OFDM-systems, combined with adaptive modulation methods, has already been active for some years.

Traditionally the different layers of the OSI stack have been individually optimized. However, by allowing exchange of information between the different layers the network throughput may be substantially increased. For example, link layer information gathered at the MAC layer can be communicated to the routing layer for optimal route selection. To fully take advantage of adaptive radio nodes cross-layer communication should be implemented.

1.2 Outline

In Chapter 2, a description of the investigated system is given. A number of different techniques, such as; OFDM, transmit and receive diversity, channel estimation, pilot insertion, adaptive modulation, SNR-estimation etc. are also described. The set-up for the simulations is described in Chapter 3 together with the results from the simulations. Some ideas for future work are given in Chapter 4 and in Chapter 5 conclusions can be found.

2 System Description

The purpose of the simulations is to investigate the performance improvements gained by using different adaptive techniques – such as adaptive modulation, and transmit/receive diversity – in the radio nodes of a mobile radio network. The Medium Access Control (MAC) protocol is assumed to be Time Division Multiple Access (TDMA). To model the radio wave propagation a channel model, denoted Channel3D [1], is used to calculate impulse responses for specific transmitter and receiver locations. The impulse responses are then used by the communication system simulator, which simulates the transmission and reception by the adaptive radio node over the specific radio channel.

2.1 Radio Node Model Overview

An overview of the baseband radio transceiver model can be seen in Figure 2. The radio node model is based on an OFDM scheme employing adaptive modulation. The SNR is estimated on a sequence of received OFDM-symbols (a time slot of symbols). From the estimated SNR the highest possible modulation that can be used, while still maintaining a certain bit error rate target, is calculated and fed back to the transmitter. The transmitter adjusts its parameters accordingly and initiates the next transmission.

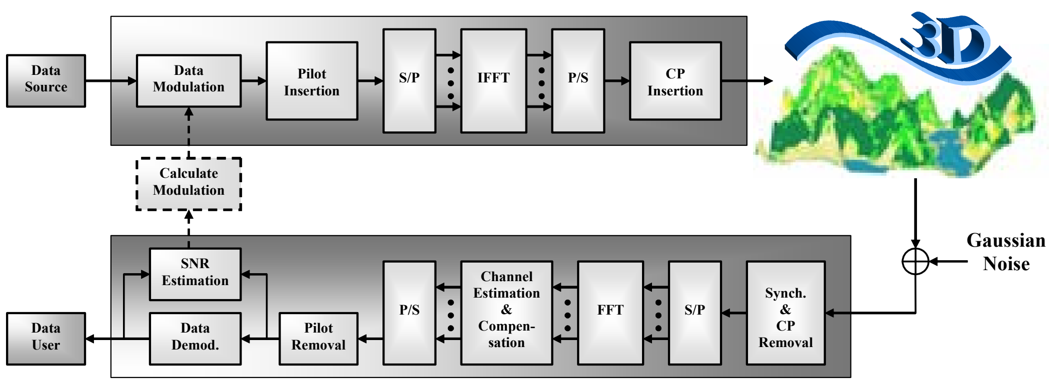

Figure 2: Baseband radio transceiver model and radio channel model.

Three different types of space diversity techniques have been implemented. The techniques are:

- SIMO (Single Input Multiple Output) - two-antenna receive diversity by Maximal Ratio Combining (MRC).
- MISO (Multiple Input Single Output) - two-antenna transmit diversity by Space-Frequency Block Coding (SFBC).
- MIMO (Multiple Input Multiple Output) - combined two-antenna transmit diversity by SFBC and two-antenna receive diversity by MRC.

Transmission without space diversity, i.e. one transmit and one receive antenna, is denoted SISO (Single Input Single Output). A scheme of the different transmission techniques is shown in Figure 3.

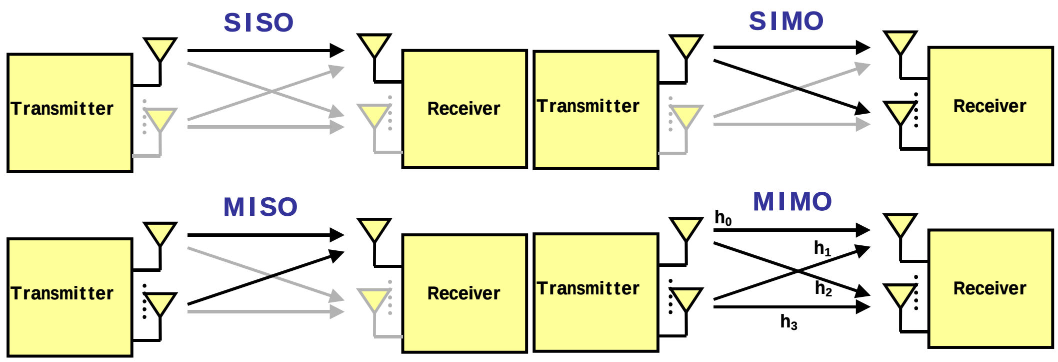

Figure 3: Different space diversity techniques; SISO, SIMO, MISO and MIMO.

2.2 Radio Channel Model

A novel deterministic map-based channel model, denoted Channel3D, has recently been developed, see [1]. It is based on physical optics and diffraction theory. In order to compute channel impulse responses a height and terrain database is used. The database contains a Digital Elevation Model (DEM) for non-urban areas for most parts of Sweden, the DEM has a resolution of 50 m in the xy-plane. In Channel3D, the contribution from the direct component is combined with all the ray contributions off the terrain surfaces, which can reach the receiver through a single reflection or scattering. Diffracted components are combined with coherent ground reflections and incoherent contributions from the scattering to yield dynamic impulse responses for the chosen scenario. The path loss for each ray is also calculated. The channel model includes directional information for each received ray as well as fading characteristics over time and frequency, for multiple antenna configurations.

In Channel3D, a static solution is first calculated where the contributions to the impulse response from all first order reflection or scattering rays are calculated. Thereafter, a dynamic (time-variant) impulse response is calculated by changing the phase of each received ray according to the specified position change. This approach is deemed valid for shorter position changes, but for vehicles moving over a large area, new static solutions must be calculated after some specified position change. We have chosen to recalculate the static solution after 50 meters. In Chapter 3 we use Channel3D to obtain time-varying impulse responses in order to demonstrate the effects of adaptive modulation for an OFDM-system in specific tactical scenarios.

2.3 Multiple Access Protocol

In order to mimic the behavior of a TDMA-schedule the simulation time is divided into time slots. Each time slot is 16 OFDM-symbols long (4 ms) and a transmission is performed every twentieth time slot. Figure 4 shows the TDMA-schedule.

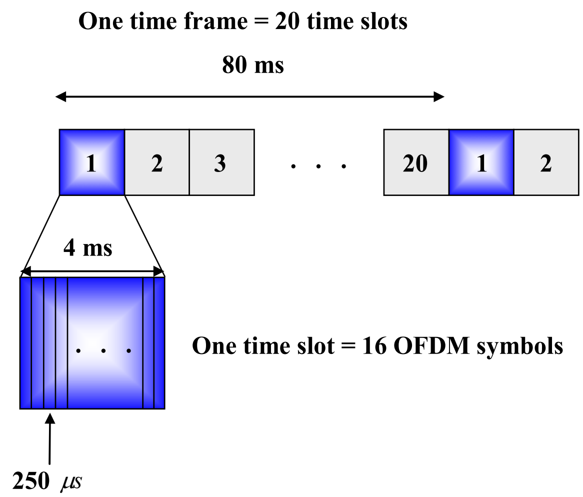

Figure 4: TDMA-schedule with 16 OFDM symbols in a time slot.

The channel is recalculated for each new time slot with Channel3D as described in the previous section. In the simulations a constant channel, *h*, is assumed during each time slot although a new realization of the noise, *n,* is applied to each OFDM-symbol. The received signal, *r*, is formed by convolving the OFDM-symbol, *s*, with the channel impulse response and then noise is added,

$$r = s * h + n\,. \tag{2-1}$$

2.4 Transmitter

2.4.1 Data generation

A random sequence of ones and zeros representing the information to be transmitted is generated by the data source. This information sequence is later compared with the received sequence to generate the bit error pattern i.e. a sequence showing which bits are correct and which are incorrect.

2.4.2 Data modulation, pilot insertion and OFDM-modulation

The information bits are mapped to symbols in one of several available modulation constellations (QPSK, 8-PSK, 16-QAM, 64-QAM). Known symbols, so-called pilot symbols, are inserted in the information sequence and then the sequence is passed to an Inverse Fast Fourier Transform (IFFT) to form the OFDM-symbol. Before transmission a cyclic prefix is added to the OFDM-symbol. A number of OFDM-symbols are generated and transmitted in sequence once a time slot becomes available. The transmission slot can be viewed as the time-frequency grid shown in Figure 5 containing 16 OFDM-symbols. Each symbol consists of 1106 subcarriers of which 1024 carries information and 82 are pilots.

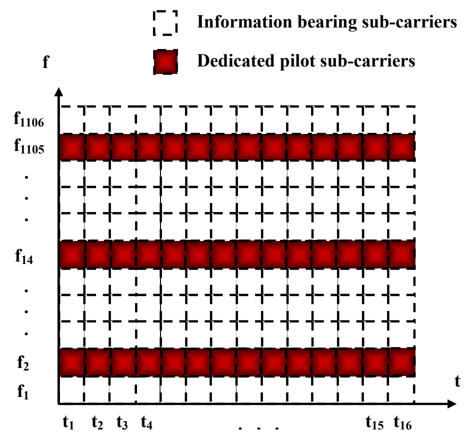

Figure 5: Pilot pattern shown in the time-frequency grid.

A typical pilot pattern is shown in Figure 5 where pilots are transmitted at the same frequencies for each OFDM symbol. In this case the pilots are evenly distributed in frequency, i.e. transmitted on approximately every 12th subcarrier f_2, f_{14} etc. This pilot pattern is not optimal and the effect of other pilot distributions are investigated in for example [3]. A detailed description of existing OFDM-systems and standards, for wireless local area networks can be found in [2].

2.4.3 Transmit diversity

Transmit diversity has been implemented for two transmit antennas. Space-Frequency Block Coding (SFBC) is used to map the symbols onto the carriers of the OFDM-symbols. Transmit diversity is implemented in a similar way as in [4] but instead of a space-time mapping of the symbols to be transmitted they are space-frequency mapped onto different subcarriers of the OFDM-symbol.

The mapping procedure, where the data vector $\bar{s}$ is mapped to the two OFDM-symbols $\bar{s}_{tx0}$ for antenna 0 and $\bar{s}_{tx1}$ for antenna 1, is given by equation 2-2. For clarity, the mapping of the first two data symbols is also described in Table 1.

$$\begin{aligned} \bar{s} &= \left[s_0 \;\; s_1 \cdots s_{K-2} \;\; s_{K-1} \right]^T \\ \bar{s}_{tx0} &= \left[s_0 \; - s_1^* \cdots s_{K-2} \; - s_{K-1}^* \right]^T \\ \bar{s}_{tx1} &= \left[s_1 \;\; s_0^* \cdots s_{K-1} \;\; s_{K-2}^* \right]^T \end{aligned}, \qquad (2\text{-}2)$$

Table 1: Encoding and transmission sequence for the two antenna transmit diversity scheme.

	tx antenna 0	tx antenna 1
subcarrier 0	s_0	s_1
subcarrier 1	$-s_1^*$	s_0^*

The data vector $\bar{s}$ consists of K complex symbols from one or several modulation constellations and * denotes the complex conjugate.

2.5 Receiver

2.5.1 Synchronization

The first thing to take place in the receiver is synchronization. The goal of the synchronization procedure is to find the start of the first OFDM-symbol and to align the subcarriers before passing them into the Fast Fourier Transform (FFT). This is a sensitive part of an OFDM-system. Synchronization is done by exploiting the correlation of the cyclic prefix with the tail of the OFDM-symbol, a standard procedure used in many OFDM-systems. The Maximum Likelihood algorithm presented in [5] has been implemented and is used to perform synchronization. After the synchronization the cyclic prefix is removed.

2.5.2 OFDM-demodulation, channel estimation and equalization

OFDM-demodulation is done by performing an FFT operation on the OFDM-symbol. After the FFT-operation the complex channel response is estimated by comparing the received pilot subcarriers with the known transmitted pilot subcarriers. The channel response for the information carrying subcarriers is then estimated by interpolating between the channel estimates of the pilot subcarriers, see Figure 6. An equalization of each subcarrier with its corresponding channel estimates of amplitude and phase is subsequently performed. Channel estimation in OFDM-systems by transmission of pilot symbols is discussed in for example [3].

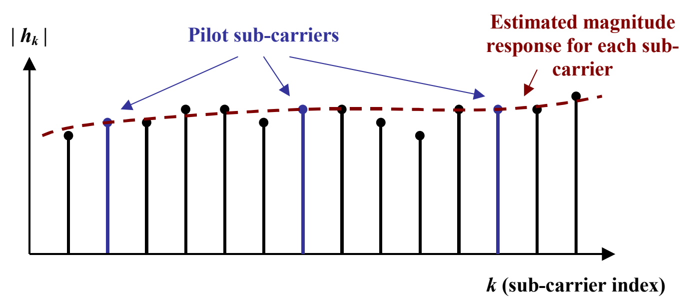

Figure 6: Illustration of pilot-based estimation of the magnitude of the channel transfer function for data carrying subcarriers.

After the channel compensation, the data sequence is stripped of the pilot symbols and the data symbols are demodulated.

2.5.3 Receive combining

When either transmit or receive diversity, or both, are used, the estimated channel response for each subcarrier is used in the combining process. To get an understanding of how the transmit and receive antenna diversity schemes work the mapping of the symbols on individual subcarriers, in the transmitter, and the combining scheme, used in the receiver, are provided in equations (2-3) to (2-8). The parameters used in the mapping and combining schemes are defined in Table 23. Table 2 gives the notation of the received signals on the different subcarriers and receive antennas. Table 3 defines the channels between transmit and receive antennas, see also Figure 3. Worth to note is that in SIMO and MISO there are two channels to estimate, whereas for MIMO four channels have to be estimated in the receiver. None of the diversity schemes needs any channel knowledge in the transmitter. A brief description of the combining schemes is given below and a more thorough explanation can be found in [4].

Table 2: Encoding and transmission sequence for the two antenna transmit diversity scheme, and notation of received signals.

	rx antenna 0	rx antenna 1
subcarrier 0	r_0	r_2
subcarrier 1	r_1	r_3

Table 3: The definition of channels between transmit and receive antennas.

	rx antenna 0	rx antenna 1
tx antenna 0	h_0	h_2
tx antenna 1	h_1	h_3

CLASSICAL TWO-BRANCH MAXIMAL RATIO RECEIVE COMBINING (MRRC)

In this case one transmit antenna and two receive antennas and MRRC is used. This space diversity scheme is referred to as SIMO.

The received signals at subcarrier 0 and 1 are:s

$$\begin{aligned} r_0 &= h_0 s_0 + n_0 \\ r_2 &= h_2 s_0 + n_2 \end{aligned} . \qquad (2\text{-}3)$$

The signals are combined to an estimate of the signal:

$$\tilde{s}_0 = h_0^* r_0 + h_2^* r_2 = h_0^*(h_0 s_0 + n_0) + h_2^*(h_2 s_0 + n_2) = (\alpha_0^2 + \alpha_2^2) s_0 + h_0^* n_0 + h_2^* n_2 , \qquad (2\text{-}4)$$

where α_0 and α_2 are the amplitudes of the channel responses between the transmit antenna and respective receive antenna. n_i represents both receiver thermal noise and interference.

After combining $\tilde{s}_0$ is sent to a maximum likelihood detector to produce the ML estimate of the transmitted symbol.

TWO-BRANCH TRANSMIT DIVERSITY WITH ONE RECEIVE ANTENNA

In this case two transmit antennas and one receive antenna is used. The data vector to be transmitted is subject to a space-frequency mapping according to Table 2. This space diversity scheme is referred to as MISO.

The received signals at subcarrier 0 and 1 are:

$$\begin{aligned} r_0 &= h_0 s_0 + h_1 s_1 + n_0 \\ r_1 &= -h_0 s_1^* + h_1 s_0^* + n_1 \end{aligned}, \tag{2-5}$$

Combining scheme:

$$\begin{aligned} \tilde{s}_0 &= h_0^* r_0 + h_1 r_1^* = (\alpha_0^2 + \alpha_1^2) s_0 + h_0^* n_0 + h_1 n_1^* \\ \tilde{s}_1 &= h_1^* r_0 - h_0 r_1^* = (\alpha_0^2 + \alpha_1^2) s_1 - h_0 n_1^* + h_1^* n_0 \end{aligned}, \tag{2-6}$$

The combined signals are then sent to the ML detector to produce the estimates of the transmitted symbols.

TWO-BRANCH TRANSMIT DIVERSITY WITH TWO RECEIVE ANTENNAS AND MRRC

In this case two transmit antennas and one receive antenna is used. The data vector to be transmitted is subject to a space-frequency mapping according to Table 2. The signals are in this case received on two antennas. This space diversity scheme is referred to as MIMO.

The received signals at subcarrier 0 and 1 are:

$$\begin{aligned} r_0 &= h_0 s_0 + h_1 s_1 + n_0 \\ r_1 &= -h_0 s_1^* + h_1 s_0^* + n_1 \\ r_2 &= h_2 s_0 + h_3 s_1 + n_2 \\ r_3 &= -h_2 s_1^* + h_3 s_0^* + n_3 \end{aligned}, \tag{2-7}$$

Combining scheme:

$$\begin{aligned} \tilde{s}_0 &= h_0^* r_0 + h_1 r_1^* + h_2^* r_2 + h_3 r_3^* = (\alpha_0^2 + \alpha_1^2 + \alpha_2^2 + \alpha_3^2) s_0 + h_0^* n_0 + h_1 n_1^* + h_2^* n_2 + h_3 n_3^* \\ \tilde{s}_1 &= h_1^* r_0 - h_0 r_1^* + h_3^* r_2 - h_2 r_3^* = (\alpha_0^2 + \alpha_1^2 + \alpha_2^2 + \alpha_3^2) s_1 - h_0 n_1^* + h_1^* n_0 - h_2 n_3^* + h_3^* n_2 \end{aligned}, \tag{2-8}$$

The combined signals are then sent to the ML detector to produce the estimates of the transmitted symbols.

2.5.4 SNR-estimation

The signal-to-noise ratio (SNR) is the metric used to decide which modulation to use. The SNR is estimated by a decision-feedback procedure where each of the demodulated information symbols is compared with the corresponding received information symbol prior to demodulation, see Figure 7.

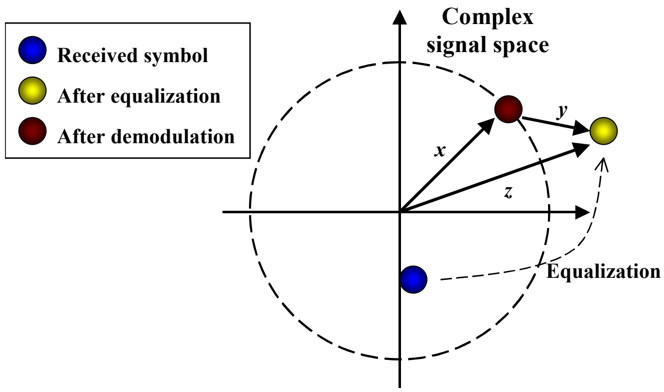

Figure 7: The complex signal space and the received, equalized and demodulated symbols.

The SNR is calculated as

$$\mathrm{SNR} = 10\log\left(\frac{\text{Signal Power}}{\text{Noise Power}}\right) = 10\log\left(\frac{\boldsymbol{x}\boldsymbol{x}^{*}}{(\boldsymbol{z}-\boldsymbol{x})(\boldsymbol{z}-\boldsymbol{x})^{*}}\right)[\mathrm{dB}], \qquad (2\text{-}9)$$

where $(\cdot)^{*}$ denotes the complex conjugate operation.

The decision-feedback approach is based on that the information symbols are demodulated correctly. If they are not, an error will be induced in the estimated SNR and as a consequence the SNR-estimation works the best for symbols with few bit errors. The sub-carries are clustered in groups of a given size and the SNR is estimated for each group.

2.5.5 Adaptive modulation

Different applications/services have different demands on the tolerable bit error rate (BER). Speech applications for example can tolerate more errors than a file transfer; on the other hand file transfers can in general tolerate a larger delay than speech applications. Different modulation schemes have different BER performance for the same SNR and are hence useful in different situations.

A general approach to adaptive modulation is to estimate the channel quality and make the choice of modulation based on that. In the OFDM-system described here the SNR is used to quantify the channel quality. Furthermore, the SNR is estimated for groups of 16 carriers. Hence, the 16 adjacent carriers will use the same modulation, since they are assumed to have the same SNR. A larger number of carriers can be grouped together and use the same modulation in order to reduce the amount of feedback to the transmitter.

SNR-METHOD

In the SNR-method adaptive modulation is performed by estimating the channel quality in terms of SNR, and choosing the highest modulation mode that still satisfies the requirement on BER. For a specific target BER, SNR-thresholds can be calculated for the different modulation schemes. For a specific modulation the requirement on BER is fulfilled for SNR values higher than the threshold. Hence, the thresholds can then be used to determine, for a given SNR, the highest modulation scheme that still satisfies the required BER.

If more carriers are grouped together into a modulation group this approach will use the lowest SNR in the group for the adaptation. This is a conservative approach that results in lower throughput if the SNR varies for the carriers adapted together. However, if the channel quality is constant over the larger group sizes the performance is the same for the two group sizes.

BER-METHOD

Another approach for adaptation that is useful if the channel quality varies substantially over the carriers in a modulation group is to estimate the BER. This approach involves calculating the total BER from all the estimated SNR values in a modulation group and for all modulation modes. The highest modulation mode that has a lower BER than the target BER is then chosen for the carriers. In this approach, all the estimated SNR values in a group affect the choice of modulation, not only the carrier with the lowest SNR, which leads to improved throughput. Another advantage of this approach is that it is easily adjusted to different values of the target BER.

We have performed simulations to examine the performance of these two adaptive modulation approaches for an OFDM-system. In the simulations, both the SNR-method and the BER-method are described in [6].

2.5.6 Feedback

The feedback to the transmitter may consist of the SNR-values estimated in the receiver. From the SNR-estimates the transmitter can decide which modulation to use. Another way is to let the receiver decide on the modulation and only feed back this information to the transmitter. The latter approach yields less feedback because a short identification number, that identifies the modulation mode, is transmitted for each modulation group compared to transmitting an SNR-estimate for each estimation group.

The rationale for clustering the subcarriers into estimation groups is that adjacent subcarriers will experience similar channels and by treating a group of subcarriers the same way the amount of feedback to the transmitter can be reduced. The more subcarriers that are clustered in a group, the smaller the number of groups per OFDM-symbol, and the less feedback to the transmitter. This of course comes at a price. If the subcarrier groups are too large, compared to the channel coherence bandwidth, the SNR estimation will not capture the variations of the channel. This will result in that the wrong modulation is used and either the capacity will be too low or the bit error rate too high. In order not to load the feedback link excessively it is desirable to find the optimal amount of feedback needed to characterize the radio channel.

In a system where the feedback consists of the chosen modulation order the size of the modulation groups is important. The benefit of using small modulation groups is that the channel is the same for all carriers in the modulation group. Hence, the chosen modulation mode is suitable for all carriers. The drawback is that the feedback to the transmitter can be large. On the other hand, for large modulation groups the amount feedback to the transmitter is lower but the choice of modulation mode is more difficult since the carriers in a modulation group can experience different channel conditions.

There is also a delay associated with the feedback information, originating from the processing in the transmitter and receiver, transmission delay, access protocol etc. If the feedback information is too old, i.e., the coherence time of the channel is shorter than the time it takes to feed back the information, a reduction in performance is inevitable.

In a TDMA protocol feedback information cannot be transmitted more often than a time slot becomes available. Therefore, during the simulations, the SNR of an estimation group is averaged over the entire slot before the modulation decision is taken for the next available time slot. The average value over a time slot has a lower variance than the estimate of each group.

3 Simulation Setup and Results

Before the simulations are run a number of scenarios are made in Channel3D and the impulse responses are calculated. Our simulations are made for different scenarios taking place in Älvdalen, a hilly terrain where multipath is expected. In Table 4 the parameters for the simulations are given.

Table 4: Parameters used in the simulations.

Transmit power	25 W
Transmitter speed	0 m/s
Receiver speed	10 m/s
Antenna height	3 m
Antenna polarization	vertical
Simulation time	200 s
Channel frequency	300 MHz
Time slot length (contains 16 OFDM-symbols)	4 ms
Time between transmissions	80 ms
Bandwidth	5.5 MHz
Guard interval	50 µs
Useful symbol time	200 µs
Information carrying subcarriers	1024
Pilot subcarriers	82
Subcarrier spacing	5 kHz
Modulation types	No Tx / QPSK / 8-PSK / 16-QAM / 64-QAM
Target bit error rate	10^{-3}
Channel coding	No
Maximum achievable data rate	1.2 Mbps

3.1 Different scenarios

The channel model is deterministic and therefore the results from the simulations depend highly on the chosen scenario. We compare two different scenarios to illustrate the impact of the scenario on the radio system performance. Both scenarios take place in the same area in Älvdalen but the actual positions for the transmitter and receiver differ. Estimated SNR-values for the two different scenarios are shown in Figure 8, together with the thresholds for adaptive modulation with the SNR-method and a target BER of 10^{-3}. The SNR values are averages over all carriers in an OFDM symbol and over a time slot. As can be seen in Figure 8 the SNR-values are quite different for the two scenarios, and with higher values for scenario one most of the time. Therefore, the performance of the system with adaptive modulation is expected to be better for the scenario with high SNR, since the system automatically step up in capacity when the signal level allows it. The use of different types of modulation is shown in Figure 9. The bars show the part of the time different modulation methods have been used. In the figure it can for example be seen that 64 QAM, the modulation method with most bits per symbol, has not been used for scenario two. This can be understood when looking in Figure 8, where the SNR for scenario two never exceeds the threshold for 64 QAM, which is at about 23 dB. In Figure 9 it can also be seen that higher modulations are used more often in scenario one and therefore the transmitted number of information bits are expected to be higher. In scenario one $68 \cdot 10^6$ bits are transmitted and in scenario two the corresponding number is $44 \cdot 10^6$ information bits.

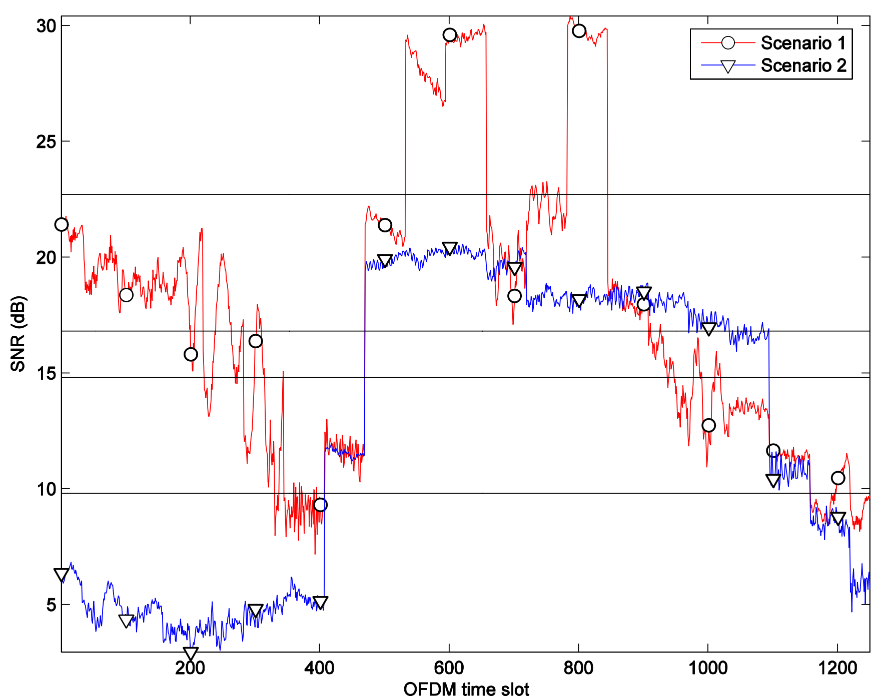

Figure 8: Estimated SNR for two different scenarios.

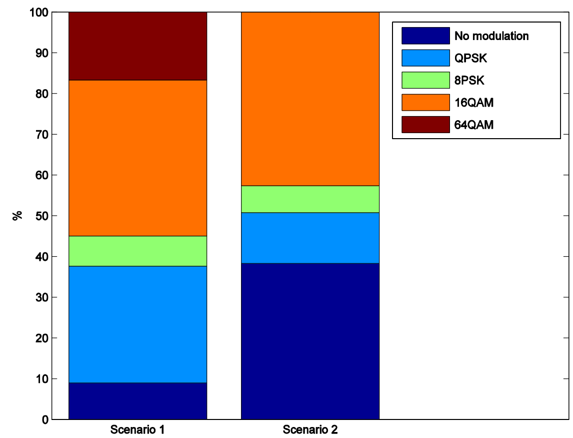

Figure 9: Part of the time different modulations are used for the two different scenarios.

3.2 Comparison between different adaptive modulation methods

We have performed simulations to examine the performance of the two adaptive modulation approaches for an OFDM-system; the SNR method and the BER-method, described in section 2.5.5. We compare the two methods with 1024 subcarriers in each modulation group. When using modulation groups with 16 carriers the BER- and SNR-methods yield the same result since there is only one estimated SNR-value per modulation group. Figure 10 shows that higher modulations are used for the BER-method than for the SNR-method since the latter uses the lowest SNR to choose modulation. The total number of information bits transmitted with the BER-method was $98 \cdot 10^6$ and for the SNR-method $76 \cdot 10^6$ information bits were transmitted. The corresponding BER was $3 \cdot 10^{-4}$ for the BER method and $1 \cdot 10^{-4}$ for the SNR-method. The SNR-method has slightly better BER performance since it is more conservative. However, the BER is well below the requirement 10^{-3} for both methods.

The BER-method is more complex since it uses all SNR values and calculates the BER for different modulation methods, whereas the SNR-method only considers the lowest SNR value and thresholds. However, compared to other signal processing in the receiver neither of the methods is to be considered computationally demanding. Moreover, for large modulation groups the BER-method yields better performance and is preferable and the increase in complexity can probably be neglected. However, for small modulation groups, in the same size as the groups used to estimate the SNR, the performance of the methods is equal. In the remainder of this report the BER-method is used.

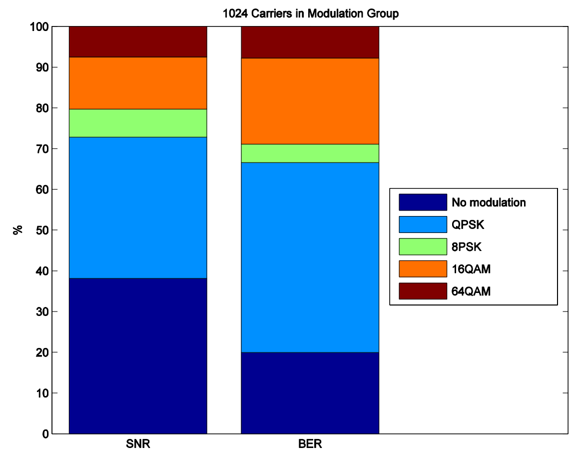

Figure 10: Part of the time different modulations are used for two different methods for adaptive modulation.

3.3 Diversity techniques

The impact from different diversity techniques on an adaptive radio system has been investigated through simulations. Figure 11 shows the estimated average SNR for each time slot over the scenario and Figure 12 shows a part of the same scenario in more detail. It can be seen that the SIMO and MIMO systems constantly perform better than the SISO and MISO systems in terms of SNR, i.e. a higher average SNR is maintained at the detector. This is due to the fact that when two receive antennas are used twice the power is received as compared to a system with one receive antenna. The theoretical maximum gain of a two receive antenna SIMO system over a SISO system is therefore 3 dB, which is in good agreement with the results in Figure 11 and Figure 12.

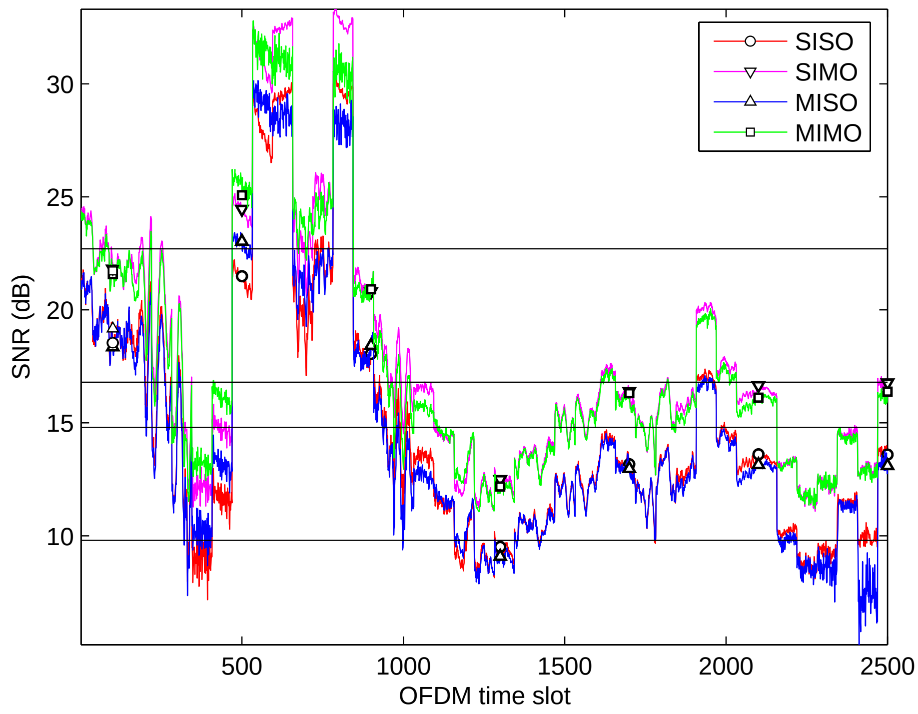

Figure 11: Estimated SNR in the time slots with different diversity methods.

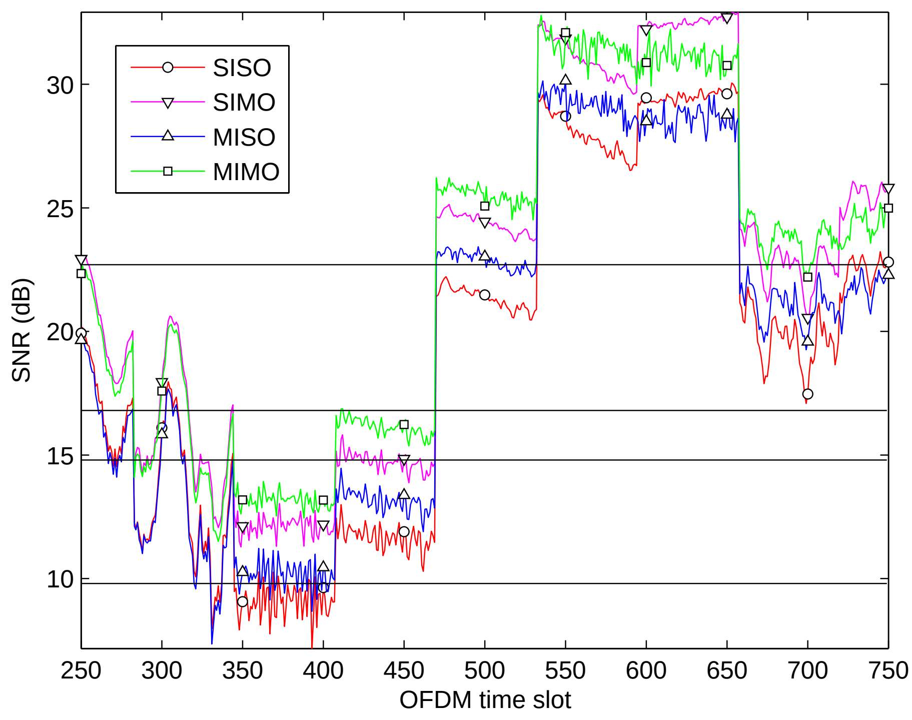

Figure 12: Estimated SNR in the time slots with different diversity methods, for a part of the scenario.

When employing two-antenna transmit diversity, the transmit power is split between the transmit antennas to allow a fair comparison with the other space diversity techniques.

When using MISO or MIMO the number of pilot tones per transmit antenna (or sub-channel) is halved compared to a system transmitting with one antenna. If the number of pilots per channel had been kept constant, i.e. a doubling of the total number of pilots, capacity would have been sacrificed. To reduce, or maintain, the number of pilots per channel for MISO as compared to SISO is a trade-off between capacity and the resolution at which the channel must be estimated.

The reduced transmit power, and number of pilots, per MIMO/MISO sub-channel results in that the MIMO/MISO sub-channels cannot be estimated as accurately as the SISO and SIMO channels.

Looking at the estimated SNR for the three different antenna diversity techniques and SISO in Figure 12 it is easy to see that the performance of the techniques to a large extent depends on the scenario. For example, for the time slots between 250 and 350, SISO and MISO perform about the same and SIMO and MIMO perform about the same. During this interval it can be concluded that there are no obvious advantages of using multiple transmit antennas. However, the two receive antennas for SIMO and MIMO give the expected 3 dB increase in SNR.

In the interval between 350 and 525 time slots the performance of the systems show a completely different order. The MIMO system performs the best, second best is SIMO, then MISO and last SISO. In this interval it is clear that the more antennas a system can use the larger the gain in SNR, which is then converted to a higher capacity by the adaptive modulation system.

The varying performance of the systems in the different intervals of the scenario is due to that the diversity gains are larger the more uncorrelated the sub-channels are. At times when the sub-channels are very similar (high correlation) the diversity gain of the antenna system is small, e.g., there is nothing to gain from using a MISO system compared to a SISO system. However, when the sub-channels are highly correlated the antenna system could be used to perform beamforming to direct a beam in the line-of-sight direction to the transmitter or receiver, or both, and thereby increase the effective SNR. This shows that an adaptive radio employing multiple antennas for transmission or reception should be designed to adapte between different antenna array techniques such as antenna diversity or beamforming. Furthermore, if the sub-channels are highly uncorrelated spatial multiplexing could be used to increase the capacity. Spatial multiplexing uses the sub-channels as separate channels to transmit different information over.

Results from the simulations are shown in Figure 13. The figure shows the part of the time that different modulation schemes are used for different diversity methods for modulation groups of 64 carriers. The left part of the figure shows the results from the whole simulation over 200 seconds. The corresponding SNR is shown in Figure 11. The right part of the figure corresponds to the part of the scenario shown in Figure 12. The use of higher modulation is more common in the part of the scenario (right figure) than in the whole scenario. This is due to that the average SNR is higher for this part of the scenario.

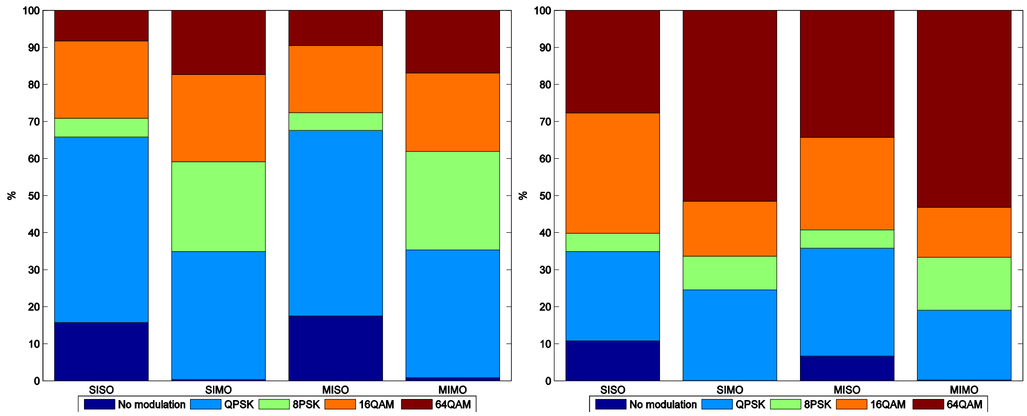

Figure 13: Part of the time different modulation schemes are used for different diversity systems and with 64 carriers in a modulation group. Results for the whole scenario to the left and for a part of the scenario to the right.

In Figure 13 it can be seen that the systems without receive diversity, SISO and MISO, show similar performance and that the system with receive diversity, SIMO and MIMO show similar performance. Hence, the techniques with highest use of higher modulations are SIMO and MIMO. This corresponds with earlier discussions of an increased SNR with use of receive diversity. In Table 5 the number of transmitted information bits during the part of the scenario is shown together with the average BER. The MIMO-system transmits the most number of information bits, with SIMO close behind and the SISO system transmits the fewest. The BER is below the requirement 10-3 for all systems and the SIMO system had the lowest BER:

Table 5: Results from simulations over the short scenario for different diversity techniques.

	Information bits	BER
SISO	$29.42 \cdot 10^6$	$0.37 \cdot 10^{-3}$
SIMO	$36.43 \cdot 10^6$	$0.25 \cdot 10^{-3}$
MISO	$31.02 \cdot 10^6$	$0.53 \cdot 10^{-3}$
MIMO	$37.15 \cdot 10^6$	$0.34 \cdot 10^{-3}$

Simulations with different numbers of carriers that are modulated together have been performed, and the results shown here are for the part of the scenario shown in Figure 12. Since the SNR-estimation is performed on a group of 16 carriers, i.e. from 16 carriers one SNR-value is estimated, this is the smallest number that can form a modulation group. The other extreme is that all 1024 carriers in an OFDM symbol form a modulation group. Groups with 64 carriers are also simulated as a complement. The simulations are made with different diversity techniques. In Figure 14, the results from different modulation groups are shown for SISO, SIMO, MISO and MIMO. The diagrams show that for a specific diversity technique the modulation group size only has a little impact on the performance. When the modulation group size increases the use of different modulations only change a little, and hence the performance is slightly better for the case with small modulation groups.

For the SISO case, the number of transmitted information bits is given in Table 6 where it also can be seen that the number of bits decreases slightly, from $29.6 \cdot 10^6$ to $28.7 \cdot 10^6$, with increased size of the modulation groups. When MIMO is used the difference is larger from $37.5 \cdot 10^6$ to $36.1 \cdot 10^6$. The bit error rate is almost the same for all the simulations and always below the requirement 10^{-3}. However, with the use of larger modulation groups the feedback to the receiver can be decreased. For example, if 3 bits can represent the chosen modulation the total amount of feedback during a simulation is

3·Carriers/(Carriers in a modulation group)·Time slots.

For a scenario with 2.500 time slots and 16 carriers in a modulation group, the total amount of feedback is 480 000 bits. On the other hand, with 1024 carriers in a modulation group the figure is 7 500 bits.

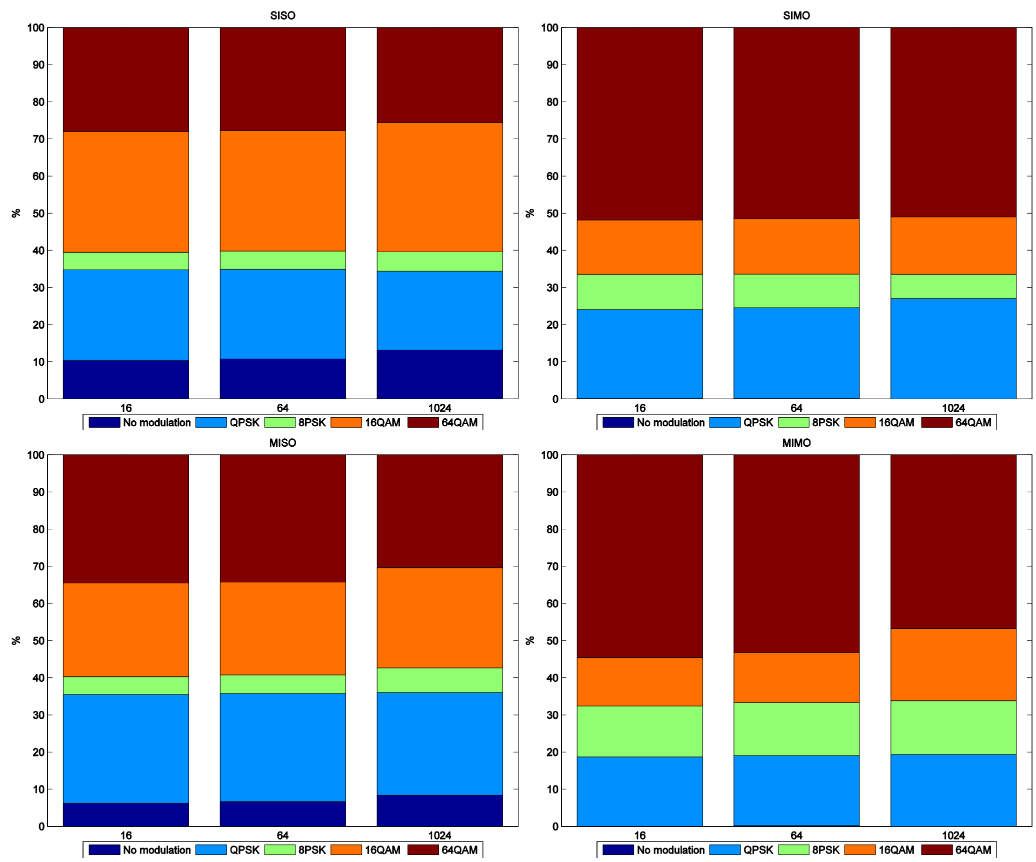

Figure 14: Part of the time different modulation schemes are used for different diversity systems and different sizes of the modulation groups for a part of the scenario.

Table 6: The total number of transmitted information bits for the short scenario and the average bit error rate.

	SISO		MIMO	
Group size	Information bits	BER	Information bits	BER
16	$29.6 \cdot 10^6$	$0.40 \cdot 10^{-3}$	$37.5 \cdot 10^6$	$0.36 \cdot 10^{-3}$
64	$29.4 \cdot 10^6$	$0.37 \cdot 10^{-3}$	$37.2 \cdot 10^6$	$0.34 \cdot 10^{-3}$
1024	$28.7 \cdot 10^6$	$0.36 \cdot 10^{-3}$	$36.1 \cdot 10^6$	$0.36 \cdot 10^{-3}$

In our simulations the modulation can be changed between two time slots in the TDMA-scheme. However, if the modulation is changed or not depends on the changes in the estimated SNR. The SNR follows the changes in the channel but also depends on if diversity is used and on possible estimation errors. Also, the size of the modulation groups has an impact on the performance of the system. In Table 7, the percentage of modulation changes over the scenario in Figure 12 is shown. A 100% modulation change means that the system changes modulation whenever possible, i.e., a new modulation is used in each modulation group in every time slot. From Table 7 it can be seen that for larger modulation groups the percentage of modulation changes is lower than for smaller modulation groups. Since, the SNR varies over the carriers in an OFDM symbol the variations in the average SNR between two time slots is larger for a smaller group. The use of diversity reduces the variations in SNR and hence the modulation is not changed as often, compare SISO and MIMO in the table.

Table 7: Percent of the timeslots where the modulation is changed from the previous slot.

	16	64	1024
SISO	13 %	12 %	8 %
MIMO	8 %	6 %	4 %

3.4 Feedback delay

To investigate the effect of feedback delay on adaptive modulation, simulations are performed where an OFDM-symbol is sent every 10 ms. The information used for determining the modulation scheme can be taken from the previous symbol or a number of symbols old, i.e. multiples of 10 ms old. We have investigated the effects of feedback delays between 10 ms and 1 s. The target BER was 10^{-3}, and the power was 25 W. Channel3D was used to calculate impulse responses every tenth millisecond for 100 seconds and during this time 10 000 OFDM symbols are transmitted.

The BER and number of transmitted information bits are shown in Figure 15 as functions of the feedback delay. For each delay a 100 seconds long simulation is made for each diversity technique. The BER, solid lines in the figure, increases with increased feedback delay. The shape of the BER curve depends on the scenario that is used. Hence, the results in the figure should be treated as one example of effects from feedback delays.

The two systems with receive diversity have a higher SNR compared to the other systems due to the combining in the receiver mentioned earlier. Hence, systems with receive diversity can transmit more information bits. In Figure 15 the number of transmitted information bits are shown as dotted lines. It is hard to make any conclusions about the difference between the two systems with receive diversity (SIMO and MIMO) since the difference between them is small and results depend on the scenario and for the same reason it is difficult to compare SISO and MISO. However, the differences between systems with and without receive diversity is larger and does not only depend on the scenario.

The both systems with receive diversity have the best BER performance and also the highest number of transmitted bits during a simulation. The number of transmitted information bits is almost constant for all delays, i.e. a delay in the feedback loop does not change the number of bits transmitted over the channel but affects the BER.

In the simulations the target BER was 10^{-3}. In Figure 15 it can be seen that for delays shorter than 0.25 seconds all the systems fulfil this requirement. For this scenario the MIMO and SIMO systems had the best BER performance and they fulfilled the requirement for delays up to 0.6 seconds for SIMO and almost 0.5 seconds for MIMO. Hence, the use of diversity makes the communication system less vulnerable to delays in the feedback loop.

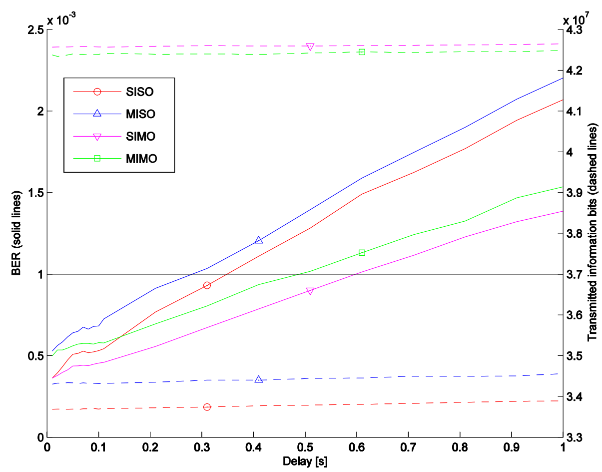

Figure 15: BER (solid lines) and number of transmitted information bits (dotted lines) as a function of the feedback delay. The target BER of 10^{-3} is illustrated by a black line.

4 Future work

In this report different air-interface techniques are investigated in a rural environment. The performance of communication systems is often highly dependant on the radio channel, and as a consequence it would be interesting to evaluate the techniques in other environments. For example, it would be interesting to consider an urban scenario since the channel conditions in this environment is significantly different from a rural scenario. In an urban environment the channel conditions are probably more difficult for the communication system, due to more reflections from buildings, diffraction over rooftops etc. However, for MIMO technologies larger gains are expected in scenarios with more multipath.

To study the effect of channel conditions on adaptive techniques more thoroughly, a statistical channel model should be implemented. In a statistical model it is easier to change the channel parameters and more systematically investigate the channel effects on performance. It must be possible to use the channel model for wideband OFDM-system simulations, and the channel model must hence represent channel behavior over a wide frequency range i.e. be broadband. The channel model must also be possible to use for simulations of multiple transmit and receive antennas, i.e. MIMO.

Traditionally the different layers of the OSI stack have been individually optimized. However, by allowing exchange of information between the different layers the network throughput can be substantially increased. For example, link layer information gathered at the MAC layer can be communicated to the routing layer for optimal route selection. To fully take advantage of adaptive radio nodes cross-layer communication should be implemented.

In a tactical situation multiple radio nodes want to use the same frequency band. A way to solve this is to assign time slots in which the channel is dedicated to a node, or to divide the frequency band into smaller bands dedicated to nodes. With an OFDM-based system it is possible to schedule different carriers in the OFDM-symbol to different users, which may result in an even better utilization of the spectrum resources. However, when several nodes are to transmit to a single node a problem arises. If the individual transmissions do not reach the receiver at the same time the OFDM-symbol will be distorted. To avoid this, the transmitting nodes must be synchronized such that their individual transmissions arrive at the receiver simultaneously. This may require that the transmitting nodes start their transmissions at different times due to propagation delay. If such a scheduling is feasible in a mobile ad hoc network is still unknown.

5 Conclusions

In this report performance studies of adaptive techniques for an air-interface of a tactical waveform have been carried out. The investigated system is an OFDM-system employing different space diversity techniques and adaptive modulation. Simulations were performed for a specific scenario, using a deterministic map-based channel model.

Two different methods for adaptive modulation, the SNR and BER methods, have been compared. Of the two methods, the BER method has better performance if the number of carriers that are adapted together is large. The rationale for adapting many carriers together is to reduce the amount of feedback to the transmitter. For a smaller number of carriers that are adapted together the performances of the methods are identical.

Simulations with receive space diversity and adaptive modulation show that receive diversity methods increase the usage of higher modulations and thereby increase the capacity of the radio link. The gains with transmit diversity techniques are lower than expected in the simulations performed here. The reason is probably that the amount of multipath in the scenarios is too low to exploit the benefits of transmit diversity. As a consequence it is desirable to further analyze the space diversity techniques in scenarios with more multipath.

The influence of delay in the feedback loop was also investigated. Simulations with feedback delays between 10 ms and 1 s showed that the risk of not reaching the target BER increases with an increased delay. However the use of space diversity techniques decreased the sensitivity to delays.

6 References

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