Adaptive Techniques for Tactical Communication Systems

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ABSTRACT

In the future Swedish Defence the capacity requirements on the communication network is expected to be substantially increased. To satisfy these demands, high capacity radio nodes must be developed. The communication system should also be able to work in different communication environments. To provide robustness and capacity in diverse environments, it would be preferable with dynamic flexible 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.

Orthogonal Frequency Division Multiplexing (OFDM) is a promising technique for tactical communication systems since it is flexible and can be adjusted to a number of different scenarios. In this work we have examined the use of adaptive techniques for an OFDM-system. Two different adaptive modulation approaches for an OFDM-system, as well as different modulation group sizes (i.e. the number of neighbouring sub-carriers employing the same modulation), are evaluated through simulations. The influence of delays in the feedback loop is also investigated. Results from simulations with two different diversity techniques combined with adaptive modulation are also presented. The investigated diversity techniques are; space diversity in the receiver with maximal ratio combining (MRC) and transmit diversity with space frequency block coding (SFBC).

1.0 INTRODUCTION

The Swedish Armed Forces are currently undergoing a transformation to provide enhanced battlefield awareness, and thereby improved striking power, and efficiency of the military forces. The Network Based Defence (NBD) concept is the enabler to provide flexible, rapid and controlled engagement capabilities. In order to achieve the Network Based Defence concept, the requirements on the command and control system is substantially increased. For instance, the distribution of situation awareness data, a prioritised service, will lead to an increased data flow within the communication network. A high capacity tactical mobile radio network, with ad hoc functionality, capable of conveying mixed services, and the ability to support varying stringent quality-of-service demands, is an essential enabler for the NBD concept.

Today, military radio solutions are normally optimised for the worst-case scenario, for example high jamming resistance. At times where there is no jamming present this is inefficient since robustness is often achieved at the expense of capacity. Hence, the communication network is expected to benefit from the use of flexible adaptive radio nodes, which can adapt to changes in the radio channel, signal environment, toward user- or service-specific demands, and toward the communication network.

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2.0 ADAPTIVE RADIO

The goal of 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, to obtain the best possible performance. The adaptive radio should be capable of automatic adaptation to continuously maximize one (or several) given performance measure(s), for instance maximal capacity or minimal power consumption, while closely tracking variations in the service demands on error rates, delays, availability, robustness, stealth, etc. In this work we have focused on capacity as performance measure.

When attempting to adapt towards changes in the wave propagation conditions and signal environment, knowledge of the channel is required. In order to adapt efficiently, it is necessary for the node to monitor the radio channel and signal environment, track variations, and determine when adaptation is required. Furthermore, a feedback channel is usually required since the transmitter often needs information about the channel conditions experienced by the receiver. However, full channel knowledge, which is often complex to obtain and may require substantial feedback information or long training sequences, is not necessary. It is instead essential to determine suitable metrics that give sufficient information for various adaptation methods.

In order to swiftly follow 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 adaptation, towards the network conditions or slowly changing channel conditions, will be performed at a much longer time scale.

An adaptive radio node based on a Multiple-Input Multiple-Output Orthogonal Frequency Division Multiplexing (MIMO-OFDM) system is a promising candidate for future software defined radio waveforms. An OFDM system is flexible and offers high spectrum efficiency and capacity. The 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 beamforming approaches.

In order to achieve low BER in an OFDM-system channel coding is often required. For different scenarios, different codes will have the best performance and it is therefore of interest to be able to adapt the coding. In addition, with adaptive coding sufficient error correcting capability can be achieved without unnecessary loss of capacity. Moreover, adaptive modulation where the modulation level is adapted according to the perceived channel quality can be employed and yield substantial capacity gains. If both coding and modulation are adapted they should be adapted together to get the best overall performance.

2.1 OFDM

Orthogonal Frequency Division Multiplexing (OFDM) is a highly flexible multi-carrier technique that can achieve high capacity at 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 narrowband sub-carriers. Hence, instead of transmitting very short data symbols over a large bandwidth, the symbols are long and transmitted on multiple narrowband sub-carriers. A detailed description of existing OFDM-systems and standards, for Wireless Local Area Networks, can be found in [6].

The OFDM-symbols are designed so that the length of each symbol is much larger than the delay spread of the channel. By using orthogonal sub-carriers the interference between different carriers (inter-carrier interference, ICI) is minimized. A cyclic prefix, which should be longer than the channel delay spread, is added as a guard interval in the beginning of each OFDM-symbol [6]. In the receiver, the cyclic prefix is removed, thereby eliminating inter-symbol interference (ISI) from the remaining received signal. Also, the cyclic prefix helps maintaining the orthogonality between sub-carriers in multipath environments, by converting the linear convolution channel to a cyclic convolution. The cyclic prefix can also be used for synchronization in the receiver. Naturally, the bandwidth efficiency is reduced due to the insertion of the cyclic prefix. Furthermore, known symbols (pilot symbols) are transmitted on pre-defined sub-carriers in order to facilitate synchronization and channel estimation in the receiver.

2.2 Adaptive Modulation

Adaptive modulation has the potential to substantially increase the spectral efficiency of tactical communication systems [5]. Different applications/services have different demands on the tolerable bit error rate (BER). Adaptive modulation is performed by estimating the channel quality and choosing the highest modulation mode, which still satisfies the requirement on BER. In Figure 1, the BER is calculated for different SNR-values and modulations, and the SNR regions where the different modulation schemes should be used can be seen.

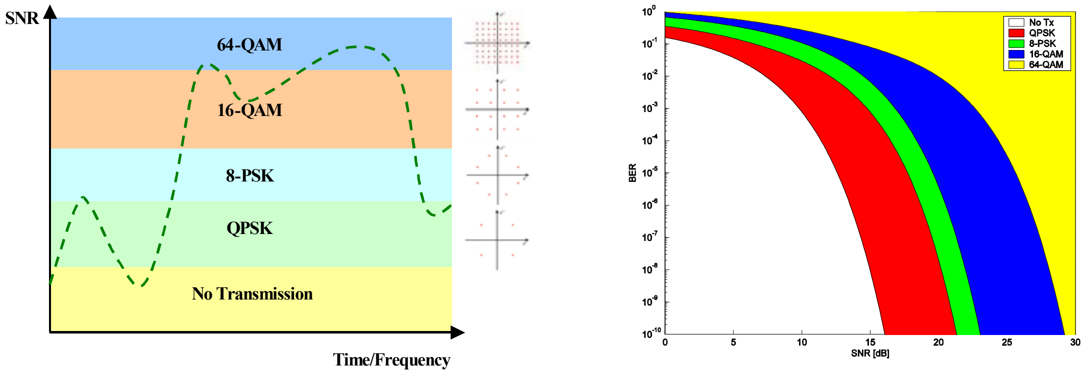

Figure 1: To the left, illustration of adaptive modulation based on estimated SNR. To the right, the BER is shown as a function of SNR for different modulation methods, for an AWGN channel. Different modulation methods yield, for a specified BER requirement, the highest spectral efficiency in different SNR-regions.

2.2.1 Size of modulation sub-bands

In an OFDM-system the adaptive modulation may be performed on a sub-carrier-by-sub-carrier basis, which has the advantage that the number of transmitted bits is maximized. The drawback is that the required amount of feedback to the transmitter becomes large. In a practical system the SNR is often estimated for a group of adjacent sub-carriers. Since only one SNR-value is estimated for the group the adaptation has to be performed on the whole estimation group instead of on the individual carriers. The adaptation can also be performed for even larger groups, i.e. several SNR-values are estimated for each modulation sub-band in order to reduce the feedback to the transmitter, assuming that it is the receiver that chooses appropriate modulation modes for the sub-bands. An assumption for this sub-band approach to achieve good performance is that the channel is similar for all carriers in a sub-band, i.e. that the bandwidth of the sub-band is smaller than the coherence bandwidth of the channel.

2.2.2 SNR-threshold method

For a specific target BER, SNR-thresholds, i.e. the SNR required to meet the BER required, can be calculated for the different modulation schemes. These thresholds are then used to determine, for a given instantaneous SNR, the highest modulation scheme that still satisfies the required BER [4]. This straightforward method for performing adaptive modulation aims at maximising the spectral efficiency while keeping the instantaneous BER below the specified target BER. Other more complex methods have also been proposed, which instead tries to keep the *average* BER below the specified value, thereby increasing the spectral efficiency [5].

The SNR- threshold method can be used for sub-band adaptation. If the SNR varies over the sub-band, the lowest SNR in the sub-band is used for the adaptation. This is a conservative approach that results in lower throughput than the sub-carrier-by-sub-carrier approach if the SNR varies within the sub-bands.

2.2.3 BER method

Another approach for adaptation if the channel quality is not constant for a sub-band is to estimate the BER. This approach involves calculating the total BER for a sub-band for all modulation modes. The highest modulation mode that has a BER lower than the target BER is then chosen for the sub-band. In this approach, all carriers in a sub-band affect the chosen modulation, not only the sub-carrier with the lowest SNR and this leads to improved throughput [5]. This is in effect an averaging operation, however not an average over SNR.

2.3 Transmit and Receive Diversity

Space diversity is a bandwidth efficient method for combating the negative effects of fading. The principle is straightforward; if two or more antennas are spaced sufficiently apart the received signals in the different antenna elements will fade differently and ultimately independently. Thus, by using the signal from the antenna that for the moment experiences the best channel conditions, or by combining the signals from the antennas intelligently, the effects of the fading can be significantly reduced. Bandwidth efficient space diversity can be achieved at the receiver by employing several antennas, but it can also be achieved by using multiple transmit antennas and by coding the signal over both space and time (or frequency). Space diversity yields a reduction of the signal variations, caused by fading, and it can also result in an enhanced average SNR. The combination of OFDM and diversity combats the fading in two ways. OFDM transforms a frequency selective channel into a number of flat fading channels, and diversity methods reduce the signal variations if the different branches do not experience deep fades simultaneously.

2.3.1 Receive Diversity - Maximal Ratio Combining (MRC)

Maximal ratio combining (MRC) is the optimal receive diversity method. The individual sub-carriers from the different antennas are phase aligned and amplitude-weighted and thereafter added. Hence, the sub-carriers are combined separately. The weight applied to each sub-carrier is proportional to the SNR at that sub-carrier, so that a sub-carrier with high signal strength (when compared to the corresponding sub-carrier from the other antennas) will be given a larger weight. Maximal ratio combining optimises the SNR for each sub-carrier. However, it requires that channel estimates are available in the receiver, as all combination methods do.

2.3.2 Transmit diversity through Space-Frequency-Block-Coding

Space-Frequency-Block-Coding (SFBC) is a bandwidth efficient technique, with low computational complexity, to achieve transmit diversity gains for OFDM-systems [2]. The encoding and transmission scheme for Alamouti's SFBC scheme for two transmit antennas is shown in Table 1. The main advantage with Alamouti's transmit diversity scheme is the simple combining, which is the result of the chosen encoding scheme [1].

Table 1: Encoding and transmission scheme for Alamouti's SFBC with two transmit antennas.

	Transmit on antenna 1	Transmit on antenna 2
Sub-carrier *k*	s_1	s_2
Sub-carrier *k+1*	$-s_2^*$	s_1^*

SFBC combining is performed, separately for each pair of sub-carriers, as follows:

$$\hat{s}_1 = h_{1,1}^* r_1 + h_{2,1} r_2^*$$
$$\hat{s}_2 = h_{2,1}^* r_1 - h_{1,1} r_2^*$$

where $\hat{s}_i$ denotes the combined symbol *i*, r_i denotes the received signals on antenna element *i*, and $h_{m,n}$ is the channel frequency response between transmit antenna *m* and receive antenna *n* (for sub-carrier *k* and sub-carrier *k+1*). The two symbols can then be successfully combined and detected, provided that the channel responses for the two neighbouring sub-carriers are identical. Hence, on two sub-carriers it is possible to transmit two symbols, for each OFDM-symbol. Also, in order to perform SFBC, the channel response between all antenna combinations must first be estimated. However, no channel knowledge is required in the transmitter. The complexity of this transmit diversity combining is similar to that for MRC.

The described SFBC combining can easily be extended to also incorporate receive diversity through MRC [1]. By employing both transmit diversity and receive diversity the diversity order is multiplied, i.e. a diversity order of eight is obtained by using two transmit antennas and four receive antennas. However, if more than two transmit antennas are employed it is not certain that full rate SFBC is possible, and the diversity order may then be achieved at the cost of a reduced capacity.

3.0 SIMULATION SET-UP

In order to investigate the performance of an adaptive radio, a baseband simulation tool has been developed, and the simulation structure is shown in Figure 2.

In the transmitter, the digital data is modulated according to the perceived channel quality in the receiver, which is fed back to the transmitter. The adaptive modulation methods were designed to achieve a maximum BER of 10^{-3} that is assumed to be sufficiently low to support some services, e.g. voice, without channel coding. Neighbouring sub-carriers are grouped into groups of 16, 64, 256, or 1024 sub-carriers and the same modulation is used for all sub-carriers in the group. Known pilot symbols are inserted at regular intervals, and an IFFT is performed. A cyclic prefix is added in the time domain. The signal is thereafter convolved with the channel impulse responses calculated with Channel3D, a channel model tool described in the next section. Additive White Gaussian Noise (AWGN) is added, and the resulting signal is sent to the receiver.

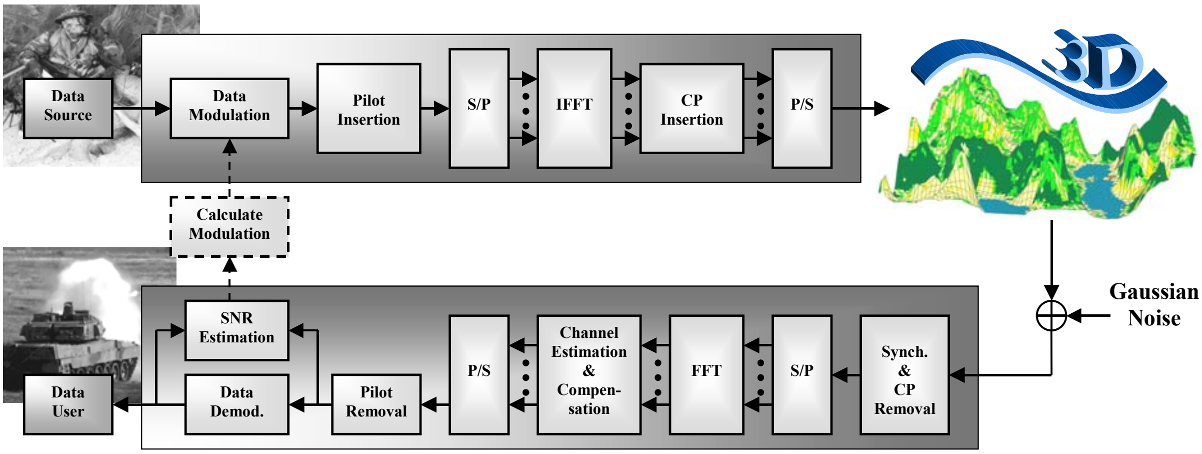

Figure 2: Simulation structure for the adaptive radio node.

In the receiver, the cyclic prefix is used to perform synchronization. A correlation-based approach, similar to the method described in [3], is used to find the beginning of each OFDM-symbol. After synchronization, the cyclic prefix is removed and an FFT is performed on the received data.

A pilot-symbol-assisted-modulation (PSAM) approach is used in the simulations [10]. For each individual pilot sub-carrier, the complex channel response is estimated by comparing the known transmitted pilot symbol to the received symbol. Thereafter, the channel for the data carrying sub-carriers is estimated through interpolation between the channel estimates for the pilot sub-carriers. These channel estimates are used to compensate for the channel effects on each data carrying sub-carrier, i.e. each sub-carrier is "equalized" in the frequency domain. After the channel compensation, the pilot symbols are removed and the data signal is demodulated.

The SNR for a group of sub-carriers is estimated by comparing the demodulated data symbols for each of the sub-carriers with the corresponding received data symbols (prior to the demodulation), and thereafter taking the mean over the sub-carriers in the group [9]. Since the SNR-estimation is based on a decision-feedback procedure, the estimates are valid only for situations where the erroneous detections (i.e. bit errors) are few. Finally, the estimated SNR is used to calculate appropriate modulation types for the sub-carriers for the next OFDM-symbol and this information about the modulation type is feedback to the receiver.

3.1 Wireless Channel Model

A novel deterministic map-based channel model, called Channel3D, has recently been developed [7, 8]. It is based on physical optics and diffraction theory. In order to compute channel impulse responses for non-urban areas, a digital terrain database is used that includes height and terrain type information for most of Sweden, for terrain pixels of 50×50 m^2. 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 antennas. 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.

In Channel3D, a scenario was chosen, including transmitter and receiver positions and their movement and the channel impulse responses were calculated for the scenario. The graphical user interface (GUI) for Channel3D is shown in Figure 3, for the chosen scenario in Älvdalen. It represents one of the more difficult radio propagation environments in Sweden; it is a hilly area and has deep valleys. This fairly difficult scenario was chosen so that we would have substantial path loss variations, and frequency-selective fading, for a relatively short simulation run.

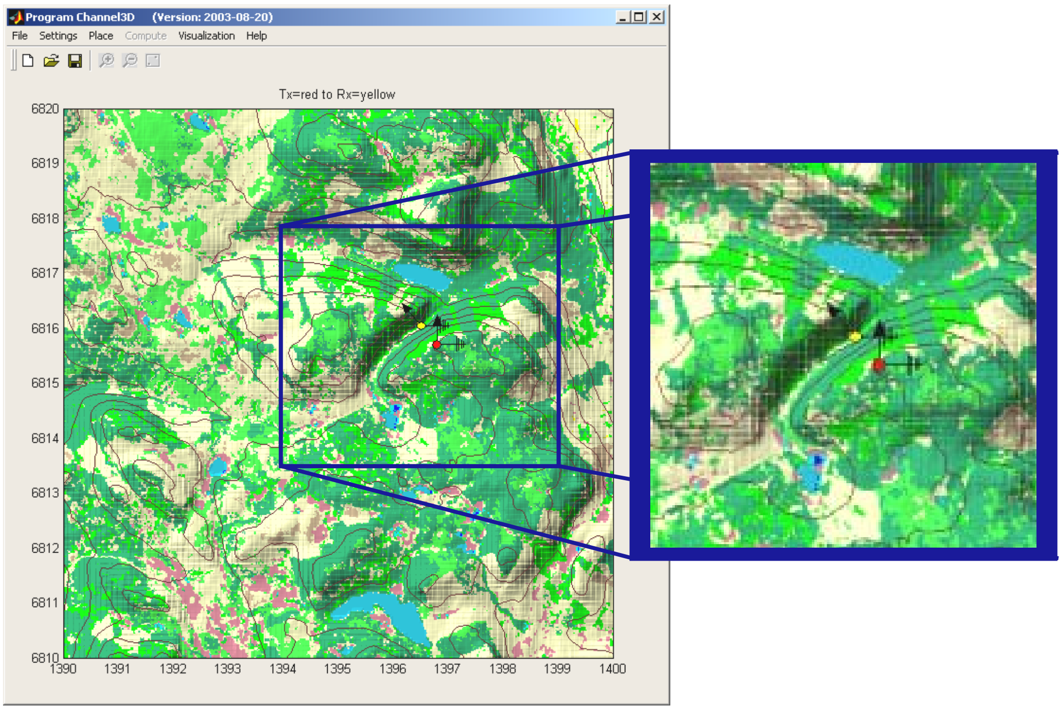

Figure 3: The chosen simulation scenario, in Älvdalen, as seen in the Channel3D GUI. The transmitter (red) is stationary while the receiver (yellow) moves at a speed of 10 m/s, in the direction of the arrow (north-west).

3.2 Simulation parameters

In order to mimic the behaviour of a TDMA-schedule time is divided into time slots. Each time slot is 16 OFDM-symbols long and transmission is performed every twentieth time slot. The channel is recalculated for each new time slot. In the simulations performed, we have assumed a constant channel during each time slot. However, the SNR is estimated for the previous OFDM-symbol, thus, the noise contribution differs from the estimation to the actual data transmission.

The simulation was performed over 100 s, which corresponds to a position change of 1 km for the receiver since it moves with at a speed of 10 m/s. During these 100 seconds 20 000 OFDM-symbols were sent in 1 250 time slots. A transmit power of 25 W was used. Antenna heights (vertically polarized antennas) were 3 m for both transmitter and receiver. In Table 2 the parameters for the simulations are given.

Table 2: Parameters used in the simulations.

Power	25 W
Transmitter speed	0 m/s
Receiver speed	10 m/s
Antenna height	3 m
Antenna polarization	vertical
Simulation time	100 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 sub-carriers	1024
Pilot sub-carriers	82
Sub-carrier spacing	5 kHz
Modulation types	No Tx / QPSK / 8-PSK / 16-QAM / 64-QAM
Channel coding	No
Maximum achievable data rate	1.2 Mbps

4.0 RESULTS

4.1 Adaptive Modulation

We have performed simulations to examine the performance of the two adaptive modulation approaches for an OFDM-system described in Section 2.2; the SNR-threshold method and the BER-method. The SNR was estimated in the receiver for groups of 16 sub-carriers. Hence, the smallest modulation group in the adaptive modulation scheme was 16 sub-carriers. Also, we examined the effect of using 64, 256 and 1024 sub-carriers in each modulation group. The estimated average SNR for the scenario is shown in Figure 4.

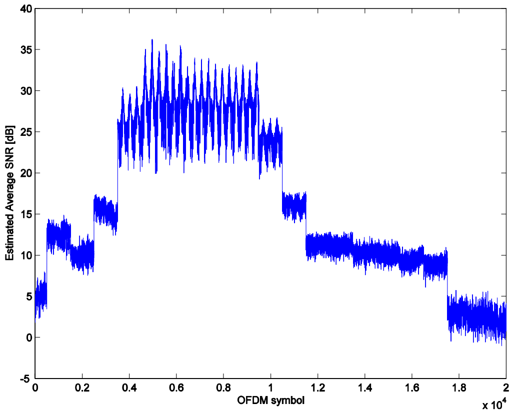

Figure 4: Estimated average SNR for the scenario.

In Figure 5 it can be seen that the capacity is reduced when increasing the number of sub-carriers in each modulation group. Dark blue represents no transmission, while the blue, green, orange and brown colours represent the usage of QPSK, 8-PSK, 16-QAM, and 64-QAM, respectively. For example, when using the SNR-threshold method with 16 sub-carriers in each modulation group, almost 30 % of the sub-carriers use 64-QAM, averaged over the scenario. In contrast, when using 256 sub-carriers in each modulation group, about 13 % of the sub-carriers use 64-QAM. The reason for the performance degradation is that in the SNR-threshold method the lowest SNR value in the modulation group is used to choose modulation and with larger groups the risk that SNR varies within a group increases. The advantage of having larger modulation groups is that the amount of feedback to the transmitter can be reduced.

The performance decreases less for the BER method than for the SNR-threshold method when using larger modulation groups. This is intuitive, since the SNR-threshold method is conservative and chooses the modulation according to the sub-carrier with the lowest SNR, while the BER method instead estimates the BER from all the available SNR-estimates. Hence, the BER method gives better results when adapting the modulation for larger groups. Of course, this result is valid for scenarios where the channel within the modulation group varies; if the channel is constant over the modulation group the two methods will yield identical results, as when using 16 sub-carriers in each modulation group.

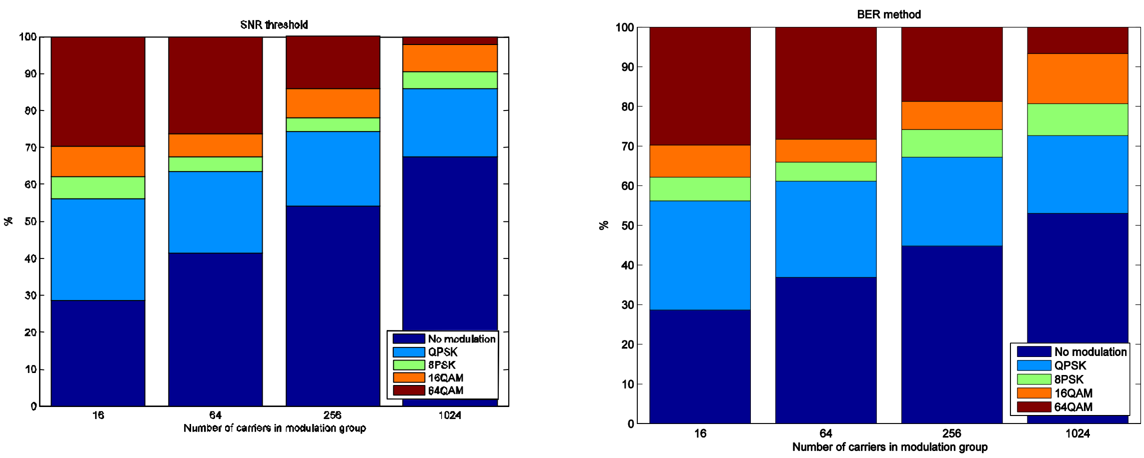

Figure 5: Percentage of sub-carriers using the different modulation types, compared for different group sizes.

In Table 3 the results from the simulations are summarized. The number of transmitted information bits decreases as the modulation group size increases, as expected considering the results in Figure 5. For the SNR-threshold method the number of transmitted information bits when using the largest group size is less than 1/3 comparing to the smallest group size. For the BER-method the reduction in transmitted information bits is less than ½ when using the largest modulation group size compared to the smallest group size. Furthermore, the average BER over the scenario is between $0.5 \cdot 10^{-3}$ and $2.2 \cdot 10^{-3}$. The BER is somewhat lower for the SNR-threshold method, since it on average uses lower modulation orders. The target BER 10^{-3} is not always reached since it assumes perfect channel knowledge - in our simulations the SNR used for the adaptive modulation is estimated on the previous OFDM-symbol.

Table 3: Total number of transmitted information bits, and bit error rate over the scenario.

SNR-threshold method	Sub-band size	Transmitted information bits	Bit error rate
	16	$58 \cdot 10^6$	0.0022
	64	$48 \cdot 10^6$	0.0009
	256	$34 \cdot 10^6$	0.0006
	1024	$18 \cdot 10^6$	0.0005
BER-method	16	$58 \cdot 10^6$	0.0022
	64	$52 \cdot 10^6$	0.0012
	256	$42 \cdot 10^6$	0.0012
	1024	$31 \cdot 10^6$	0.0012

4.2 Adaptive Modulation and Feedback Delay

A challenge when performing adaptation in a wireless communication system lies in the fact that the transmitter does not have instantaneous knowledge about the channel quality. In order to adapt efficiently it is necessary for the node to monitor the radio channel and signal environment, track variations, and determine when adaptation is required. The delay of the feedback information is an important part of the overall performance of the communication system. If the delay is too long compared to the channel coherence time the channel information is incorrect. When adaptive modulation is used a long feedback delay may lead to that the wrong modulation mode is used, either a too low mode is used and capacity is lost or a too high mode is used resulting in an increased BER.

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 order can be from the previous symbol or a number of symbols old, i.e. a multiple of 10 ms old. In this section 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 has been used to calculate impulse responses every tenth millisecond for 100 seconds and during this time 10 000 OFDM symbols are sent in the simulations. Two different kind of scenarios were used, one scenario with a large amount of multipath, Älvdalen see section 3.1, and one scenario with one strong line of sight component. The estimated average SNR is shown in Figure 6, with SNR from the scenario with hilly terrain in blue and SNR from the more flat scenario in red.

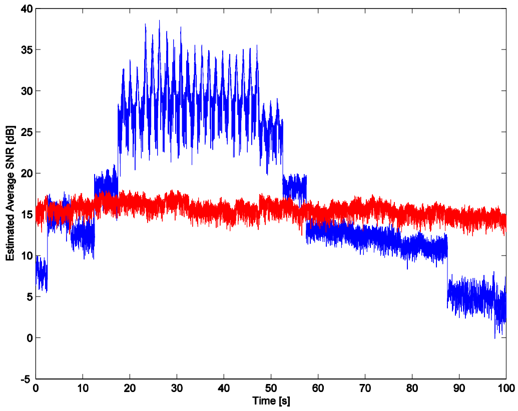

Figure 6: Estimated average SNR for the two scenarios. The blue is from the scenario with hilly terrain and the red is from the scenario with flat terrain

The results from the simulations can be seen in Figure 7. The figure to the left shows results for the rough terrain and the right is from the more flat terrain. The figures show the BER and the number of transmitted information bits for the simulations with different feedback delays. In the figures we can se that the results depend on the scenario at hand, but with increasing delay the BER is also increasing. However, the increase of the BER is not a monotone function of the delay but dependent on the scenario.

In a system with a non- negligible delay, an SNR offset may have to be added to the SNR-thresholds used for adaptive modulation in order to be able to satisfy the target BER.

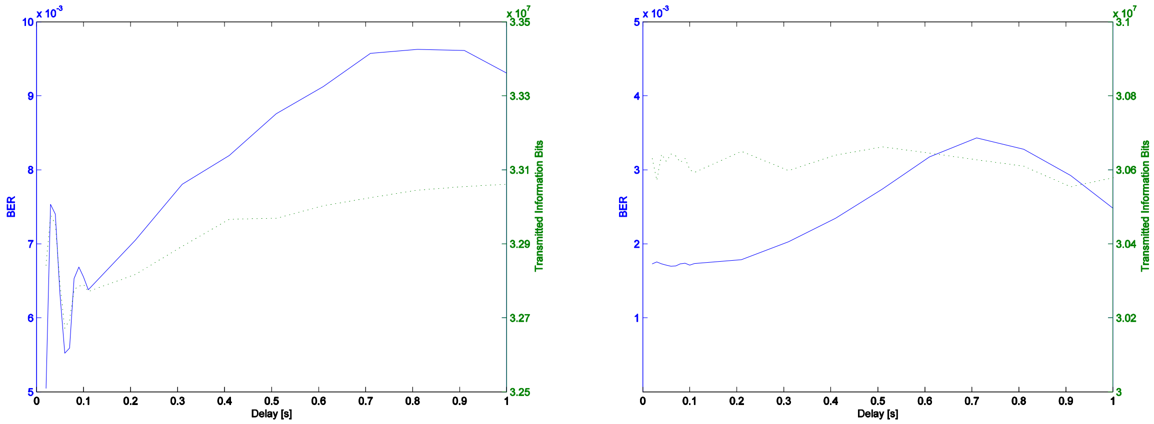

Figure 7: BER and number of transmitted information bits as a function of the feedback delay, for two different scenarios, to the left is a scenario with rich multipath and to the right is a scenario with a strong LOS component.

4.3 Diversity methods

The SIMO-system considered in this section use space diversity (maximal ratio combining) with one transmit antenna and two receive antennas, the MISO-system employ two transmit antennas (SFBC) and one receive antenna. The antenna elements in the arrays were separated 1.4 meters apart, which at a frequency of 300 MHz correspond to 1.4 wavelengths.

The SNR-threshold method was used to perform adaptive modulation, with a modulation group size of 16 sub-carriers, the same size as the estimation groups for SNR-estimation. The transmit power is 25 W. For MISO- and SIMO-combining perfect channel knowledge is assumed.

In Figure 8 the estimated average SNR for each OFDM symbol over the scenario is shown. Three different space diversity systems are considered. One system without space diversity (SISO), one system with SFBC transmit diversity (MISO), and one system with MRC receive diversity (SIMO).

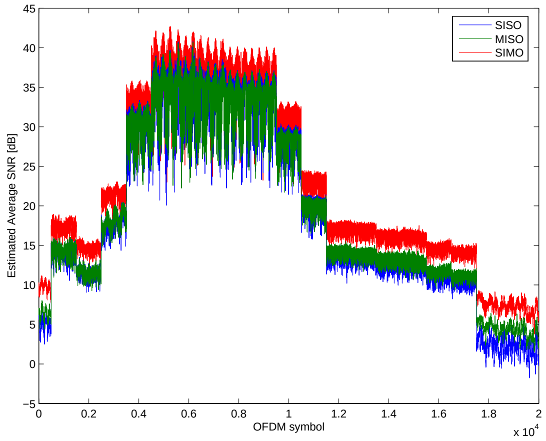

Figure 8: The estimated average SNR for each OFDM symbol for a system without space diversity (SISO), with SFBC transmit diversity (MISO), and with MRC receive diversity (SIMO).

The use of space diversity (SIMO or MISO) results in a reduced variance of the SNR compared to a system with a single transmit and a single receive antenna (SISO). As a result, a communication system employing space diversity have a more stable signal at the detector than a SISO-system. Figure 8 shows that there is a general increase of the average SNR level in the order of 3 dB for the SIMO-system compared to the SISO- and MISO-systems. This is due to the fact that with two receive antennas twice as much energy is received, resulting in an 3 dB increase of the average SNR level. One could argue that a MISO-system transmitting with two antennas and receiving with one antenna should have a comparable performance to a SIMO-system transmitting with one antenna and receiving with two antennas. This would indeed be true if the MISO-system was to transmit twice as much power as the SIMO-system. In our case when employing MISO and transmitting with two antennas the transmitted power from each antenna has been halved in order to maintain the same total output power as the SIMO and SISO implementations and thereby enable a fair comparison between the systems considering a limited power budget. This is the reason why the average SNR-levels of the SISO- and MISO-systems, in Figure 8, have a comparable average SNR and both are about 3 dB lower than for the SIMO-system. The MISO system still gives a reduced variance of the SNR compared to the SISO system.

To make a fair comparison of the systems the MISO sub-channels must be estimated with the same resolution as the SISO- and SIMO channel. This essentially means that the number of pilot tones transmitted from each antenna element must be the same for all the systems in order not to favour the channel estimation of any of the systems. The increase in the total number of pilots for the MISO-system will result in a slight decrease of its spectral efficiency.

When employing multiple transmit and/or receive antennas with an OFDM-system, which uses adaptive modulation, the system can capitalize on the more stable and higher average SNR by switching to higher modulation modes on the sub-carriers and thereby enable a higher capacity than a SISO-system.

In Figure 9, the percentage of sub-carriers that uses the different modulation modes is shown. Dark blue represents no transmission, while the blue, green, orange and brown colours represent the usage of QPSK, 8-PSK, 16-QAM, and 64-QAM, respectively.

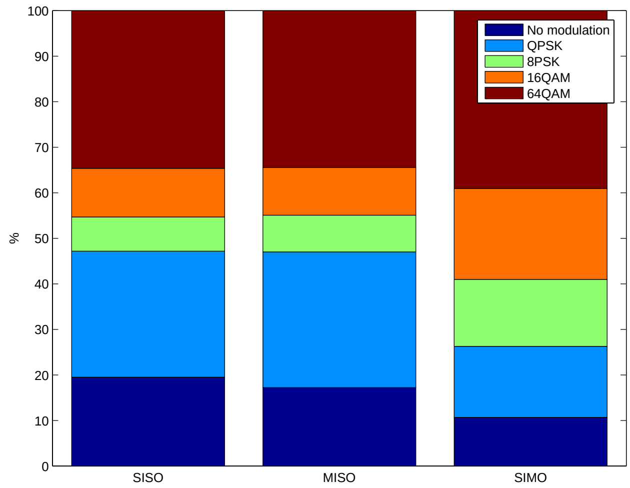

Figure 9: Percentage of sub-carriers using the different modulation modes during the scenario for a system without space diversity (SISO), with SFBC transmit diversity (MISO), and with MRC receive diversity (SIMO).

It can be seen that the 3 dB SNR increase of the SIMO-system compared to the SISO-system has been used to more often select higher order modulation modes (64-QAM, 16-QAM and 8-PSK) at the same time as the lower order modulation QPSK has been selected more seldom. The amount of time the system chooses not to send at all has also been reduced. The SISO-and MISO-systems use approximately the same percentage of the different modulation modes. However, the reduced SNR-variance of the MISO-system results in that the time of no transmission is slightly reduced compared to the SISO-system.

Table 4 shows the number of transmitted information bits and the bit error rate for the different systems. It can be seen that it is possible to transfer more information bits with both the MISO- and SIMO-system that the SISO-system. The MISO- and SIMO-systems also have a lower bit error rate that the SISO-system.

Table 4: Total number of transmitted information bits and bit error rate over the scenario.

	Transmitted information bits	**Bit error rate**
SISO (1 Tx 1 Rx)	$67 \cdot 10^6$	$5.6 \cdot 10^{-4}$
MISO (2 Tx 1 Rx)	$68 \cdot 10^6$	$4.0 \cdot 10^{-4}$
SIMO (1 Tx 2Rx)	$80 \cdot 10^6$	$4.9 \cdot 10^{-4}$

In adaptive modulation systems where the switching of modulation modes is based on the estimated SNR the reduced variance of SNR in the SIMO- and MISO-systems is an attractive feature since it will reduce the probability of "modulation bouncing" near the modulation thresholds. The increased average SNR level will result in an increased probability of higher order modulation modes being selected and hence a higher spectral efficiency is obtained.

5.0 CONCLUSIONS

In this paper we have examined the use of adaptive techniques for tactical communication systems. Various adaptive techniques for an OFDM-system are presented and simulations are performed for a scenario, using a deterministic map-based channel model.

Simulations have been performed for two different types of adaptive modulation and with different number of carriers that are adapted together. The performance of the two methods was similar for small group sizes, but with larger group sizes the method that try to estimate the BER was favourable. The BER-method gives a reasonable trade-off between amount of feedback information and capacity.

The influence of delays in the feedback loop was also investigated. Simulations over different scenarios with feedback delays between 10 ms and 1 s show that with an increased delay the risk of not reaching the target BER increases. However the resulting BER was depending on the scenario and not a monotone function of the delay.

Simulations with transmit diversity by SFBC (MISO-system) and receive diversity with MRC (SIMO-system) have been performed. For transmit diversity the total output power is the same as for a SISO-system, i.e. the output power is halved on the two antenna elements. The number of pilots used must also be increased compared to a SISO-system. Hence, the performance of the MISO-system is just a little better than a SISO-system. Simulations with receive space diversity and adaptive modulation show that receive diversity methods increase the usage of higher modulations and thereby increase the system throughput.

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