Evaluation of downlink IEEE802.16e communication at airports

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Abstract

Mobile WiMAX technology is proposed for ATS and AOC communications in airport areas. This technology provides a large amount of flexibility, incorporating optional use of advanced communication techniques and signal processing. Of particular importance is the use of multiple antenna techniques.

In this paper the performance of Mobile WiMAX technology is assessed by means of simulations for communications over channel models suited for airport communications. The simulations include space time coding (STC) and spatial multiplexing (SM). The results illustrate the gain obtained using multiple antenna techniques in the case of non line-of-sight between transmitter and receiver, which may be exploited for increased cell size or increased throughput per cell. In addition, the effect of Weibull fading is illustrated for *b*-factors lower than 2. This leads to worse than Rayleigh fading, and should be taken into account when setting thresholds in the adaptive coding and modulation scheme.

Introduction

In order to support the requirements of future ATM services, it is recognised that the capacity of air ground communication systems must be increased. As a response to this demand, new frequency bands have recently been opened to aeronautical communications systems. One of these frequency bands is the 5091-5150 MHz MLS extension band, which will be used for communications at and around airports. As no communication system currently exists for airport communication occupying this frequency band, a new system must be developed. Adopting technologies conforming to commercial standards instead of developing a completely new and dedicated system will reduce cost related to development and purchase as well as maintenance and upgrade. The solution proposed by EUROCONTROL and FAA for communications at and near airports is to implement Mobile WiMAX technology[1, 2].

WiMAX technology is already in use in airports. In Aéroports de Paris, Alcatel and Hub télécom has have installed WiMAX networks to deliver public and private communication services to passengers and airport professionals. The system operates in the licensed 3.5 GHz band, and is based on the IEEE802.16-2004 standard. Proximetry's GateSync is another system developed to facilitate commercial airlines' need to update on board information and entertainment each time an aircraft land at an airport. This system is also based in the IEEE802.16-2004 standard.

Mobile WiMAX is based on the IEEE802.16e amendment of the IEEE802.16 standard. This standard is highly advanced in the sense that it incorporates state-of-the-art communication techniques such as Orthogonal Frequency division Multiplexing Access (OFDMA), adaptive coding and modulation, hybrid ARQ, smart antenna systems and iterative decoding (Turbo-codes, LDPC codes). Some of these techniques are mandatory in any equipment, others are optional. The standard is in addition flexible both with regards to operational frequency, bandwidth and type of physical interface (single carrier, OFDM, OFDMA). In order for a product to be WiMAX certified, it must be approved by the WiMAX forum. In April 2008 the first eight Mobile WiMAX products received the WiMAX Forum Certified Seal of Approval for use in the 2.3 GHz band. Products for use in the 2.5 GHz band will be certified in the coming months.

When developing a WiMAX profile for airport communications in the 5.1 GHz band, careful consideration must be given to the properties of the frequency band and to the particular characteristics of airport communications, such as the speed of aircrafts during taxing and during takeoff and landing, communication distances, types and density of buildings and structures in the signal propagation path etc.

Several publications have already considered the use of Mobile WiMAX for communications at airports, but then typically only considering the OFDM physical layer[2] or OFDMA without Adaptive Antenna Systems (AAS)[3,4]. The physical layer adapted to airport environment is expected to be based on OFDMA and to take advantage of AAS to improve the performance and robustness against rapidly changing channel conditions. In this publication simulation results are given for communication over typical channel models using OFDMA and AAS. The channel models used are the standard Rayleigh model for non-line-of-sight (NLOS) communication and the “worse than Rayleigh” Weibull model considered suitable for airport environment. Both space time coding (STC) and spatial multiplexing (SM), which are the two main AAS techniques in the specifications, are included.

The paper is organized as follows: In the next section the properties and characteristics of the system are described more in detail. The simulation model is described in Sec 3, while simulation results are included in Sec. 4 together with an assessment of their consequences on system performance. Finally, the conclusions are drawn in Sec. 5.

System description

Figure 1 Airport communication

The WiMAX specifications contain three physical interfaces: single carrier, OFDM and OFDMA, and both Time Division Duplexing (TDD) and Frequency Division Duplexing (FDD). The WiMAX forum develops profiles for various usages of the WiMAX technology, including mobile usage. The release 1 of the WiMAX Forum Mobile System Profile[5] only considers OFDMA as physical interface and TDD as duplexing mode. It is reasonable to expect a future airport WiMAX profile to also be based on OFDMA and TDD, and only this mode is considered in this publication.

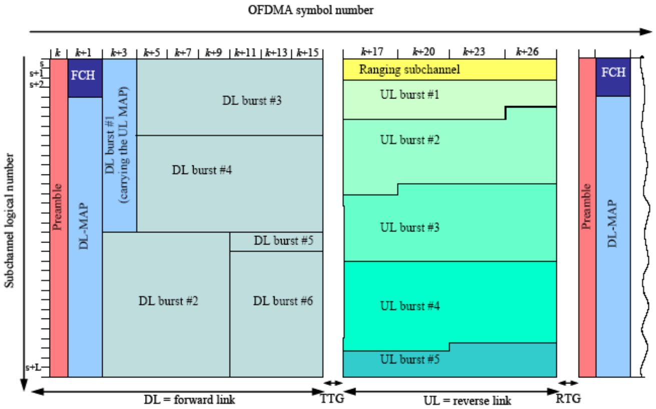

Figure 2 OFDMA frame structure

The OFDMA frame structure is illustrated in Figure 2. The main difference between OFDMA and the more traditional OFDM scheme is that the sub-carriers of the OFDMA symbols may be divided into groups, and that different groups of sub-carriers may be allocated to different mobile stations (MSs). In TDD mode, the base station (BS) transmits a block of OFDMA symbols first, and then, after a transmission gap, the MSs transmit a block of OFDMA symbols back to the BS. One burst, which is a group of sub-carriers within a number of OFDMA symbols is allocated to a communication link between the BS and one MS. Each burst has its proper coding and modulation scheme and other parameter settings adapted to the service requirements and to the quality of the channel between the BS and the particular MS. Information about downlink (DL) OFDMA resource allocation is provided in the DL-MAP field in the beginning of the OFDMA frame. Similarly, the resource allocation in the uplink (UL) is provided in the UL-MAP field. The distribution of resources between MSs both in DL and UL may be changed dynamically between each OFDMA frame. Various frame durations are allowed. In the WiMAX Forum Mobile System Profile however, frame length of 5 ms is recommended.

Bandwidth - scalability

The Mobile WiMAX technology provides flexibility in signal bandwidth which may be selected from 1.25 MHz to 20 MHz. The sub-carrier spacing is fixed for all bandwidths, so that the varying bandwidth is obtained by varying the Fast Fourier Transform (FFT) size in the OFDMA modulator. The lowest bandwidth of 1.25 MHz corresponds to a FFT size of 128, and the largest bandwidth to a FFT size of 2048.

The duration of an OFDMA symbol is independent of the bandwidth and equal to 91.4 μs plus the length of the cyclic prefix. The allowed lengths of the cyclic prefix are 1/4, 1/8, 1/16 and 1/32 of the OFDMA symbol length. In the Mobile WiMAX Forum System Profile, cyclic prefix length equal to 1/8 of the OFDMA symbol length is recommended.

Sub-carrier allocation

For the downlink, there are two mandatory sub-channel allocation schemes: Full Usage of Sub-Carriers (DL-FUSC) and Partial Usage of Sub-Carriers (DL-PUSC). In addition there are a number of optional schemes. For the uplink, UL-PUSC is mandatory, while a number of permutation schemes are optional. In this publication we only consider DL-PUSC.

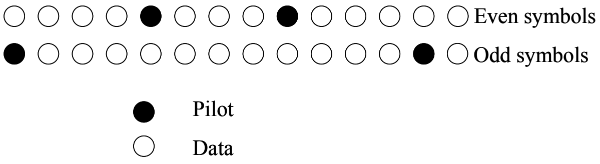

Figure 3 DL-PUSC cluster (SISO)

In DL-PUSC, the sub-carriers are allocated into clusters containing 14 contiguous sub-carriers and two OFDMA symbols. Each cluster contains four symbols which are known by the receiver and which are used by the channel estimation algorithm. The distribution of pilot symbols within each cluster is illustrated in Figure 3. The maximum number of clusters within the OFDMA symbol depends on the FFT size. For 128 FFT the number of clusters is 6 while it is 120 for 2048 FFT. Physical clusters are allocated into logical clusters using a renumbering sequence, logical clusters are divided into six major groups, and finally sub-carriers are partitioned into sub-channels containing 24 sub-carriers each. The result is that a data stream is spread over the physical sub-carriers and thus obtaining frequency diversity in the case of frequency selective fading.

Pilot symbols and channel estimation

In order to perform coherent detection of the received signal, the channel gains must be estimated. This is done using the pilot symbols embedded into the OFDMA block. The variations of the channel in both time and frequency domains and the strength of the additive white noise are factors determining how accurately the channel is estimated. The channel estimation error increases with the distance between pilot symbols. However, transmitting pilot symbols means spending power without transmitting information and leads to reduced spectral efficiency. Transmitting many pilot symbols is especially expensive in WiMAX systems, as pilot symbols are boosted 2.5 dB with respect to information symbols. Choosing the optimal density of pilot symbols is therefore a trade-off between estimation accuracy and spending energy on non-information bearing pilot symbols. The distribution of pilot symbols depends on the sub-channel allocation scheme. For DL-PUSC signals with one transmit antenna, the distribution of pilot symbols is given by Figure 3.

Coding and modulations

In the IEEE802.16 standards a number of coding and modulation schemes involving QAM modulation and convolutional coding are mandatory. These are listed in Table 1. By implementing link adaptation, the optimal mode providing the maximum number of information bits per symbol can be selected assuring sufficiently low bit error rate (BER) for reliable communication. In addition to convolutional coding, block and convolutional turbo coding and Low Density Parity Coding (LPDC) are optional schemes in the specifications. In this publication only the mandatory coding schemes listed in Table 1 are employed.

Table 1 Coding and modulation schemes

Mode	Modulation	Convolutional coding rate	Information bits per symbol
1	QPSK	1/2	1
2	QPSK	3/4	1.5
3	16QAM	1/2	2
4	16QAM	3/4	3
5	64QAM	1/2	3
6	64QAM	2/3	4
7	64QAM	3/4	4.5

Adaptive Antenna Systems (AAS)

The IEEE802.16e-2005 specifications include the optional use of several advanced multiple antenna techniques. Using multiple antennas in both ends of a transmission, and hence forming a multiple input-multiple output (MIMO) system, provides significant performance gain. This gain may be exploited to obtain extended range, extended capacity and/or better interference suppression depending on which MIMO technique that is employed in the system. In this publication, the focus is on Space-Time Coding (STC) and Spatial Multiplexing (SM).

The STC scheme included in the specifications is Alamouti's transmit diversity scheme and is referred to as matrix A. For DL transmission from 2-antenna BSs, matrix A is given by:

$$A = \begin{bmatrix} s_i & -s_{i+1}^* \\ s_{i+1} & s_i^* \end{bmatrix}$$

The procedure is as follows. For each sub-carrier in the transmitter, two and two consecutive symbols in the data stream are grouped in pairs (s_i, s_{i+1}). During the first symbol period t_i, transmit antenna 1 transmits symbol s_i and transmit antenna 2 transmits symbol s_{i+1}. During the second symbol period t_{i+1}, transmit antenna 1 transmits symbol $-s_{i+1}^*$ and transmit antenna 2 transmits symbol s_i^*, where $(^*)$ denotes complex conjugate. This transmit diversity scheme provides a diversity gain of order 2. In the receiver, the signals can be received by one or two antennas. With two receive antennas, maximum ratio combining is used (MRC). MRC provides an additional diversity gain of order 2, so that a 2×2 MIMO system employing STC obtains a total diversity gain of order 4.

The SM scheme included in the specifications is referred to as matrix B, and is given by:

$$B = \begin{bmatrix} s_i \\ s_{i+1} \end{bmatrix}$$

Transmit antenna 1 transmits the first symbol s_i and transmit antenna 2 transmit the second symbol s_{i+1} in parallel. The transmit side does not offer any diversity gain, but instead offers a coding gain of 2. If the signal is received by two receive antennas, the receive side offers a diversity gain of 2 provided that a maximal likelihood (ML) detector is used.

Adaptive MIMO switching (AMS) is included in the specifications. AMS implies that a transmitter can switch between STC and SM from block to block in the same way as the coding and modulation scheme may change. This provides additional flexibility in the system to efficiently distribute the frequency and time resources between BSs in dynamic environments.

Range

The range of a WiMAX BS will in most cases be limited by the required signal level at receivers. The length of the gaps between DL and UL blocks may also be a limiting factor (see Figure 2 for definition of the gaps TTG and RTG). The TTG must be so long that any MS does not start to transmit before it has received the total DL block. Similarly, the RTG must be so long that the BS does not start to transmit before it receives all of the preceding uplink data block. In the standard it is required that the both TTG and RTG must be longer than 5 µs. In the WiMAX Forum Mobile System Profile the values depend on the bandwidth. For 10 MHz channels TTG is 296 PS (106 µs) and RTG is

168 PS (60 μs), where PS is the Physical slot which is defined as $4/F_s$ where F_s is the sampling frequency. During 60 μs a signal propagates 18 km, well above the practical range of a BS. In systems conforming to the WiMAX profile the lengths of the gaps are therefore not a limiting factor. During 5 μs, which is the minimum value set in the IEEE802.16 standards, a signal propagates 1500 meters. Implementing such small gaps may therefore limit the range of some WiMAX networks.

Simulation model

The model used in the simulations is illustrated in Figure 4. It includes a transmitter chain, a 2×2 MIMO channel and a receiver chain.

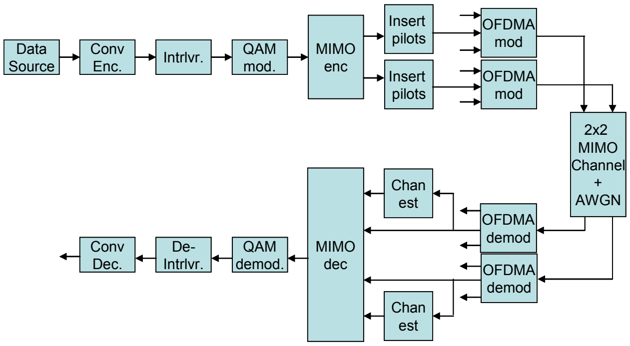

Figure 4 Simulation block diagram

Transmitter chain

Randomization, which is part of the standard, is not included in the simulation model as it will not have any impact on the BER performance. The convolutional encoder uses a rate 1/2 convolutional code. The code rates 2/3 and 3/4 are obtained by puncturing the basis code.

Two interleavers are defined in the specifications. In the simulations, the mandatory interleaver is implemented. It first assures that adjacent coded bits are mapped into non-adjacent subcarriers. It then assures that adjacent bits are mapped into less or more significant bits of the constellation. It is important to note that no interleaving is performed in the time domain, i.e. between OFDMA symbols. So in conditions with flat slow-varying fading, the results will most likely be bursts of errors that the decoder is not capable to recover from.

The interleaved bit stream is modulated into QPSK, 16QAM or 64 QAM symbols using Gray mapping. Then either STC or SM is used to provide signals to the two transmit chains of the 2×2 MIMO scheme. Pilot symbols are then inserted in the symbol stream as illustrated in Figure 3.

In the simulations, only one DL-PUSC cluster is used to transmit data. In frequency flat fading this will not have any impact on the results. In the case of frequency selective fading however, some improved performance must be expected when several clusters are used due to the effect of frequency diversity.

The smallest FFT size allowed in the specifications is used, i.e. 128. As only one cluster is used in the results included in this paper, there is no sense in implementing a larger FFT. In the case of several clusters, increased FFT size could provide enhanced performance as a larger FFT size implies larger bandwidth and hence better frequency selectivity.

Channel models

The airport environment is illustrated in Figure 1 and include communications between fixed installations, ground based vehicles and aircraft. In this publication only communication with aircraft is considered. Three different modes of the communication channel are considered: departing/approaching mode, taxing mode and terminal mode.

When an airplane is departing or approaching the airport, it is assumed that the propagation channel can be modeled as a line-of-sight (LOS) channel. The maximum speed of approaching or departing airplanes is set to 150 m/s. At 5.1 GHz this corresponds to a maximum Doppler shift of:

$$f_d = \frac{v}{c} f_c = 2530 \text{ Hz}$$

According to Ref. [6], this Doppler shift together with a symbol time T_s equal to 0.1 ms will give rise to Inter Channel Interference (ICI) of about -10 dB. Hence, ICI may in this case lead to significant performance loss.

In taxing mode, the channel is modeled as a specular non-line-of-sight channel (S-NLOS) channel, which means that there is line of sight between transmitter and receiver resulting in a noticeable and often dominant specular component in addition to significant amount of multipath fading. On the ground, the speed of airplanes is limited to 15 m/s, which corresponds to a maximum Doppler shift of:

$$f_d = \frac{v}{c} f_c = 253 \text{ Hz}$$

This Doppler shift will give rise to an ICI of about -30 dB, which may cause minor performance loss.

In terminal mode, the channel is assumed to be a NLOS channel. Hence, there is no line of sight between transmitter and receiver. In this case the maximum speed of the airplanes is set to 5.5 m/s, which corresponds to a maximum Doppler shift of:

$$f_d = \frac{v}{c} f_c = 93 \text{ Hz}$$

Such a Doppler shift will give rise to negligible ICI. The Doppler spread will however give rise to a significant coherence time that can be calculated using the following equation:

$$T_c = \sqrt{\frac{9}{16\pi f_d^2}} \approx 4.5 \text{ ms}$$

The OFDMA symbol rate is in the vicinity of 0.1 ms including the cyclic prefix, and each second OFDMA symbol contains pilot symbols. This should be sufficiently often for the impact of channel estimation error to be relatively low.

This work will focus on the taxing and parking scenarios under the assumption that the channel is NLOS. The NLOS channel is by far the most demanding environment, and also the one that is most likely to benefit from the added diversity offered by MIMO configurations.

As this publication is restricted to DL-PUSC only, the full high-resolution channel models described in Ref [7] can be replaced by a flat fading model. The reasoning is as follows; One DL-PUSC symbol has a total bandwidth of

$$BW = 14 \cdot 10600 \text{ Hz} = 148.4 \text{ kHz}$$

and will thus experience flat fading for coherence times significantly less than 6.7 μs. On the other hand, the model described in [7] is based on a bandwidth of 50 MHz and has a length of 50 taps, corresponding to a delay spread of 1 μs – well below 6.7 μs.

The entire OFDMA channel bandwidth may as mentioned above range from 1.25 MHz to 20 MHz. For these bandwidths a channel with delay spread of 1 μs will be frequency selective. The frequency selectivity will be particularly important for the wider channel bandwidth options as 10 MHz and 20 MHz. Not including the entire OFDMA bandwidth in the signal will fail to take advantage of the frequency diversity gained from randomizing the location of the sub-channels between OFDMA symbols. However, the goal of this study is not to estimate the full throughput of the channel, but rather to investigate the use of spatial diversity through space-time coding and spatial multiplexing.

Based on the findings in [7], both the well-known Rayleigh fading channel and the Weibull fading channel are investigated. The latter channel model is a two-parameter model considered to be "worse-than-Rayleigh" for shape parameters b less than two. For b=2 the Weibull channel is exactly identical to the Rayleigh fading channel. The following two shape parameters are considered:

$$b \in \{1.6, 1.8\},$$

Both these parameters describe channels with more severe fading than Rayleigh; lower numbers corresponding to worsening channel. The shape parameters have been chosen to represent the typical and extreme values found in [7].

Receiver chain

In the receiver, the signal goes through an OFDMA demodulator, and the relevant cluster of sub-carriers is extracted from the OFDMA symbols.

The channel estimators use the pilot symbols embedded on the received signal. There is a substantial literature on how to do pilot based channel estimation of OFDM signals. The channel estimation algorithms employed in this publication first interpolate along the time dimension (between OFDMA symbols), and then in the frequency domain (between sub-carriers). The interpolation filters used are Finite Impulse Response (FIR) low-pass filters of variable length.

The received data symbols and the channel estimates are fed to the MIMO decoder, which is either space time coding or spatial multiplexing. In both cases MRC is used to obtain a receive diversity gain of 2. Hard QAM detection is then performed before deinterleaving and convolutional decoding.

Simulation results

In this publication simulation results for SISO, 2×1 STC, 2×2 STC and 2×2 SM are included. The figures illustrate the effect of the seven coding and modulation ratios, the effect of implementing MIMO techniques, and finally, the difference between the standard Rayleigh channel model and the Weibull channel model.

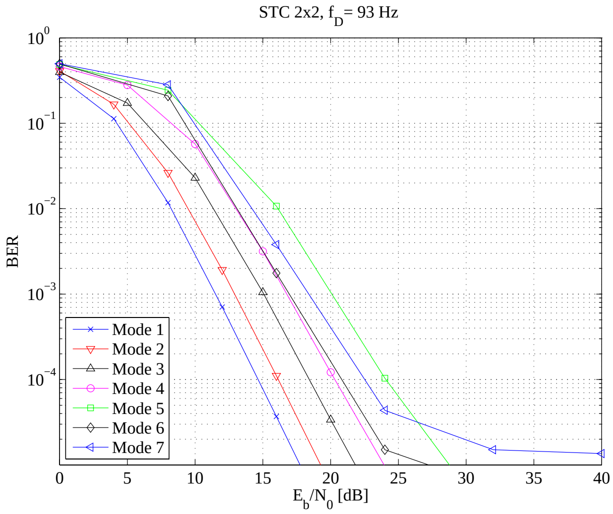

Figure 5 Simulated performance for 2×2STC, f_d= 93 Hz.

In Figure 5 and Figure 6, the performance of the seven coding and modulation modes is illustrated for 2×2 STC and for Doppler spreads 93 Hz and 253 Hz, respectively. The lower Doppler spread corresponds to the terminal channel mode. The higher Doppler spread corresponds to the taxing channel mode, but using the NLOS model instead of the S-NLOS model. This may therefore be considered as a worst case for the taxing channel when there is no line-of-sight between the BS and the MS. In the low E_b / N_0 region, the lowest mode corresponding to the lowest spectral efficiency generally obtains the best performance as expected. Mode 5 does however perform slightly worse than modes 6 and 7 for some reason. In the high E_b / N_0 region where the BER performance is limited by channel estimation errors, it becomes apparent how the higher modes are more sensitive to estimation errors than the lower modes. As expected the effect of channel estimation errors is more apparent for the higher Doppler spread case, resulting in severe error floors in particular for the higher modes. It is important to note, however, that in the high velocity case, the channel will in most cases contain a line-of-sight component, which will reduce the fading. The result will be smaller channel estimation errors and performance closer to that of a Gaussian channel. On the other hand, the effect of using MIMO techniques will be reduced.

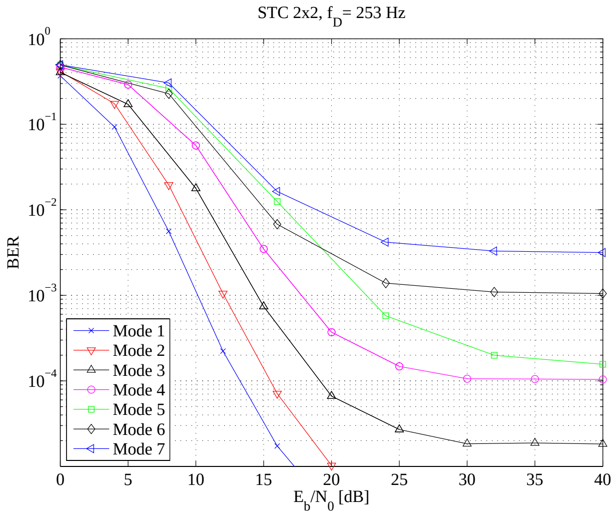

Figure 6 Simulated performance for 2×2STC, f_d= 253 Hz.

In Figure 7 and Figure 8 the performance of the different MIMO techniques are compared for mode 1 and mode 7, respectively. The curves illustrate the gain obtained by increased diversity. The SISO case have no diversity gain and performs worst, 2×1 STC provides a diversity gain of factor 2, while 2×2 STC provides a diversity gain of 4 and has the best performance. SM also provides a diversity gain of factor 2 in addition to a coding rate equal to 2. In particular for mode 7 SM performs poorly, illustrating its sensitivity for channel estimation errors.

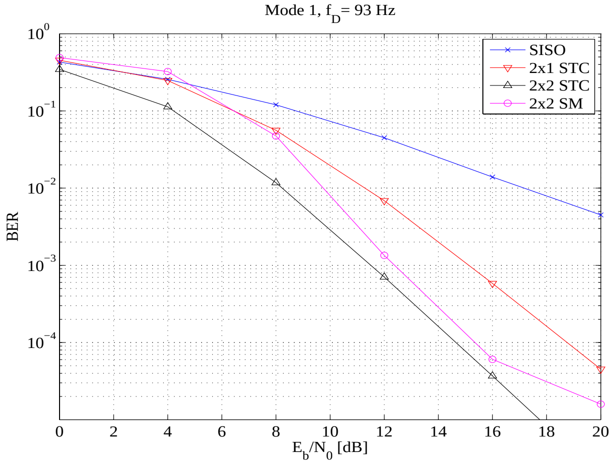

Figure 7 Simulated performance for mode 1.

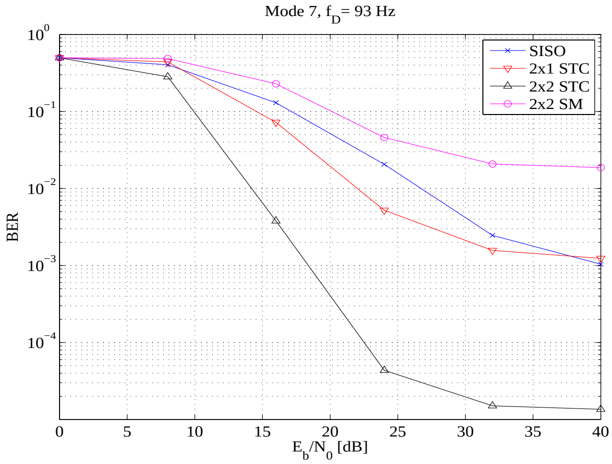

Figure 8 Simulated performance for mode 7.

In Figure 9, 2×2 STC and 2×2 SM are compared for modes providing similar number of information bits per symbol. The number of information bits per symbol for both 2×2 STC mode 3 and 2×2 SM mode 1 is 2, while 2×2 STC mode 6 and 2×2 SM mode 3 both have 4 information bits per symbol. The curves show that for the same number of information bits per symbol, SM performs slightly better than STC in the low E_b / N_0 region. SM is however more sensitive to channel estimation errors.

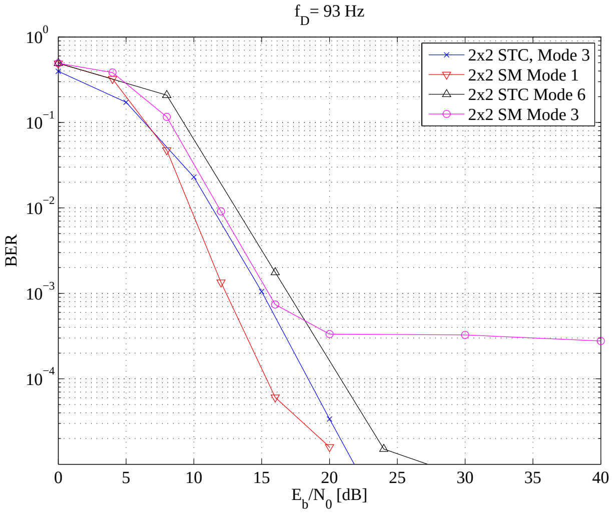

Figure 9 Comparison between STC and SM.

Only one DL-PUSC cluster within the OFDMA symbol is simulated, which means that only flat fading is captured by the simulator. A more realistic situation would be to simulate more clusters distributed over the OFDMA symbol. For typical channel lengths in airport environment, the signals would then experience frequency diversity. Together with forward error correction, this frequency diversity would lead to some diversity gain and hence improved performance in the lower E_b / N_0 regions compared to the results presented in this publication. In the high E_b / N_0 region where channel estimation errors are dominating the additive noise, the results would be similar.

Simulations results of communications over Weibull channels are in this publication limited to the 2×1 STC case, and to a maximum Doppler spread of 93 Hz. The Weibull channel is parameterized by the shape parameter *b*, and the selected values of *b* are 1.8 and 1.6. Lower values for *b* corresponds to increasingly worse channel conditions than a Rayleigh fading channel (a Weibull channel with *b* = 2.0 is identical to a Rayleigh channel). The choice of two values 1.8 and 1.6 are motivated by [7] where channel taps typically hovered around 1.8, with extremes at 1.6.

The curves in Figure 10 illustrate that the performance degrades when the channel conditions go from Rayleigh fading to increasingly severe Weibull fading. This is in accordance to theory, where the channel capacity decreases with *b*.

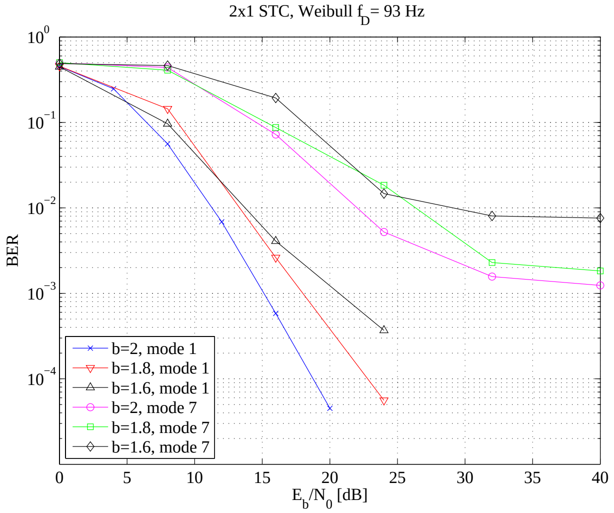

Figure 10 Simulated results with Weibull channel.

Conclusions

In this publication simulation results for different MIMO techniques included in the IEEE802.16e standard have been compared for typical channels models for airport environments. The results illustrate the gain that can be achieved in required E_b / N_0 at the receiver to obtain the required bit error rate for various services. This gain can be exploited to increase the size of a WiMAX cell or to increase the throughput within a call by choosing higher coding and modulation schemes for any given communication. The MIMO techniques are however best suited for the terminal channel mode, where the velocity of the aircraft is low and where there is generally no line-of-sight between the transmitter and the receiver.

Measurement campaigns reported in the literature indicate that the "worse than Rayleigh" Weibull channel may be a better model for the airport environment. As expected, the bit error rate for a given E_b / N_0 is worse for the Weibull channels than for the Rayleigh channel. A consequence is that the thresholds between the different rates of the adaptive coding and modulation should be adjusted compared to those given for communications over a Rayleigh channel to avoid too high bit error rates.

This publication contains simulations of DL-PUSC communication only including one cluster of 14 adjacent sub-carriers. In further studies, simulations including sub-carriers distributed over the complete OFDMA symbol will be included in order to capture the frequency diversity gain. Effects of the choices of FFT size, sub-carrier allocation schemes (PUSC, FUSC, TUSC, AMC) should be further assessed in order to select the optimal set of parameters for future Mobile WiMAX communication systems for aeronautical at airports.

Acknowledgements

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