Effects of Channel Estimation Errors in OFDM-MIMO-based Underwater Communications

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Abstract

State-of-the-art radio communication systems are in a large extent based on multi-carrier communication (OFDM) and multiple antennas (MIMO). In this paper the performance of such systems adapted to an underwater acoustic communication channel is assessed. The effect of the channel characteristics on an OFDM-MIMO scheme similar to that used in WiMAX (IEEE802.16e) is analyzed, in particular related to channel estimation error. Simulation results illustrate the relation between estimation error and BER performance for single antenna systems (SISO) and when a MIMO technique is applied.

1. Introduction

Traditionally, underwater acoustic communication systems have been based on non-coherent detection techniques such as Frequency Shift Keying (FSK) characterized by high reliability rather than bandwidth efficiency. However, during the last years a number of scientific publications have assessed coherent solutions for underwater communications, and measurements and trials have been conducted. In particular solutions based on Orthogonal Frequency Division Multiplexing (OFDM) have generated significant interest due to OFDM's good complexity-performance trade-off for frequency dispersive channels.

There are two important challenges related to underwater OFDM communications. The first one is non-uniform Doppler shift across the sub-carriers. In traditional radio communications, the center frequency is so high compared to the signal bandwidth that the Doppler shift resulting from movements of the transmitter or receiver can be considered constant for all sub-carriers. This is not the case for underwater communications, leading to loss of orthogonality between sub-carriers and hence introducing Inter Channel Interference (ICI). Algorithms for non-uniform Doppler compensation are proposed in e.g. [1]. The second challenge is the double spread fading channel, possessing both long delay spreads in the order of milliseconds of even tens of milliseconds and Doppler spreads in the order of several Hertz, making accurate channel estimation and coherent detection difficult. The main remedies for these channel impairments are powerful codes such as Low Density Parity Check (LDPC) codes and Multiple Input Multiple Output (MIMO) techniques (see e.g. [2]), allowing the receiver to yield good performance at low signal-to-noise ratios (SNRs). Most experimental results found in the literature are however obtained with relatively favorable channel conditions with delay spreads in the order of a few milliseconds and small Doppler spreads. Other strategies have been proposed for severely dispersive channels, such as passive time reversal for impulse response shortening [3]. A coherent alternative to multi-carrier communication is traditional single carrier communication, involving high complexity equalization in the receiver. To reduce the complexity, channel shortening and solutions based on sparse channel impulse response assumption have been proposed (see e.g. [4]).

In this publication the effect of channel estimation errors on the BER performance is assessed for combined OFDM and MIMO. The scope is to investigate at which delay and Doppler spreads the decoding of the signal in the receiver becomes

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erroneous, and how the parameter settings affect the performance for different channel conditions. It is assumed that there is no non-uniform Doppler shift, or that it is compensated for by means not included in this publication. A standard developed for radio communication (IEEE802.16e) is used as a starting point, and then modified to match underwater communication conditions. The system parameters are taken from real measurements conducted in the Trondheim fjord in Norway in 2007 and reported in [5]. The main focus is on the mean square error (MSE) of the channel estimator as function of the delay and Doppler spreads of the channel, and the effect this estimation error has on the BER performance of the system both using conventional antennas (Single Input Single Output - SISO) and when using MIMO.

The remaining of this publication is organized as follows. In the next section the system under consideration is described, including the relevant parts of the IEEE802.16 standard and the adaptations that are made to it. In Sec. 3, a comparison is made between the propagation conditions for radio communication in air and for acoustic communication in water. In Sec. 4, simulation results of the performance are given before conclusions are drawn in Sec. 5.

2. System description

WiMAX systems are based on the IEEE802.16 standard. This work concentrates on the IEEE802.16e amendment of the standard developed for mobile users. The physical interface is based on OFDMA, which is a multiuser multicarrier modulation techniques, in which the different sub-carriers of each symbol may be shared between several users. The bandwidth can be scaled from 1.25 MHz (corresponding to 128 sub-carriers) to 20 MHz (corresponding to 2048 sub-carriers), leading to significant flexibility in system design. The bandwidth of each sub-carrier is 10.94 kHz in all configurations leading to a constant OFDM symbol duration of 91.4 μs, not including the cyclic prefix.

Several coding and modulation schemes are contained in the standard. There are seven mandatory schemes including modulations from QPSK to 64 QAM and convolutional coding with rates 1/2, 2/3 and 3/4. The spectral efficiency can then be varied from one information bit per symbol to 4.5 information bits per symbol and hence enabling systems to adapt to varying received SNRs. In addition to the mandatory coding and modulation schemes there are several optional schemes based on iterative decoding (LDPC-codes and “turbo”-codes).

Multiple antenna techniques further enhance the performance of the technology. There are mainly two MIMO techniques included in the standard: Spatial Multiplexing (SM) and Space-Time Coding (STC). In spatial multiplexing, two transmit antennas transmit independent symbol streams, doubling the spectral efficiency with respect to conventional single antenna systems. In space-time coding, the Alamouti scheme is used to exploit transmit diversity and hence increase the BER performance at given channel conditions.

An important part of the receiver is the channel estimator, as coherent detection is required. Pilot symbols are embedded in the transmit signal in order to allow the receiver to track the channel variations due to multipath propagation. Several sub-carrier allocation schemes are included in the standard, and in this work we concentrate on DL-PUSC (Down Link Partial Usage of Sub-Carriers). The OFDM symbol is then divided into clusters of size 14x2, i.e. 14 sub-carriers and two symbols. For single antenna systems, each cluster contains 4 pilot symbols and 24 data symbols. The distribution of pilot symbols within a cluster for single antenna systems is illustrated in Figure 1. If the channel varies too fast, either across each symbol (i.e. in the frequency domain) or between symbols (i.e. in the time domain) the estimation error will be significant and jeopardize the decoding performance. In the simulator used in this work, a 2 dimensional cubic interpolator using Delaunay triangulation [6] is applied.

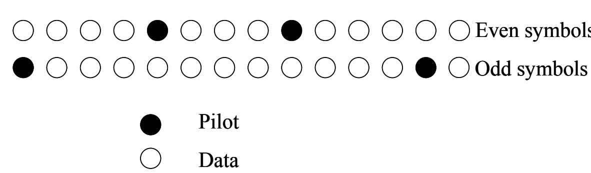

Figure 1 DL-PUSC cluster (SISO)

3. Comparison between radio and underwater acoustic propagation

WiMAX systems may operate in many different frequency bands. However, they generally operate in licensed band such as the 2.3 GHz, 2.5 GHz or 3.5 GHz bands. As described earlier, the bandwidth may range from 1.25 MHz to 20 MHz. In order to compare WiMAX with underwater communications, the signal parameters are in this publication fixed to the values given in Table 1.

Underwater communication systems may also operate at a range of frequencies and with different bandwidths. In the work presented in [5], the parameters given in Table 1 were used.

Table 1 Signal parameters

	Acoustic	Radio
Center frequency	38 kHz	2.5 GHz
Bandwidth	3 kHz	10 MHz
Propagation speed	1500 m/s	$3 \cdot 10^8$ m/s

Two important parameters determining the performance of the system is the Doppler spread f_d and the delay spread τ of the propagation channel. In order to compare the two systems the normalized versions of these parameters are convenient to use:

$$f_d^* = \frac{f_d}{\Delta f}, \tau^* = \frac{\tau}{T_s},$$

where Δf is the sub-carrier bandwidth and T_s is the OFDM symbol length. These two system parameters are the inverse of each other: $\Delta f = 1/T_s$. A common way of classifying fading channels with respect to channel estimation is as follows. If f_d^* (or similarly τ^*) is:

- Smaller than 0.01: there is no problem to estimate the channel.
- Between 0.01 and 0.1: it is challenging to estimate the channel.
- Larger than 0.1: it is impossible to estimate the channel.

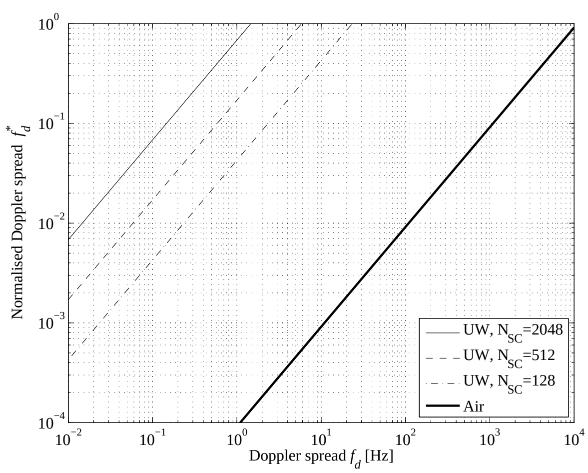

Figure 2 f_d^* for underwater communication

This classification can be used as guideline when assessing whether a system is able to communicate over a given channel.

Figure 2 illustrates how the normalized Doppler spread corresponds to actual Doppler spread for communication systems in air and underwater. In order to make channel estimation straightforward, the maximum Doppler spread for a system in air will be about 100 Hz, while decoding may be possible up to 1 kHz. This corresponds to speeds of 12 m/s and 120 m/s, respectively, for a system operating at 2.5 GHz. Hence, in areas with a Rayleigh type of fading, decoding will become impossible for speeds somewhere between 43 km/h and 430 km/h, depending on the estimation techniques and other system aspects. Mobile WiMAX systems are designed to provide connection for vehicular speeds up to 120 km/h. For underwater communication, the total bandwidth is chosen to be fixed so that the bandwidth per sub-carrier depends on the number of sub-carriers N_{SC}. Figure 2 shows that the underwater communication system is much more sensitive to Doppler spread. For $N_{SC} = 128$, channel estimation errors make decoding impossible for $f_d > 2.5$ Hz corresponding to speeds above 0.1 m/s and straightforward for $f_d < 0.25$ Hz corresponding to speeds below 0.01 m/s. As the number of sub-carriers increases (and keeping the total bandwidth fixed to 3 kHz) the OFDM symbol length increases as well, making the system even more sensitive to Doppler spreads. For $N_{SC} = 2048$, channel estimation errors will make decoding impossible for speeds as low as 0.006 m/s.

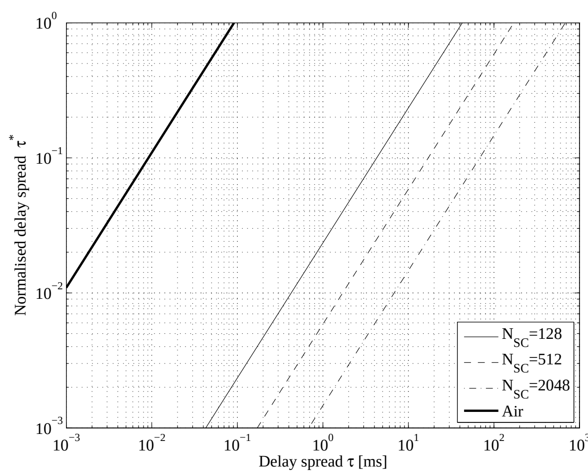

Figure 3 τ^* for underwater communication

In Figure 3 the relation between normalized delay spread and actual delay spread is illustrated. For the communication system in air, the delay spread should be less than 1 µs to avoid problems related to channel estimation. This corresponds to a difference in path length of 300 meters. Channel estimation errors make decoding troublesome for difference in path lengths in the order of 3 km. Underwater communications permit longer delay spread in time. A signal with 2048 sub-carriers may tolerate delay spreads as long as 7 ms without encountering problems with channel estimations and up to 70 ms before estimation errors make decoding very difficult. Fewer sub-carriers make each sub-carrier wider in frequency and hence the system more sensitive to channel estimation errors in the frequency domain. For $N_{SC} = 128$, channel estimation is straight forward for $\tau < 0.5$ ms, while estimation errors will make decoding very cumbersome for $\tau > 5$ ms. The delay spread actually encountered in a real system is very dependent on the environment and type of system. In [5], measurements conducted across a harbor area at different times of the year show variations between less than 1 ms to 20 ms.

Designing a system for communication across a propagation channel exhibiting both delay and Doppler spreads will involve a compromise, as a large number of sub-carriers will provide a relatively good robustness against delay spread, but make the system more sensitive to Doppler spread. For channels experiencing varying conditions, the system should consequently be adaptive in terms of the number of sub-carriers used.

4. Underwater system performance

The results in the previous section are based on a very general rule. In order to verify that a WiMAX-like system adapted to underwater communication performs according to this rule, a simulator developed for WiMAX communication in air was adapted to underwater communications. The simulator includes all mandatory coding and modulation schemes and MIMO techniques included in the standard.

The channel model used in this work is a basic Rayleigh fading channel with additive white Gaussian noise, which is commonly used in analysis of radio communication systems. Most underwater acoustic channels have somewhat different characteristics than the traditional radio channel, and the modeling should reflect these differences. Moreover, the underwater propagation environment varies greatly, as equipment may be installed in rivers, in shallow water, in deep sea etc. To validate analytical and simulation results by real measurements is therefore even more important when assessing and developing underwater communication systems than for the more mature area of radio communications.

4.1 MSE performance of the channel estimator

In Figure 4 and Figure 5, the simulated MSE of the channel estimator as function of the Doppler spread is shown for 128 and 2048 sub-carriers, respectively. The curves show good correspondence with the results from the previous section. The curves corresponding to a normalized Doppler spread of 0.01 shows little degradation compared to the case of no Doppler spread, while the curves corresponding to a normalized Doppler spread of 0.1 exhibits an error floor that starts to appear at E_b / N_0 below 10 dB, which is lower than the operating point for most of the system configurations.

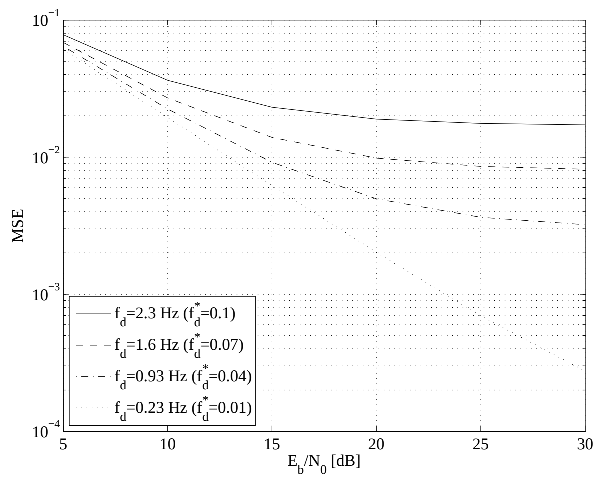

Figure 4 MSE of estimator with τ=0 ms, N_{sc}=128.

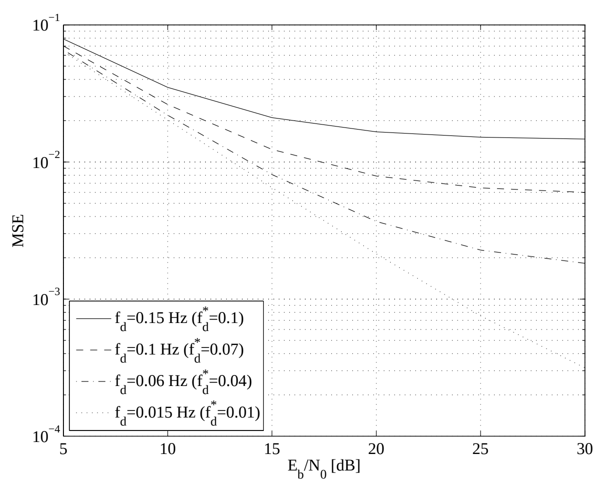

Figure 5 MSE of estimator with τ=0 ms, N_{sc}=2048.

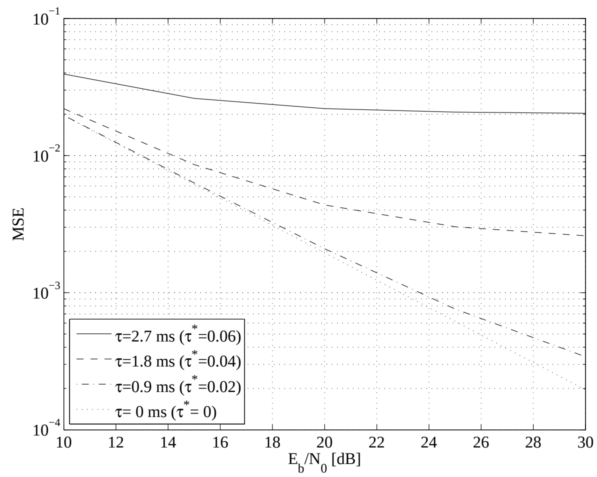

Figure 6 MSE of estimator for f_d=0 Hz, N_{sc}=128.

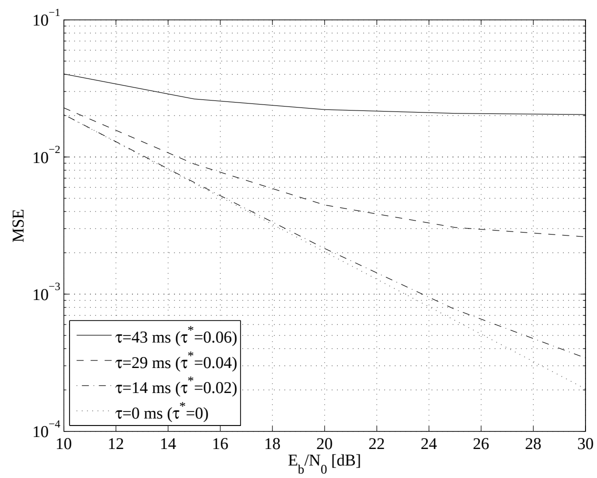

Figure 7 MSE of estimator for f_d=0 Hz, N_{sc}=2048.

In Figure 6 and Figure 7 the simulated MSE as function of delay spread is illustrated without Doppler spread and with $N_{SC} = 128$ and $N_{SC} = 2048$, respectively. The channel is created using two taps of equal energy separated by τ, which is the worst case in the sense that the channel energy is spread as far from the mean of the channel response as possible. The curves indicate that the general rule of the previous section also applies for delay spreads.

4.2 BER performance of the system

Simulated BER with 1/2-rate convolutional coding, QPSK modulation and single transmit and receive antennas is shown in Figure 8 and Figure 9. The scheme corresponds to mode 1 coding in the IEEE802.16 standard. The curves indicate that the estimation error starts to become critical for Doppler spread around 1-2 Hz (corresponding to normalized Doppler spread around 0.05 and 0.1) and delay spread around 1 ms (corresponding to normalized delay spread in the order of 0.01). To obtain BERs in the order of 10^{-5}, Doppler and delay spread should be lower than these figures.

In Figure 10 and Figure 11 the simulated BER is shown for 2x2 STC. The antenna elements both at the transmitter and receiver are assumed to be located so far from each other that the channels are uncorrelated and maximum diversity gain is obtained. The result is that the system may operate at lower SNRs than single antenna systems. As a result, the system becomes more robust against estimation errors as well.

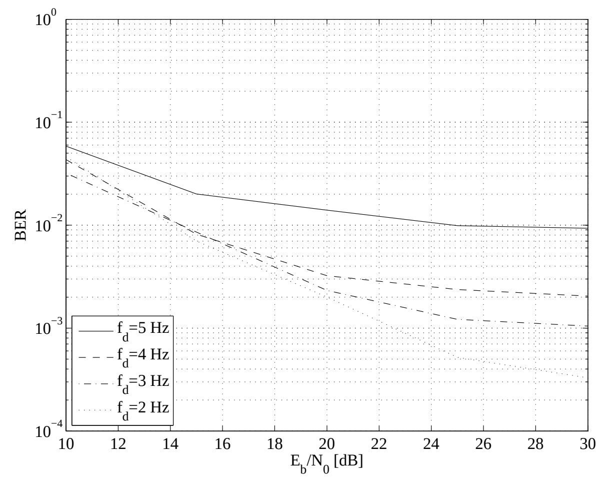

Figure 8 Simulated BER, SISO, rate-1/2 coding, QPSK, τ=0 ms, N_{sc}=128.

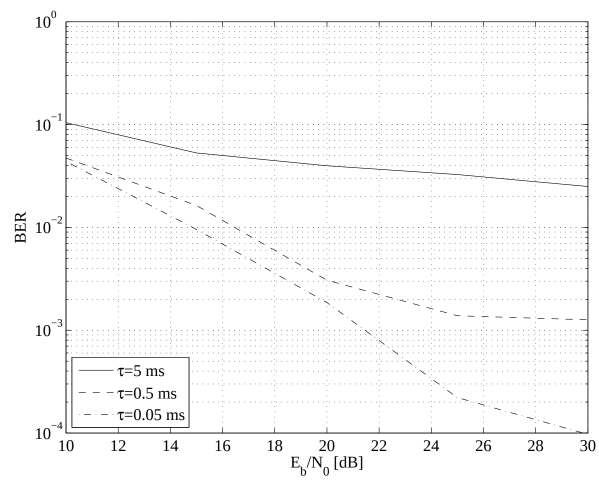

Figure 9 Simulated BER, SISO, rate-1/2 coding, QPSK, f_d=2 Hz, N_{sc}=128.

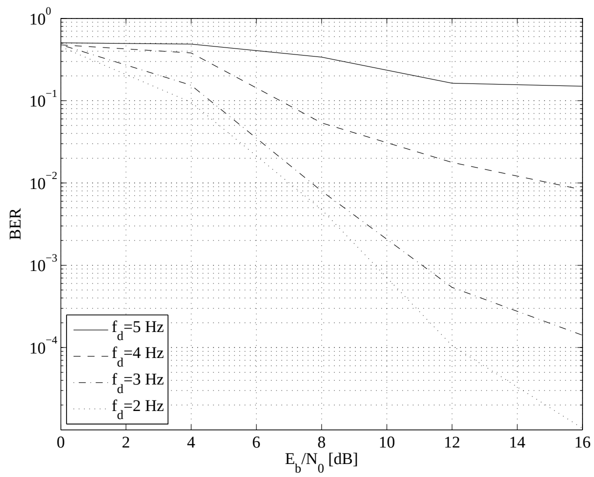

Figure 10 Simulated BER, STC, rate-1/2 coding, QPSK, τ=0 ms, N_{sc}=128.

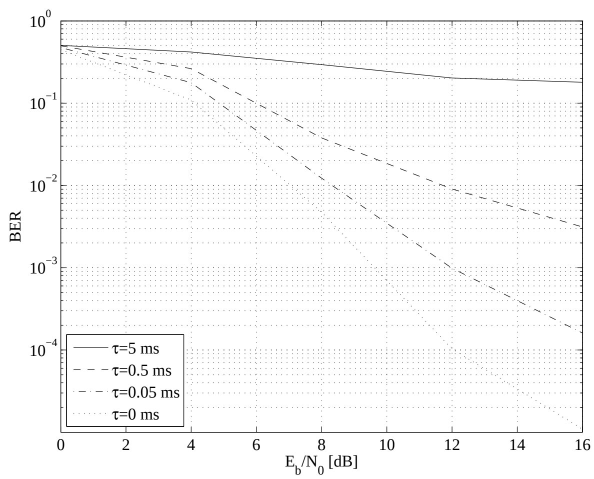

Figure 11 Simulated BER, STC, rate-1/2 coding, QPSK, fd=2 Hz, N_{sc}=128.

5. Conclusions

In this publication channel estimation in OFDM-based underwater communication is assessed together with the impact of estimation errors on system performance. The channel estimator used in this work is not optimal in the Wiener interpolator sense, which would require information about the statistical properties of the channel. The estimator used is sub-optimal, but shows good performance and has relatively low complexity. It therefore gives a good impression of the performance in real systems.

For the described system to perform well, the results indicate that movements in the water should be less than 0.01-0.1 m/s, and delay spreads should be less than 0.05-0.5 ms. In systems where the main problem is large Doppler spread, the number of sub-carriers should be small. In systems where the main problem is large delay spread, the number of sub-carriers should be large. The use of MIMO makes the system more robust against estimation errors.

The density of pilot symbols may be increased to reduce the channel estimation error somewhat, at the expense of reduced efficiency. For severe delay spread in the order of tens of milliseconds channel shortening schemes may improve the performance. The effect of channel estimation errors may be reduced by using (in addition to MIMO techniques) more powerful codes such as LDPC codes.

6. References

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