A Comparison between Alamouti Transmit Diversity and (Cyclic) Delay Diversity for a DRM+ System

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***Abstract*— DRM+ is a new system for digital broadcasting in the FM band which is going to be specified in the near future. Due to its narrowband nature, *flat fading* is a severe problem for that system. To reduce this difficulty, one may use transmit antenna diversity. We discuss two different approaches and their practical use for the system under consideration.**

I. INTRODUCTION

THE DRM (digital radio mondiale) system designed for digital broadcasting in the AM bands below 30 MHz is now going to be extended to the FM band up to 108 MHz [**?**]. This new system called DRM+ is required to be as similar as possible to the classical DRM system. In particular, it shall use use OFDM transmission together with convolutional coding. However, due to the very different frequency planning and propagation conditions between the frequency bands, new system parameters have to be designed. The bandwidth of the new system is required to be approximately 100 kHz to achieve compatibility with FM frequency planning. Such a system bandwidth is quite small compared to the coherence bandwidth which is in the order of 1 MHz e.g. for typical urban environments. Thus, the system will have to cope with severe *flat fading* conditions. Together with the relatively small Doppler spread and an interleaver delay below 1 second, the convolutional code cannot exploit very much diversity of the channel, which may lead to significant performance degradations of such a system.

One way to increase the statistical varity of the channel is the use of antenna diversity at the transmitter (TX) and/or the receiver (RX). The latter one is typically not a part of the standard and can optionally be used in any case. But for broadcasting receivers (car radios), this is often too expensive. Transmit antenna diversity is obviously a better choice for broadcasting systems.

In this paper, we compare different TX antenna diversity methods for a convolutionally coded OFDM system with 16-QAM modulation and discuss their use for DRM+. First, we consider Alamouti's [**?**] celebrated two TX antenna setup. This system is optimal in the sense that it provides the same diversity gain as a two RX antenna system with maximum ratio combining (MRC). On the other hand, is has the drawband to increase the necessary amount of pilots for channel estimation by a factor of two. Furthermore, it is quite sensitive againt *fast fading* scenarios, which may occur as well for such a broadcasting system. Secondly, as an alternative, we consider a system with delay diversity (DD) or cyclic delay diversity (CDD) [**?**]. DD simply transmits a delayed version of the same OFDM signal from another (spatially) separated antenna. The delay δ must be choosen to be less than the guard interval Δ, thereby reducing the effective duration of the guard interval to $\Delta - \delta$. This reduction can be avoided by applying a *cyclic* delay *before* appending the guard interval. (C)DD is expected to provide less diversity gain than the Alamouti scheme, but is has the benefit to add practically no modifications to the standard.

Both approaches have been investigated by mobile radio channel simulations for a possible DRM+ system parameter setup including real channel estimation by Wiener filtering.

This paper is organized as follows: In Section 2, we recall the general principles of the Alamouti TX diversity scheme and of (C)DD. In Section 3, we present possible OFDM system design parameters for DRM+ for the different TX diversity setups. In Section 4, we show performance simulations for the systems under considerations. Finally, in Section 5, we discuss the results and draw some conclusions

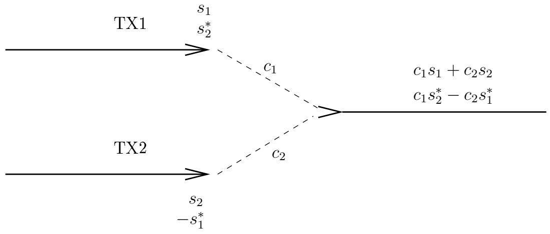

Fig. 1. Alamouti scheme.

concerning the proper choice for the DRM+ system.

II. TRANSMIT DIVERSITY TECHNIQUES

A. The Alamouti Scheme for OFDM Transmission

This scheme uses two antennas to transmit a pair of two complex symbols $\mathbf{s} = (s_1, s_2)^T$ during two time slots on the same OFDM subcarrier. These symbols will be multiplexed to the two transmit antennas TX1 and TX2 in the following way (see Figure 1). At time slot 1, the symbol s_1 is transmitted from antenna 1 (with channel coefficient c_1), and s_2 is transmitted from antenna 2 (with channel coefficient c_2). At time slot 2, the symbol s_2^* is transmitted from antenna 1 and $-s_1^*$ is transmitted from antenna 2.

Following the discussion in [**?**], [**?**], one may describe the transmission in vector notation by

$$\mathbf{r} = \mathbf{C}\mathbf{s} + \mathbf{n}, \tag{1}$$

where $\mathbf{r}$ is a vector build up from the receive symbols, $\mathbf{n} = (n_1, n_2)^T$ is the AWGN vector, and $\mathbf{C}$ is a matrix build up from the fading channel coefficients c_1 and c_2. If the channel can assumed to be constant over two acjecent time slots, $\mathbf{C}$ is proportional to a unitary matrix, and a simple optimal linear receiver can be implemented by applying the hermitian conjugate matrix $\mathbf{C}^H$.

The channel estimation scheme has to provide the receiver with estimates of two channels, each of them corresponding to one transmit antenna. Thus, the amount of pilots in a pilot grid must be twice as high compared to a single antenna scheme. For simplicity, we use a rectangular grid structure. Figure 2 shows such a pilot grid with frequency distance $K_p = 3$ and time distance $L_p = 4$. The pilots are transmitted at the frequency positions $k = 0, \pm K_p, \pm 2K_p, ...$ A time slot corresponds to the duration of one OFDM symbol. At time slot 0, only pilot symbols from TX1 are transmitted (black), while TX2 transmits zeros. At time slot 1, only pilot symbols from TX2 are transmitted (red), while TX1 transmits zeros. At time slots 2 and 3, pairs of useful QAM symbols (white) combined according to the Alamouti scheme are transmitted (the recangles in Figure 2). This scheme will repeated with the period of 4 time slots. Each (non-zero) pilot symbol is boosted by 3 dB compared to the average QAM symbol energy. Note that, because of the zero pilots, the average pilot energy is the same as the average QAM symbol energy.

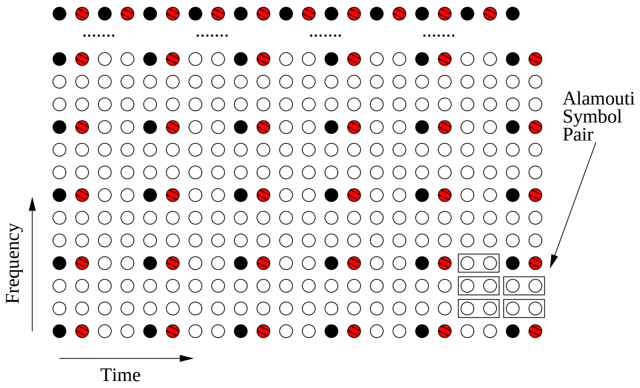

Fig. 2. Pilot grid for the Alamouti scheme.

The performance of the Alamouti scheme can be derived from the fact that the receive symbols after the combiner can be written as

$$u_i = as_i + n_i, \quad (i = 1, 2), \tag{2}$$

where

$$a = \sqrt{|c_1|^2 + |c_2|^2} \tag{3}$$

is the composed fading amplitude. Thus, the Alamouti scheme doubles the diversity degree, i.e. the exponent of the power law for the bit error rate (BER) curves for coded (or uncoded) transmission. For coded transmission, a union bound for the BER

$$P_b \leq \sum_{d=d_{free}}^{\infty} c_d P_{2d} \tag{4}$$

holds, where the error coefficients c_d depends on the code of free distance d_{free}, and the P_L are the $L-$fold diversity error probabilities [**?**]. We observe that the Alamouti scheme always improves the performance, in an ideally interleaved channel as well as for insufficient interleaving. On the other hand, the simple linear receiver for the Alamouti scheme assumes time-invariance of the channel over two consecutive time slots. As a consequence, this scheme is more sensitive against fast fading.

B. (Cyclic) Delay Diversity for OFDM

This method simply transmits the same OFDM signal with a time delay δ from another antenna.

The second antenna is assumed to be sufficiently separated, so that its fading channel can be regarded as statistically independend. The delay power spectrum of this second channel is shifted by δ. For the receiver, the resulting channel is a superposition of the channels from both antennas which has a greater delay spread than the channels from each single antenna. For scenarios with short echos, this will enhance the performance due to a better frequency interleaving. For a situation with perfect interleaving, this method will not effect the performance. Because δ reduces the size of the effective guard interval Δ to $\Delta - \delta$, it should be choosen to be sufficiently small to guarantee for the maximal physical echo duration τ_{max} the condition $\tau_{max} + \delta < \Delta$.

To avoid the reduction of the guard interval, one may apply a *cyclic delay* of the OFDM symbol *before* appending the guard interval [**?**]. That cyclic permutation of the OFDM symbol in the time domain can equivalently be implemented in the frequency domain. Let s_{kl} be the complex QAM symbol at subcarrier frequency f_k for a fixed time slot number l. Then the input symbols of the OFDM modulator (i.e. the IFFT) for the second antenna are

$$\tilde{s}_{kl} = \exp\left(-j2\pi f_k \delta\right) s_{kl}. \quad (5)$$

CDD does not reduce the effective length of the guard intervall. However, for $\tau_{max} + \delta > \Delta$, one must bear this in mind for the channel estimation. If $\tau_{max} + \delta < \Delta$ holds, then DD and CDD are exactly equivalent. In both cases, the discrete transmission channel at frequency number k and time slot l is given by

$$H_{kl} = H_{kl}^{(1)} + \mathrm{e}^{-j2\pi f_k \delta} H_{kl}^{(2)}, \quad (6)$$

where $H_{kl}^{(1)}$ and $H_{kl}^{(2)}$ are (hopefully) statistical independent realisations of the same channel.

At the receiver, (C)DD looks just like a physical channel with an additional echo. Thus, it does not require any modifications at the receiver.

Furthermore - in contrast to the Alamouti scheme - a generalisation of (C)DD to more than two antennas is easily possible.

III. TRANSMISSION PARAMETER SETUP FOR A POSSIBLE DRM+ SYSTEM

The DRM+ system is required to operate in single frequency networks (SFNs) as well as in conventional networks. For SFNs, the guard interval length Δ must be choosen large enough to absorb the long artificial echos from other transmitters on the same frequency. From the experience with SFNs with the DAB and the DVB-T system we know that $\Delta = 250\ \mu$s is a good choice. Compared to a DAB system operating at TV channel 12 (223-230 MHz), a system operating in the FM band experiences less than half the time-variance. Thus, such a system should allow twice the total OFDM symbol duration T_S, which leads to the reasonable choice of $T_S = 2.5$ ms. This decreases the relative amount of the guard interval from $\Delta/T_S = 1/5$ to $\Delta/T_S = 1/10$ and thus increases the spectral efficiency.

TABLE I

OFDM PARAMETERS OF THE PROPOSED SYSTEM.

Useful symbol length	$T = 2.25$ms
Carrier spacing	T^{-1} =444.44 Hz
Guard interval	$\Delta = 0.25$ms
Symbol duration	$T_S = T + \Delta$= 2.50 ms
Number of subcarriers	$K = 216$
Nominal Bandwidth	$B = K/T$ =96 kHz
Modulation	16-QAM
Convolutional Code	$(133, 171)_{oct}$
Interleaver	450 ms

For our simulations, we work with the modulation and coding parameters as depicted in Table I. We consider 16-QAM with Gray mapping and a convolutional code with rate $R_c = 1/2$ and memory 6.

The number of useful carriers is $K = 216$ which leads to a bandwidth in the desired order of 100 kHz. The FFT length $N_{FFT} = 288$ is the smallest choice that leads to an integer number of samples (i.e. 32) for the guard interval.

For the Alamouti setup, we use the pilot grid of Figure 2, but with $L_p = 4$ and $K_p = 4$ (in contrast to $K_p = 3$ in Figure 2). For the (C)DD setup, the red pilots of Figure 2 are replaced by useful data. The pilots are boosted by a factor 2. As indicated in Figure 2, an edge carrier of pilots has been included that may be useful for several purposes.

The useful data rate is 151.2 kbit/s for the system with the Alamouti scheme and 162 kbit/s for the (C)DD system.

For time interleaving, we use a pseudo-random bit interleaver over 450 ms. For a radio frequency of 108 MHz, the relation between the reveiver velocity v and the maximal Doppler frequency f_{Dmax} is simply given by

$$f_{Dmax}[\mathrm{Hz}] = 0.1\, v\, [\mathrm{km/h}]. \quad (7)$$

The time interleaving will work properly only for vehicle speeds $v \gg 10\,\mathrm{km/h}$.

We have used three fading environments for our simulations: 1. The GSM *Typical Urban* (TU) channel with very short echos and a delay spread $\tau_m \approx 1\,\mu\text{s}$, 2. The DAB *Hilly Terrain 1* (HT1) channel with relatively long echos and $\tau_m \approx 24\,\mu\text{s}$, and 3. The *Terrain Obstructed* (TO) channel mit moderately long echos and $\tau_m \approx 7\,\mu\text{s}$.

We note that even for the HT1 channel, the coherence bandwidth τ_m^{-1} is significantly smaller than the system bandwidth $B \approx 100\,\text{kHz}$. Thus, all channels are typically *flat and slow* and doe not provide enough diversity for the convolutional code.

IV. SIMULATION RESULTS

For our simulations, we use a 15 tap Wiener filter for channel estimation in time direction and an optimal matrix estimator in frequency direction (see [**?**] for more details). We assume that the channel estimator knows the maximal Doppler frequency f_{Dmax}, but not the SNR. All simulations have been performed with real channel estimation (CE) as well as with ideal channel estimation, but only the curves for real CE have been drawn in order not to overload the following figures. The differences between the real and ideal CE curves depend on v, and they are typically less than ≈0.5 dB for our simulation parameters.

The following figures show four simulation curves and two theoretical curves each. The first two curves (blue and green) show the simulated bit error rates (BER) for both single-antenna channels. Because both channels have the same statistics, they should be practically identical if the simulation time is long enough. The third curve (red) shows the simulated BER for the Alamouti scheme, and the fourth curve (cyan) shows the simulated (C)DD BER for a delay of $\delta = \Delta/16$ =15.625 μs corresponding to 2 samples of the guard interval. DD and CDD are equivalent for this chosen value of δ, which seems to be sufficiently large. We have tested several values up to $\delta = \Delta/2$ and could not find any further improvement. The last two curves (dash-dotted) show the theoretical curves for the system for one antenna (left) and for the Alamouti scheme (right) obtained from a bound of type (4), both for an ideally interleaved channel. The right curve represents the possible optimum (ideal CE and ideal interleaving) for one TX antenna as well as for (C)DD.

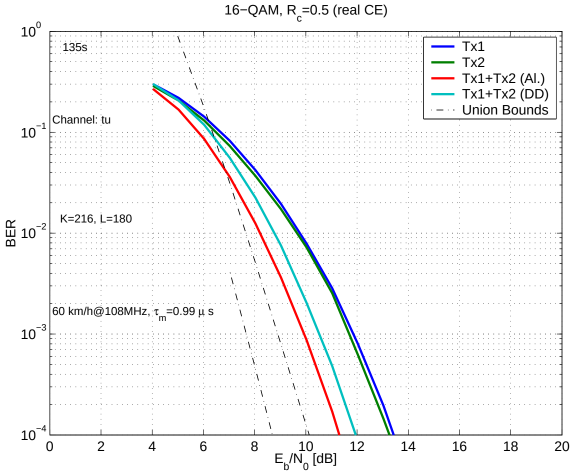

Fig. 3. Simulation of the channel *Typical Urban* at 60 km/h.

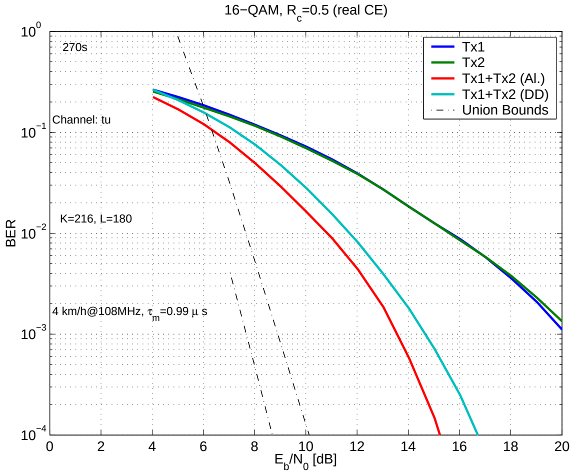

Fig. 4. Simulation of the channel *Typical Urban* at 4 km/h.

Figure 3 shows a simulation of the channel *Typical Urban* at a velocity of 60 km/h. Because the interleaving is quite poor, the single-antenna curves show a degradation of compared to the theoretical curves in the order of 3 dB at $BER = 10^{-4}$. The Alamouti scheme improves the performance by ≈2 dB, but there is still a gap of 2-3 dB to its theoretical performance curve. The (C)DD curve is only ≈ 0.6 dB poorer than the Alamouti curve.

Figure 4 shows a simulation for the same channel at a pedestian's speed. The degradations due to this very flat and extremely slow (f_{Dmax} =0.4 Hz) channel are obvious. Both diversity schemes lead to a significant improvement, but, as expected, the Alamouti scheme is better than the (C)DD scheme.

Figure 5 shows a simulation for the channel *DAB Hilly Terrain 1* at 120 km/h, which offers a better (but not yet ideal) interleaving. All curves are close together. This is surprising because the Alamouti scheme should outperform the other schemes in an ideally interleaved channel. But here the time

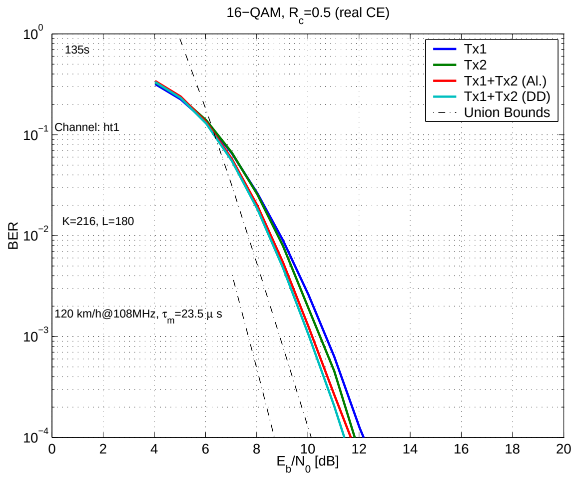

Fig. 5. Simulation of the channel *Hilly Terrain 1* at 120 km/h.

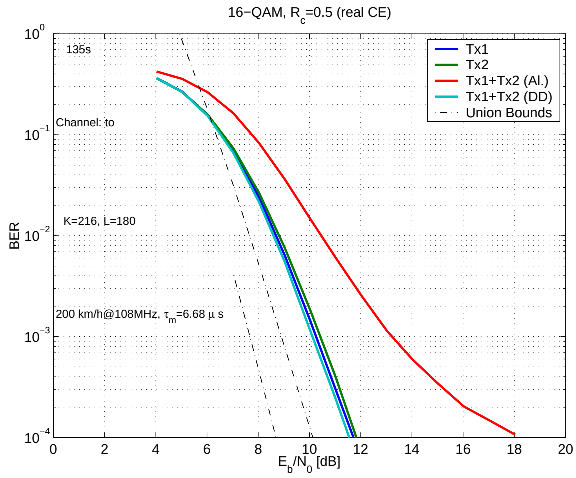

Fig. 6. Simulation of the channel *Terrain Obstructed* at 200 km/h.

variance of the channel is already so fast that it degrades the performance for the Alamouti scheme.

The problem of fast fading becomes quite obvious in Figure 6 for $v = 200$ km/h and and the channel *Terrain Obstructed*. The time variance of the channel leads to a degradation of 6 dB for the Alamouti scheme compared to the other setups.

V. DISCUSSION AND CONCLUSIONS

We have seen that the Alamouti scheme is able to improve the diversity of the transmission, thereby leading to significant performance gains. For (C)DD, the gains are slightly smaller. On the other hand, the Almouti scheme is very sensitive against fast fading. One could use a better (non-linear) LLR receiver that takes into account the time-variance of the channel (see e.g. Eq. (5) in [**?**]), but this only slightly improves the performance for the cost of more complexity, especially for higher-level QAM. Reduction of the symbol length (e.g. by a factor of two) would also help, but this would reduce the useful data rate if the guard interval is kept fixed. Further simulations have shown that for the (C)DD scheme 300 km/h or even more is possible for $T_S = 2.5$ ms. This robustness against fast fading together with the spectral efficiency seems to be a strong argument for a (C)DD setup.

For a proper DRM+ system design, one must consider all these facts to find a system that is suited for all relevant channels, thereby providing the best data capacity.

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