

Diversity Reception for Digital Audio Broadcasting

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Abstract—Antenna Diversity is a method to improve the reliability of DAB reception in mobile environment leading to less spots with undesired audio interruptions and increased coverage areas.

We performed theoretical evaluations and simulations to gain a comprehensive picture about the possible diversity gain. The diversity gain was found to depend on the correlation of the signals from the different antennas which is influenced both by the antenna separation and the power azimuth spectrum of the receive signal.

Typical power azimuth spectra in poorly covered areas in a DAB single frequency network were measured to support the theoretical assumptions.

A DAB diversity receiver was developed and used in a series of field measurements that confirmed the expected diversity gain.

Index Terms—Coverage area, Digital Audio Broadcasting, diversity, mobile reception, power azimuth spectrum

I. INTRODUCTION

Digital Audio Broadcasting (DAB) is an efficient and reliable radio broadcast system which provides very high robustness in mobile environments. Nevertheless it shows, as other digital transmission systems, undesired interruptions in spots with insufficient field strength. For economic reasons gaps in the coverage areas of existing and planned networks will not be filled in foreseeable future. Also the sizes of the coverage areas are quite limited in many countries.

Especially in vehicles on the move, an undisturbed radio reception is vitally important. Diversity reception is a technique which presents a good possibility to improve the receiving performance. Car manufacturers have been using multiple antenna systems to counteract multipath distortion for FM for several years. For DAB reception, diversity reception was not realised so far.

This paper gives a comprehensive overview about DAB diversity in theory, simulation and field tests. We performed

analytical evaluations and computer simulations to generate bit error rate curves for diversity combining and show the effect of correlation between the antennas. The correlation is influenced by two factors. First, the antenna separation which is normally less than a wavelength because of the limited dimensions of a car and second, the power azimuth spectrum (PAS) has to be considered. The measurement procedure of the PAS was already presented in [1].

To perform field tests we build up a DAB diversity receiver consisting of two RF-tuners and a baseband processing unit realised on a general purpose DSP. This implementation allows to decode the signal from the first, and the second antenna and the diversity signal in parallel. Therefore a comparison of single path reception and diversity reception is easily possible. Using a special test signal emitted from the Hanover DAB transmitter we are able to determine bit error rates before and after channel decoding. The results were analysed in detail.

II. THEORETICAL BACKGROUND

A. Diversity for DQPSK

In the DAB system, DQPSK modulation has been implemented [1]. Thus, the information is transmitted by the phase difference between two subsequent complex transmit symbols. At the demodulator, this phase information can be recovered by multiplying each complex receive symbol r_i by its complex conjugate precursor symbol r_{i-1}^* . The resulting symbol $r_i r_{i-1}^*$ consists of the original QPSK symbol, weighted by the *squared* fading channel amplitude, plus additive noise terms. This squared channel amplitude serves as a reliability factor for the subsequent Viterbi decoder. The quadratic diversity combining (QDC) receiver as depicted in Figure 1 simply adds these demodulated symbols from both diversity branches before feeding them into the Viterbi decoder:

$$v_i = r_{1,i} r_{1,i-1}^* + r_{2,i} r_{2,i-1}^*$$

Obviously, the contribution of each branch implicitly contains the squared fading amplitude as a weighting factor. The diversity branch with lower receive power is less reliable and contributes less to the decoder input.

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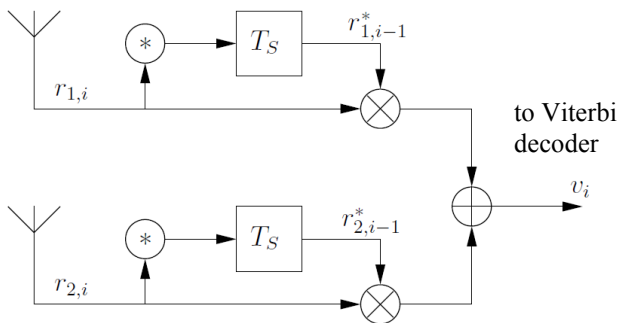


Figure 1 DQPSK demodulation in diversity receiver

The DQPSK demodulation and QDC has to be done separately for each OFDM subcarrier. Thus, the diversity receiver needs two individual RF front ends, A/D converters, and OFDM signal processors. The two processing branches merge only at the Viterbi decoder.

B. BER bounds

For a DQPSK system with convolutional channel coding and perfect time-frequency interleaving, the bit error rate (BER) can be approximated by the tight upper bounds (union bounds)

$$BER \leq \sum_{d=d_{free}}^{\infty} c_d P_d .$$

In that equation, d_{free} is the free distance of the code, and the index d runs over the Hamming distances of all possible error events of the code. The error coefficients c_d count the multiplicity of these events, and they depend only on the code. The error event probabilities P_d are functions of the signal-to-noise ratio (SNR). They depend on the transmission channel type, but not on the code. For more details and analytical formulas for P_d for an ideally interleaved Rayleigh fading channel, we refer to [3]. Tables of c_d values for the code used for DAB can be found in [4].

For 2-fold diversity with ideal spatially uncorrelated antennas, each (soft) bit from the channel is received twice. This doubles the Hamming distance of each error event of the code. As a consequence, the error event corresponding to the coefficient c_d has probability P_{2d} . Thus, the BER is now tightly upper bounded by

$$BER \leq \sum_{d=d_{free}}^{\infty} c_d P_{2d} .$$

Figure 2 shows these bounds for a slowly fading Rayleigh channel with ideal interleaving and ideal antenna separation.

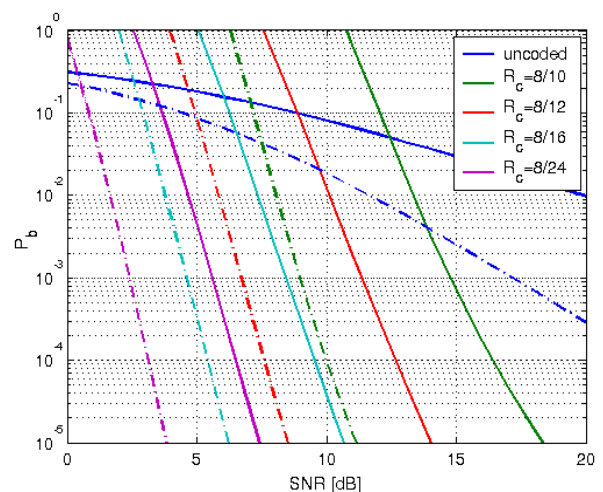


Figure 2: Union bounds for coded DQPSK with 2-fold diversity for a slowly fading Rayleigh channel with ideal interleaving and uncorrelated antennas, see text.

For the codes rates $R_c = 8/10, 8/12, 8/16, 8/24$ taken from the code family implemented in the DAB system [2], the solid curves show the BER union bounds for a slow Rayleigh fading channel and one antenna. The dash-dotted (-.-) curves of the same colours show the corresponding BER curves for two-antenna diversity. It should be pointed out that the SNR gain is higher for weak codes. For strong codes like $R_c = 8/24$, the gain is only a little bit higher than the 3 dB gain due to the doubled antenna area of the diversity system.

C. BER in simulation

To perform BER simulations for a time-variant and frequency selective Rayleigh fading channel with antenna diversity, the Monte-Carlo simulation model [3] has to be extended to include the spatial component. It is worth mentioning that the space and time variance are closely entangled because the latter is due to the motion of the vehicle through a spatial fading pattern. An appropriate simulation method that includes all these aspects has been described in [6]. For the following simulations, a DAB system with transmission Mode I as used in VHF bands has been assumed [2], [3].

Figure 3 shows the simulation results for the rather frequency selective channel *DAB hilly terrain II*, described in detail in the Appendix, and moderate time-variance characterized a Doppler frequency of 8 Hz which corresponds to a car speed of approximately 40 km/h for a carrier frequency of 225 MHz. The simulated curves (solid lines) are tightly upper bounded by the theoretical curves (dashed lines) from the union bounds. This is due to the fact that the frequency selectivity is high enough to provide sufficient interleaving. For the diversity system, the ideal case of zero-correlation between the spatial fading amplitudes at the antenna positions has been assumed in the simulations.

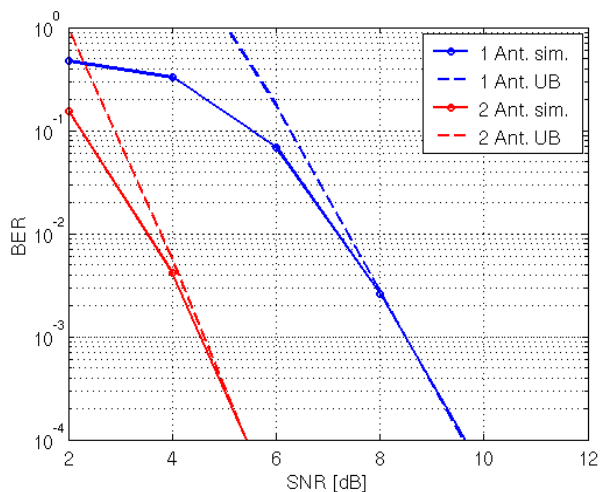


Figure 3: Simulations (sim.) and union bounds (UB) for coded DQPSK with one antenna (1 Ant.) and 2-fold diversity (2 Ant.) for a moderately time-variant Rayleigh fading channel with sufficient interleaving and uncorrelated antennas.

The situation becomes worse if the interleaving is not sufficient. This may happen for *frequency-flat* channels like the *rural area* profile [5]. Figure 4 shows a simulation for this channel with all other parameters left the same as in Figure 3. The simulated curves now show a significantly poorer performance compared to the union bounds for the ideal interleaving case. It is worth to mention that the two-antenna system proves to be more robust in that scenario: Even the *relative* degradations are much smaller compared to the one-antenna system.

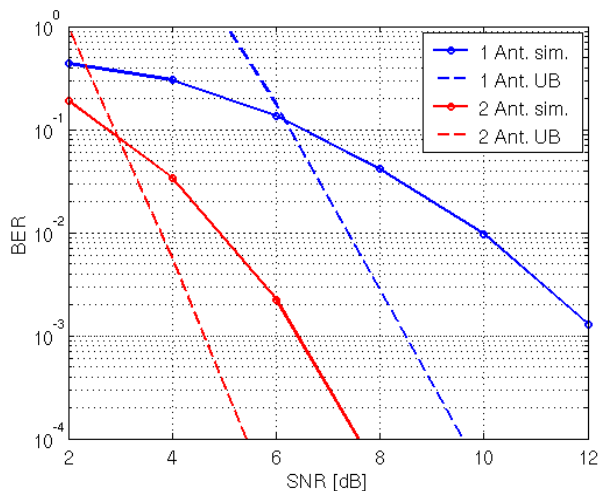


Figure 4: Simulations (sim.) and union bounds (UB) for coded DQPSK with one antenna (1 Ant.) and 2-fold diversity (2 Ant.) for a moderately time-variant Rayleigh fading channel with poor (frequency) interleaving and uncorrelated antennas.

D. Correlated signals

The inherent spatial diversity of the channel can only be fully exploited by the two-antenna system if the correlation between the spatial fading amplitudes at the two antenna positions is not too high.

These correlations are given by the values of the spatial autocorrelation function (ACF) $R(\Delta\mathbf{x})$ of the channel, where $\Delta\mathbf{x}$ is the distance (vector) between the antenna positions. When mounted on a car, the distance Δx between the antennas is typically less than one wavelength λ in the VHF bands. The function $R(\Delta\mathbf{x})$ depends on the power azimuth spectrum (PAS) $S(\alpha)$ of the channel, which is the power density of the impinging signal as a function the angle of incidence α [6]. The isotropic scattering model $S(\alpha)=1/2\pi$ which assumes that the power is uniformly distributed over all directions is very convenient for theoretical investigations but it is obviously an oversimplified model of the real world see section II.E. and Ref. [1]

For a given antenna separation, the shape of the PAS has a strong impact on the BER performance of a system with antenna diversity. Generally speaking, for a more anisotropic PAS, the decay of the spatial ACF of the channel becomes slower and hence the BER performance becomes worse.

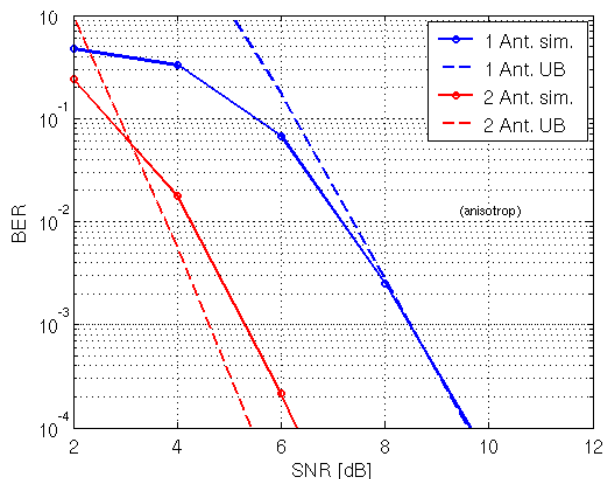


Figure 5: Simulations (sim.) and union bounds (UB) for coded DQPSK with one antenna (1 Ant.) and 2-fold diversity (2 Ant.) for a moderately time-variant Rayleigh fading channel with sufficient interleaving and correlated antennas at distance $\Delta x = \lambda / 2$.

Figure 5 shows simulations for an anisotropic PAS with a uniform distribution between 0° and 180° , i.e. the signal comes from only *one side* relative to the direction of motion. The antennas are mounted on the left and the right side of the car with separation $\Delta x = \lambda / 2$. All other parameters are the same as in Figure 3.

The performance loss due to the correlations is 1 dB. Thus, only 3 dB SNR gain is obtained by the second antenna. This is just the gain due to the doubled total antenna size.

E. Power azimuth spectrum

To estimate the antenna correlation $R(\Delta\mathbf{x})$ or to perform BER simulations with the simulation model described in [6], it is indispensable to have some model for the PAS $S(\alpha)$. The PAS and the delay power spectrum together determine the statistics of the simulation model, and the correlation $R(\Delta\mathbf{x})$ determined by $S(\alpha)$ through an integral expression [6].

The question is thus: What types of PAS occur in reality for a typical DAB single frequency network with long distances between transmitter and receiver.

For this reason, channel measurements have been performed in the VHF DAB single frequency network (SFN) in Bavaria, Germany (Channel 12D, 229.072 MHz). The measurement setup, details on the locations where the measurements were taken and data processing can be found in [1].

The PAS was recorded in areas at far distances from transmitter stations where the network provider indicated that DAB reception was expected to be poor. Although the measurements did not provide high angular resolution, the results at all spots where measurements were taken show that the PAS is highly anisotropic. As typical examples, result of measurements at Sommerodelbahn and Teufelshöhle near Pottenstein (located in a deep narrow valley at 49.762°N, 11.413°E and 49.754°N, 11.421°E respectively) are shown in Fig. 6. It can clearly be seen that the signal power received from different directions differs by almost 10 dB. Although both locations are only about 1 km away from each other, the details of the PAS differ significantly. An explanation for this is probably that signals from different transmitters are scattered or diffracted into the valley depending on the details of the topography in the immediate vicinity of the receiving site.

It turned out that for many of the measured scenarios a superposition of von-Mises probability distributions

$$P(\alpha) = \frac{e^{\kappa \cos(\alpha - \mu)}}{2\pi I_0(\kappa)}$$

(I_0 : modified Bessel function of order 0) with suitable parameters μ and κ provides a good model for analytical calculations and computer simulations. Fig. 7 shows an example for the approximation of the measured PAS at a site near Happurg (located again in a valley at 49.482°N, 11.477°E) with a superposition of three von-Mises distributions.

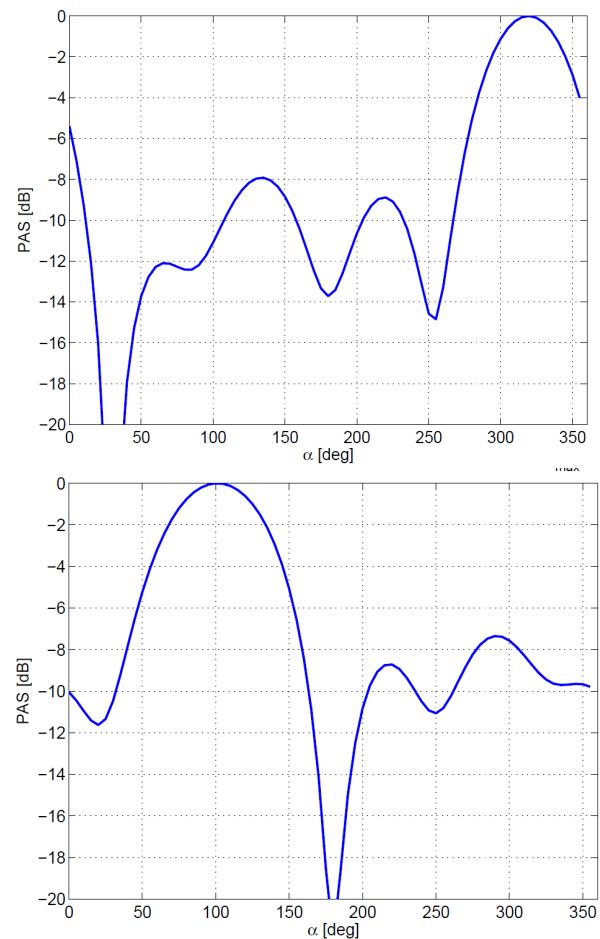


Figure 6: Results of PAS measurements in the Bavarian DAB SFN (Ch. 12D) at Sommerodelbahn (above) and Teufelshöhle near Pottenstein

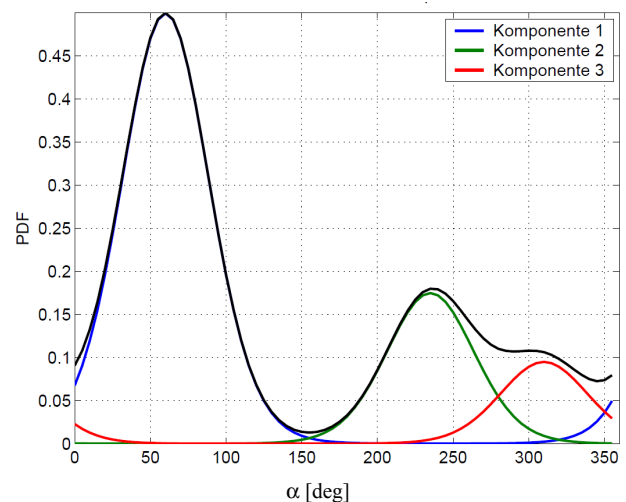


Figure 7: Results of PAS measurement in the Bavarian DAB SFN (Ch. 12D) near Happurg (black) and approximation using three von-Mises-Distributions (blue, green and red). Note that the axis is linear, different from Fig. 6

III. EXPERIMENTAL SETUP

The aim for our experimental platform was the determination of the diversity gain in a mobile environment. For this purpose we developed a diversity receiver comprising 2 RF-tuners with digital data interface and a general purpose DSP for signal processing. The RF-tuners cover Band III and

L-band whereas the emphasis of our tests was in the more used Band III, i.e. in the frequency range of 174-240 MHz. The DSP includes the complete DAB receiving chain consisting of synchronization, demodulation, diversity combining, de-interleaving, channel decoding and audio decoding. Of particular importance is the ability of the receiver to decode simultaneously the signals of the two single antennas and the diversity combined signal which allows a perfect comparison of these three signals and therefore the evaluation of the diversity gain. As evaluation metrics the BER and the CRC failure rate of the audio signal were used. The BER can be determined before and after channel decoding. For this purpose, a first metric is calculated by means of re-encoding and comparison with the received signal and a second metric is calculated from known sequences in the special transmission signal used for these tests. The performance of the receiver implementation was verified in the laboratory with two signal generators, both using fading options. The BER curves for the *typical urban* channel (TU) and *rural area* channel (RA) [5] fit very well with our simulation results indicating a good receiver implementation.

The diversity receiver was operated in a vehicle equipped with a commercial GPS receiver. The geographical coordinates were recorded together with the above explained receiver metrics. On the roof of the vehicle two passive antennas with magnetic mounts were installed. The positions of the antennas and the distance between them were modified for the different test runs. In addition, active screen antennas mounted at the opposing side windows were taken for evaluations.

IV. FIELD TEST RESULTS

A. Measurement location

Two DAB transmitters are located in the region where we conducted the field measurement campaign. The transmitters Hanover Telemax and Sibbesse are situated at $52^{\circ} 23.6' N$, $9^{\circ} 48' E$ and $52^{\circ} 04' N$, $9^{\circ} 58' E$, respectively. These locations are approximately 31 km north and 7 km southeast from the starting point of the measuring drive. Although the distances between the transmitters and the receiver are quite different, both transmit signals can be received in the measurement region approximately with the same field strength. This can be explained by the topographic situation since a flat plain expands to the north whereas the southeast is rather hilly.






In the first phase of the evaluation phase the transmitters were operated as SFN (Single Frequency Network) at frequency 223.936 MHz, in the second phase only the transmitter at Hanover was on air.

B. Measurement analysis

To visualize the BER and the audio quality in a geographical map a classification was generated according to Table 1. The relation between the audio quality and the BER was evaluated in the laboratory with fading signals on the basis of the TU and RA channel. The test runs confirmed that this relation is

valid most of the time. Especially for very low speeds the variation in the relation increases because of the decreased efficiency of the time interleaving in the DAB system.

Table 1: Audio signal quality

Audio quality	Colour	BER
good		$BER < 2 \cdot 10^{-2}$
		$2 \cdot 10^{-2} < BER < 4 \cdot 10^{-2}$
disturbed		$4 \cdot 10^{-2} < BER < 6 \cdot 10^{-2}$
		$6 \cdot 10^{-2} < BER < 8 \cdot 10^{-2}$
mute		$BER > 8 \cdot 10^{-2}$

C. Measurement results

For the field test several hundred kilometres were driven in the region of Hildesheim and Hanover to gain experience and statistics regarding the results. From the mass of data one typical test route in the SFN area was chosen for the presentation of the results. It is around 16 km long and comprises rural and urban environments. The antennas mounted in the centre of the roof were separated by 20 cm perpendicular to the driving direction.

The BER is visualized in Figures 8 to 10 for the first antenna, second antenna and the diversity result, respectively.

It can be seen that the BER of the two single antennas is mostly the same. Small discrepancies can be explained by a slight difference in tuner noise figures and antenna patterns due to the different mounting positions on the car roof. The audio signal was good for half of the route for the single antenna whereas the audio signal of the diversity system was good for nearly the whole route.

In addition the BER along the complete route is presented in Figure 11 as a function of time. This does not match exactly with the BER over the driven distance because of the variable speed of the car. The four coloured horizontal lines correspond to the BER intervals of Table 1. It can be seen that the BER of the diversity signal is always less than the BERs of the single antenna signals which is consistent with the theory. The most relevant BER range is that above 0.02 (horizontal green line) since for lower values the channel decoder is able to eliminate nearly all errors. Looking into detail, one can see that between 200 and 300 seconds the recorded BER is much lower for the diversity signal as for both of the single antenna systems. Between 300 and 400 seconds the difference in BER, i.e. also the diversity gain, is less. This effect can be explained assuming that different levels of PAS anisotropy occur along the route as shown in section II.E for the different locations.

From the data shown in Figure 11 the histogram was calculated and printed in Figure 12. Whereas the single antenna systems are in audio mute status for around 13 % of the time, the diversity system provides uninterrupted audio playback. Also the time when audio playback is disturbed is considerably reduced with the diversity system.

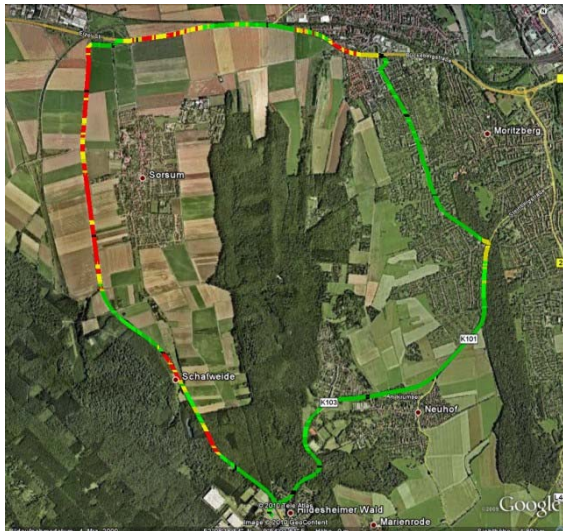


Figure 8. BER (audio quality) of antenna 1 signal

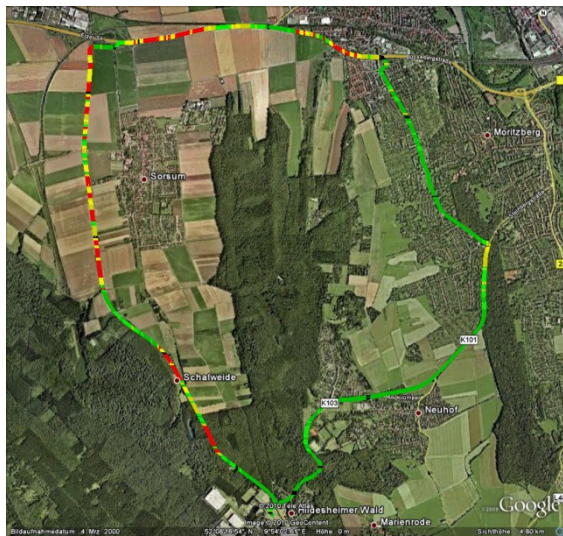


Figure 9: BER (audio quality) of antenna 2 signal

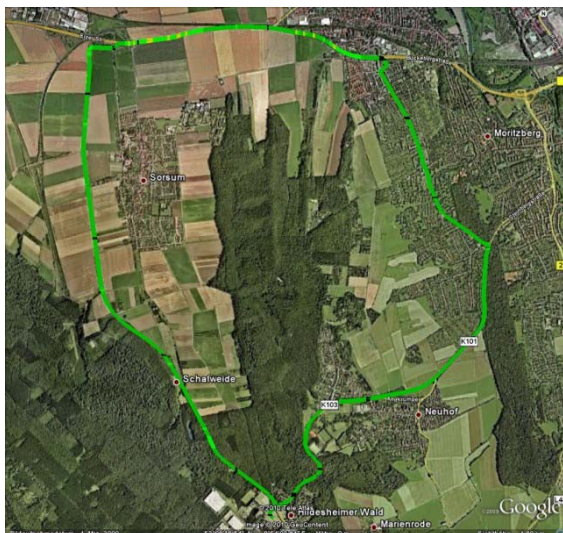


Figure 10: BER (audio quality) of diversity signal

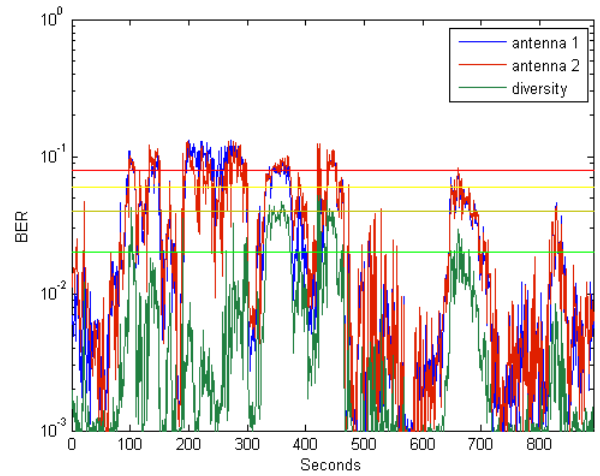


Figure 11 BER graph of test drive

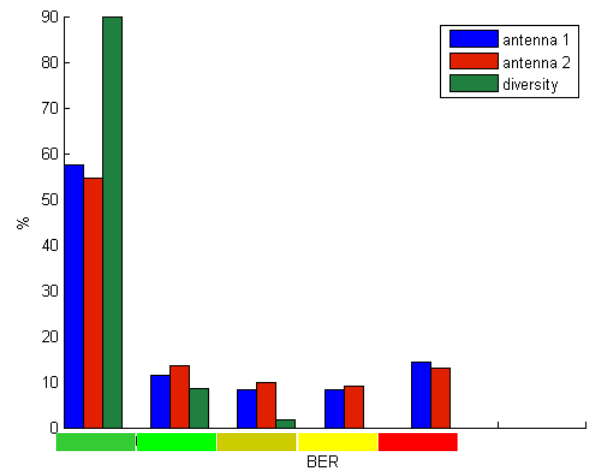


Figure 12: Histogram of BER of test drive

D. Antennas with non-omnidirectional pattern

Measurements along the same route were taken with the antennas positioned close to the opposite edges of the car roof. As a consequence the omnidirectional antenna patterns are lost and both antennas show a clear directivity in opposite directions caused by the irregular ground plane.

A detail of the test results for this setup is plotted in Figure 13. Antenna 1 was able to collect more signal energy than antenna 2 resulting in a lower BER. A comparison to Figure 11 shows a small improvement of the signals from antenna 1 and a degradation of the signals from antenna 2 in comparison to the omnidirectional pattern.

Regarding Figure 13 the diversity signal has a lower BER than that of the better antenna for most of the time as one can see for example in the interval between 350 and 400 seconds. If one of the antennas produces an even worse signal the BER of the diversity signal is still comparable to that of the better antenna, as can be seen in the interval between 400 and 450 seconds.

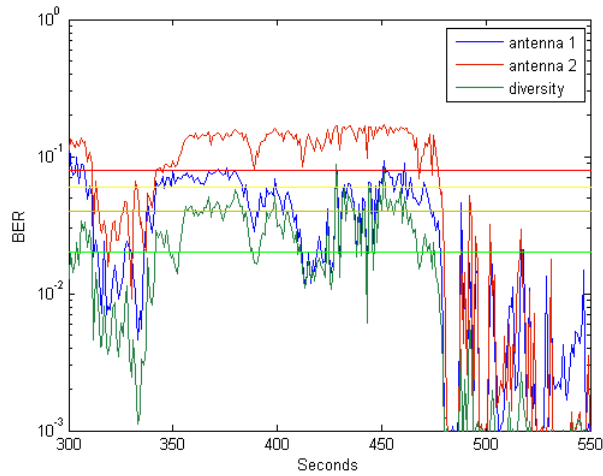


Figure 13: BER graph of part of test drive with directional antennas

V. CONCLUSION

The analytical evaluations and simulations show that a diversity gain in the range of 4 to 7 dB is possible for a two-antenna system for DAB. The higher gains of this range can be achieved especially in channels with insufficient interleaving. The correlation between the fading amplitudes of the two antenna positions leads to a small degradation of the diversity gain. It depends on the distance between the two antennas and the PAS of the signal. The field tests were conducted for different antenna configurations. In regions with insufficient coverage the performance improvements with the diversity system were impressive. So we see a differentiation potential for car manufacturers using well-designed DAB diversity receivers in future.

APPENDIX

For the simulation typical delay power spectrum should be used. Beside the well known RA and TU profiles which were developed for GSM, additional channel models representing hilly regions with longer echoes are needed for DAB. The two hilly terrain models DAB HT1 and HT2 were extracted from measurements performed by Bosch and the former Bundespost [7] in the German low mountain ranges.

The delay power spectra $P(\tau)$ are based on superposition of exponential distributions:

$$P(\tau) = \sum_{k=1}^3 \frac{a_k}{\tau_{mk}} e^{-(\tau-\tau_k)/\tau_{mk}} \cdot \mathcal{E}(\tau - \tau_k)$$

with a_k representing the weighting factors, τ_{mk} the time constants and τ_k the related delays as defined in Table 2. The unit step function is denoted by $\mathcal{E}(\tau)$.

Table 2: Echo profile DAB HT1 and HT2

Parameters	DAB HT1	DAB HT2
$(\alpha_1, \alpha_2, a_3)$	0.33, 0.5, 0.17	0.2, 0.6, 0.2
(τ_1, τ_2, τ_3)	0 μ s, 30 μ s, 80 μ s	0 μ s, 20 μ s, 40 μ s
$(\tau_{m1}, \tau_{m2}, \tau_{m3})$	0.33 μ s, 2 μ s, 1 μ s	1 μ s, 5 μ s, 2 μ s

Figure 14 illustrates the delay power spectrum of DAB HT2. For the simulation, the Doppler spectrum has been assumed to be isotropic.

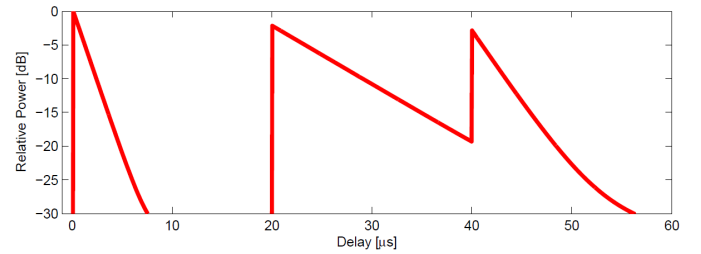


Figure 14: Delay power spectrum DAB HT2

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