DIVERSITY AND EQUALIZATION IN FREQUENCY DOMAIN - A ROBUST AND FLEXIBLE RECEIVER TECHNOLOGY FOR BROADBAND MOBILE COMMUNICATION SYSTEMS

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Abstract - A new receiver structure for broadband mobile communication systems is presented. Signals with block oriented single-carrier modulation are processed in frequency domain. By using a combination of diversity and equalization, an excellent receiver performance can be achieved even for time-variant and frequency-selective radio channels.

I. INTRODUCTION

The rapid growth of personal communication services (PCS) implies an increasing demand for broadband wireless networks to fulfill the customers needs for mobile multimedia applications. The design of appropriate radio interface technologies is one of the most challenging requirements. The radio interface should be flexible, bandwidth-efficient and robust against channel impairments on the one hand and of moderate cost and complexity on the other hand. The performance of the radio interface is a key factor for the overall system and service quality.

For an optimized radio interface design the knowledge of the mobile radio channel and its impact on system performance is of basic importance. Therefore, in section II, some basics about channel characteristics and modulation techniques are reviewed. In section III an advanced receiver approach is presented and performance results for different channel models are described in section IV.

II. IMPACT OF THE RADIO CHANNEL ON WIDEBAND SIGNAL TRANSMISSION

A. *Wideband radio channel characteristics*

The radio channel is characterized by multipath propagation. The time dispersion of the channel impulse responses (CIRs) depends on the environment (indoor, outdoor), the antenna parameters (gain, directional pattern) and the base and mobile station constellations (antenna heights, shadowing, building characteristics, etc.). It ranges from some ten ns for small rooms up to some ten μs for macro cells in mountainous regions. The time dispersion of the CIRs corresponds to frequency selective channel transfer functions. For radio systems with mobile terminals the characteristics of the channel are time-variant due to the local variation of the channel parameters. In Fig. 1 an example of measured wideband channel characteristics is shown. The measurement was carried out in a micro-cellular environment with a wideband channel sounder [1]. The radio frequency was 2 GHz and the bandwidth was 6 MHz. The magnitudes of the CIRs and the magnitudes of the corresponding channel transfer functions are plotted for a run length of 1 m. The local variation and the frequency selectivity of the channel parameters can be clearly recognized.

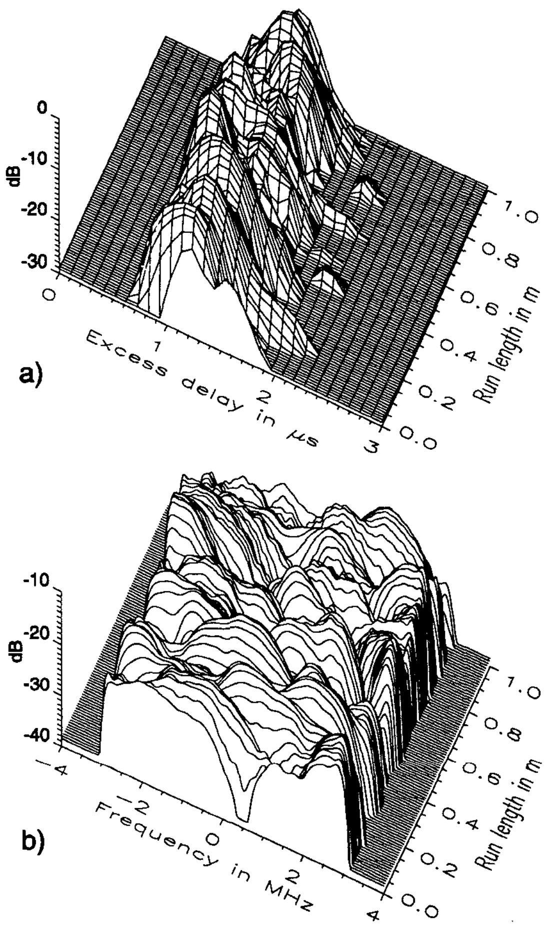

Fig.1 Wideband radio channel characteristics in a micro-cellular environment along a run length of 1 m.
a) impulse responses, b) transfer functions.

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In addition to measured channel data appropriate wideband channel models are required for channel description in connection with system studies. The model used throughout this paper is the tapped-delay-line model which represents the wideband radio channel by a number of taps, each having a given delay, a given average power and a given Doppler spectrum for the multiplicative fading process. Parameter sets for different environment categories like *Typical Urban*, *Rural Area*, etc. have been defined by COST 207 [2].

B. *Modulation schemes for time-dispersive channels*

1) Single carrier modulation schemes

Using a single-carrier modulation, the time dispersion of the channel produces intersymbol interference (ISI). The amount of ISI depends on the ratio of the CIR duration to the symbol duration. For GMSK, as used for GSM (Global System for Mobile Communications) or DECT (Digital European Cordless Telecommunications), signal reception can be accommodated without equalizer only if the delay spread is less than about 10% of the bit duration. In all other cases an adaptive equalizer is necessary. Viterbi equalizers or decision feedback equalizers (DFE) having a depth of 4 to 5 symbol durations as used for example in GSM [3,4] are state-of-the-art technology.

However, if the ISI is spread over some tens of data symbols (e.g., time dispersion 5 μs / symbol duration 0.1 μs), the complexity of an appropriate time domain equalizer would exceed by far the limits of current technology.

The advantage of single-carrier schemes is that the amplitude variations of the transmitted signal which have an impact on the linearity requirements of the transmitter amplifiers are moderate. In particular, GMSK or CPM schemes are robust against nonlinear distortions because of their constant envelope.

Another advantage is that the level variations of the received signal which cause severe performance degradation for narrowband systems are significantly reduced for wideband systems (multipath gain by independently fading paths) [5].

2) Multi carrier modulation schemes

For multi carrier modulation schemes using OFDM (orthogonal frequency division multiplexing) the transmission is performed in parallel via N narrowband subcarriers, where each subcarrier is modulated with a date rate of $1/N$ of the total data rate. If a guard interval with a duration of the CIRs is inserted between subsequent OFDM symbols, the ISI is eliminated [6].

However, multi carrier modulation schemes suffer from frequency selective fading. The information carried by sub-carriers which are heavily affected by fading can only be reconstructed in the receiver by powerful channel coding methods which reduce, however, the bandwidth efficiency. For coherent signal transmission, the received signal has to be equalized by dividing the signal spectrum by the complex channel transfer function. As an alternative, differential techniques can be applied which avoid the necessity of channel estimation even for high-order signal alphabets [7].

From an implementation point of view, it is crucial that OFDM puts high demands on phase noise and carrier synchronization. Furthermore, the linearity requirements are very high because of the Gaussian envelope distribution of the time domain signal.

III. DIVERSITY AND EQUALIZATION IN FREQUENCY DOMAIN

A. *Principle of frequency-domain equalization*

In [8] and [9] block-oriented single carrier transmission schemes with frequency-domain equalization (FDE) are described. This transmission scheme can be derived from an OFDM transmission scheme by shifting the discrete Fourier transform (DFT) from the OFDM transmitter to the FDE receiver [10]. The signal transmission has to be organized in blocks for OFDM as well as for FDE. To avoid interblock interference, a guard interval between subsequent blocks is required with a duration which is at least as long as the CIRs.

It is shown in [8] that without channel coding the performance of this approach is superior compared to the performance of multicarrier schemes. The reason is that in an OFDM system each narrowband subcarrier is affected by Rayleigh fading. Therefore, the bit error rate (BER) as function of the signal-to-noise ratio (SNR) decreases relatively slow, similar to the performance of a narrowband system in a Rayleigh fading channel. Single-carrier systems, however, spread the energy of each transmitted data symbol over the entire spectrum. If the signal bandwidth is much larger than the coherence bandwidth of the channel, only parts of the spectrum are distorted.

A FDE divides the received signal by the channel transfer function. The problem hereby is noise enhancement for parts of the spectrum where the channel transfer function has deep fades (division by very small magnitudes of the transfer function).

B. *Frequency domain equalizer with diversity*

In this paper, a combination of diversity and equalization - both performed in frequency domain - is proposed. The receiver structure is shown in Fig. 2. The signal is received by two diversity antennas. After down conversion the signals are sampled by analog/digital converters (ADC). Then, the signals of the two branches are transformed into the frequency domain by DFT. The resulting discrete signal spectra $S_{1/2}(k\Delta\omega)$ of the two diversity branches are given by

$$\begin{aligned} S_1(k\Delta\omega) &= S(k\Delta\omega)H_1(k\Delta\omega) \\ S_2(k\Delta\omega) &= S(k\Delta\omega)H_2(k\Delta\omega) \ , \end{aligned} \tag{1}$$

where $S(k\Delta\omega)$ is the transmitted signal spectrum and $H_{1/2}(k\Delta\omega)$ are the (time variant) channel transfer functions of diversity branches 1 and 2, respectively. The frequency increment $\Delta\omega = 2\pi / T_U$ depends on the duration T_U of the signal block used for the Fourier transform.

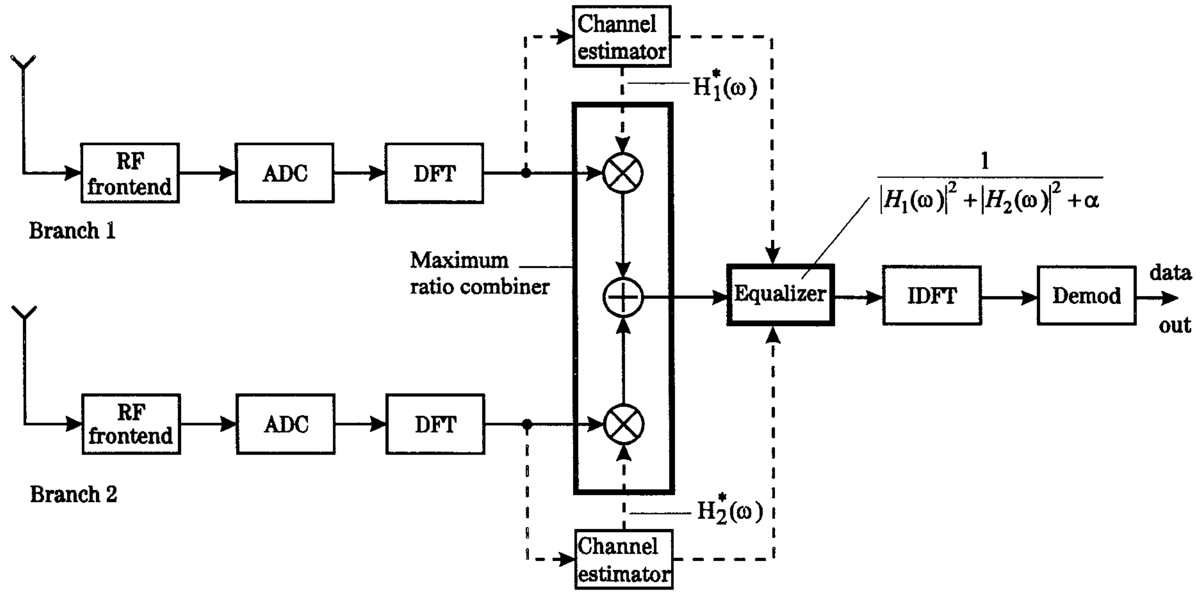

Fig. 2 Receiver structure for the simultaneous performance of antenna diversity and equalization in frequency domain. Solid lines with arrows: signal flow; dashed lines: information flow for channel estimation.

A maximum ratio combining (MRC) of the spectra of the two diversity branches is performed by multiplying the spectrum of each branch with the complex conjugate of the channel transfer function and adding the spectral components of both branches. The discrete signal spectrum S_{MRC} after the summation is given by the following expression:

$$S_{MRC}(k\Delta\omega) = S_1(k\Delta\omega)H_1^*(k\Delta\omega) + S_2(k\Delta\omega)H_2^*(k\Delta\omega). \quad (2)$$

Substitution of (1) in (2) yields

$$S_{MRC}(k\Delta\omega) = S(k\Delta\omega)\left(|H_1(k\Delta\omega)|^2 + |H_2(k\Delta\omega)|^2\right) \quad . \ (3)$$

The resulting overall "transfer function", defined as ratio of signal spectrum after MRC to transmitted signal spectrum, is a real function given by

$$H_{MRC}(k\Delta\omega) = |H_1(k\Delta\omega)|^2 + |H_2(k\Delta\omega)|^2 \quad . \quad (4)$$

In Fig. 3a) and 3b) examples of channel transfer functions gained by the COST 207 model *Typical Urban* are plotted. The power delay profile of this channel model has a maximum excess delay of 5 µs. The transfer functions are shown within a bandwidth of 10 MHz for two uncorrelated diversity branches. Fig. 3c) shows the resulting transfer function after MRC according to (4). Fig. 3 shows clearly, that the transfer functions of the two individual branches are affected by deep fades, whereas the fading of the resulting transfer function after MRC is reduced significantly.

The equalization of the received signal after MRC can be performed by dividing the signal spectrum by $H_{MRC}(k\Delta\omega)$. With this operation, the intersymbol interference will be eliminated (zero-forcing criterion). Because of the reduced fading of this function the noise enhancement problem is mitigated compared to frequency domain equalization without diversity.

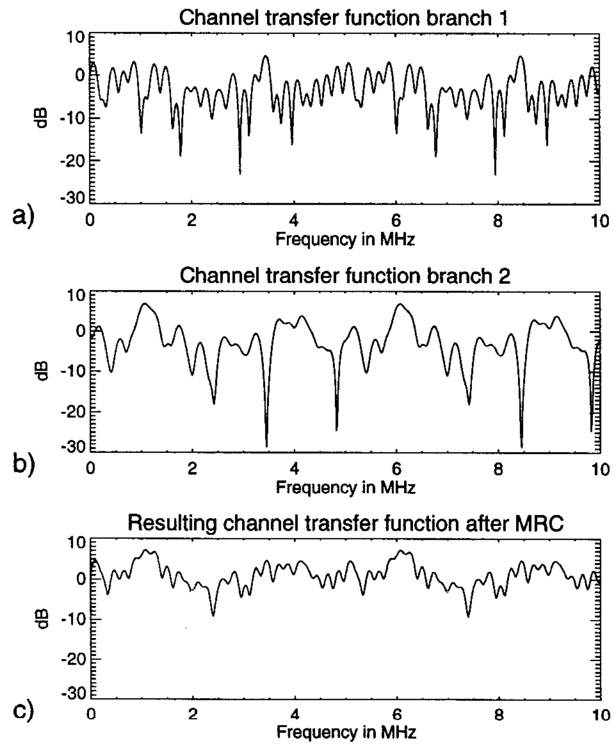

Fig. 3 Examples for channel transfer functions gained from the channel model *Typical Urban*.

A further reduction of noise enhancement can be achieved by performing the equalization using a function

$$\frac{1}{|H_1(\omega)|^2 + |H_2(\omega)|^2 + \alpha}, \quad \alpha = \frac{\sigma_{n1}^2 + \sigma_{n2}^2}{\sigma_a^2} \quad , \quad (5)$$

where σ_{n1}^2 and σ_{n2}^2 are the variances of the noise at the receiver inputs and σ_a^2 is the variance of the transmitted data symbols. The term α is an optimal compromise between noise enhancement and remaining channel distortions according to the minimum mean square error (MMSE) criterion [8].

From an implementation point of view the operations for MRC and equalization can be performed simultaneously. This means, that the signal spectra of the two diversity branches are multiplied by the complex factors

$$\frac{H_{1/2}(\omega)^*}{|H_1(\omega)|^2 + |H_2(\omega)|^2 + \alpha} \tag{6}$$

before adding the spectral components of the two diversity branches. The required information about the channel transfer functions can be provided using known signal blocks for the training of the channel estimators.

The described signal processing can be performed independently from the applied modulation scheme. Continuous phase modulations (CPM) as well as quadrature amplitude modulations (QAM) can be applied depending on different system requirements. It is possible to adapt the modulation scheme to the SNR conditions at a specific radio link. This adaptive approach is very flexible and robust and has the potential for high spectral efficiency.

IV. PERFORMANCE EVALUATIONS

Computer simulations have been performed in baseband for the investigation of the proposed receiver structure. Particular attention was paid to micro cellular propagation conditions with low mobility.

A. *Signal structure*

For the simulations a block structure of the transmitted signal according to Fig. 4 has been assumed.

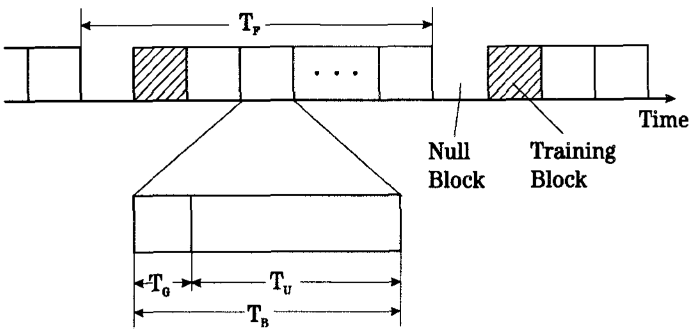

Fig. 4 Signal structure used for the FDE receiver simulations.

The signals are organized in frames having a time duration T_F. Each frame consists of N_F signal blocks, where the first block is a "null" block assisting for frame synchronization and the second block is a training block which can be used for channel estimation. Each block has a time duration T_B and consists of a useful part with a length T_U and a cyclic prefix (guard interval) with a length T_G. The useful part of each block contains N_S data symbols each having a symbol duration T_S. It was assumed that the time variance of the radio channel within a frame is negligible. The parameters used for the simulations are summarized in Tab. 1.

Tab. 1 Parameters used for the FDE receiver simulations.

Symbol duration T_S	0.1 µs
Total block duration T_B	32 µs
Useful block duration T_U	25.6 µs
Guard interval	6.4 µs
Data symbols per block	N_S=256
Block per frame	N_F=16
Frame duration T_F	512 µs
Used modulation schemes	4-QAM, 16-QAM, 64-QAM
Used channel models	AWGN, flat Rayleigh fading, Typical Urban (COST)

B. *Simulation results*

The BER performance as function of the SNR is plotted in Fig. 5 for 4-QAM and in Fig. 6 for 16-QAM. Ideal channel estimation has been assumed. According to the parameters in Tab. 1 the data rates are 14 Mbit/s for 4-QAM and 28 Mbit/s for 16-QAM. The curves A exhibit the results with receiver diversity, the curves B show the results without diversity.

The dotted curves serve as a reference for the receiver performance for an AWGN (additive white Gaussian noise) channel. The dashed curves exhibit the performance for a non-frequency-selective Rayleigh fading channel. These curves correspond to the performance of an uncoded OFDM scheme regardless if the channel is frequency-selective or not because each subcarrier is affected by Rayleigh fading in any case. The solid curves represent the receiver performance for the channel model *Typical Urban*.

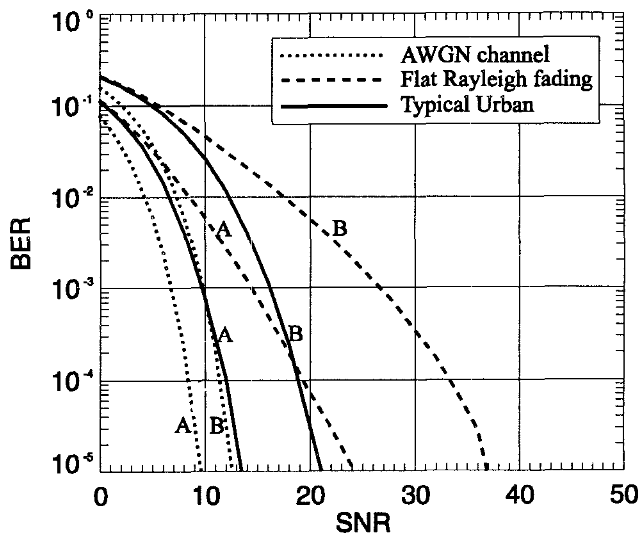

Fig. 5 Performance of the FDE for 4-QAM modulation (A: with diversity; B: without diversity).

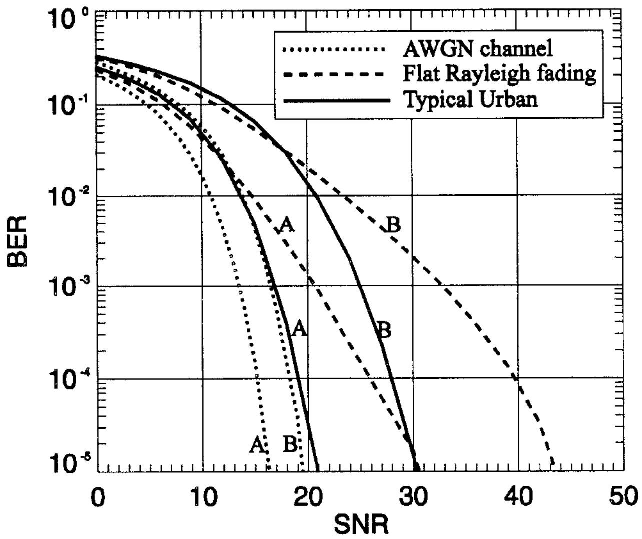

Fig. 6 Performance of the FDE for16-QAM modulation (A: with diversity; B: without diversity).

From Figs. 5 and 6 it can be read that the difference between 4-QAM and 16-QAM is in the order of 7 dB. Diversity improves the BER in all cases. The largest improvement can be observed for the flat Rayleigh fading channels (OFDM situation). For the channel model *Typical Urban* the performance is superior to the Rayleigh fading channel, even without diversity, because a multipath gain can be exploited by the FDE receiver. The FDE receiver with diversity has a performance similar to the AWGN channel (without diversity). Hence, the impact of the channel can be eliminated almost completely by the proposed receiver concept.

V. DISCUSSION AND CONCLUSION

A new receiver structure for broadband wireless systems has been presented. By using a combination of diversity and equalization - both performed in frequency domain - a high performance can be achieved in frequency-selective radio channels. The ISI is compensated completely up to the duration of the guard interval, while the multipath gain of broadband signal transmission and the gain of antenna diversity can be exploited. The multipath gain increases with increasing system bandwidth. On the other hand, the receiver sensitivity is decreasing proportional to the system bandwidth. Therefore, an optimization of the system bandwidth with respect to radio range and data rate has to be made in order to meet the requirements for different application scenarios.

From an implementation point of view, the new transmission scheme combines the advantages of broadband single carrier transmission (limited signal dynamics, moderate requirements for carrier and phase stability compared to OFDM) with the benefits of multicarrier transmission (robustness against multipath effects with limited complexity). A comparison between an FDE receiver and advanced OFDM schemes with adaptive modulation will be presented in a complementary paper [10].

The presented transmission schemes can be extended by using the proposed receiver structure at the base station for uplink reception and a pre-distortion based on the described signal processing procedures for downlink transmission. This implies the potential to obtain a reduced complexity of the mobile receiver because with an appropriate pre-distortion at the base station only a small effort for equalization would be needed at the mobile receiver.

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