# A DOPPLER-COMPENSATED NONCOHERENT OFDM-TRANSCEIVER WITH SECTORIZED ANTENNA RECEPTION

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## ABSTRACT

Frequency-selective fading channels are easily made use of by OFDM. Due to an increase of the symbol duration even channels with large delay spread can be utilized for data-transmission. However, if the channel additionally exhibits a large Doppler spread, a short symbol duration is desirable. Otherwise the channel's time-varying impulse response during one OFDM-symbol will introduce intercarrier-interference (ICI). This will inevitably produce an error-floor. Ultimately, one has to compromise between achievable data-rate and robustness against fading. We present a novel noncoherent receiver which relies on the use of directional antennas to avoid large Doppler spread before it can lead to ICI. The use of differential PSK then allows us to achieve remarkable performance without channel state information and without sacrificing bandwidth to training data.

## 1. INTRODUCTION

The use of $M$-ary differential PSK (DPSK) combined with OFDM allows for robust data-detection without channel state information (CSI) over frequency- and time-selective channels. The use of a cyclic prefix, if chosen sufficiently long, ensures both the orthogonality of the subcarriers and OFDM symbols free of intersymbol interference. Depending on whether the channel exhibits more frequency-selectivity or more time-selectivity one can choose to perform differential modulation either in time or in frequency direction. The chosen direction should point in the direction of large channel correlation such that differential demodulation can successfully restore the transmitted data without CSI.
DPSK naturally suffers from an SNR-loss compared to its coherent counterpart PSK. This is usually accepted due to the implementational ease [1, 2] since no explicit channel estimation is required. However, a coherent system which employs channel estimation requires knowledge about the channel statistics, i.e., the power delay profile and the Doppler spectrum [3]. A practical system needs to estimate these characteristics and will suffer from mismatch as well as estimation errors.
Our main concern in this paper is the data transmission over channels with large Doppler spread. Those channels are accompanied by rapid time-variations within one OFDM-symbol and will introduce ICI leading to an unacceptable error-floor. Literature contains numerous approaches to cope with this problem. A popular idea is the assumption that the channel's variation within an OFDM-symbol can be described by a linear model, e.g. [4, 5]. This allows for setting up an approximate channel matrix which can be used for equalization. This requires computing matrix inverses, which might be impractical for realization. The limit of this idea is given by those Doppler conditions which violate the necessary linearity of the model. Another approach relies on pilot symbols to estimate the time-variant channel impulse response [6]. Unfortunately, the large amount of training decreases bandwidth-efficiency drastically.
An alternative philosophy to deal with large Doppler spread is the use of multiple antennas. The authors of [7] advocate the use of multiple receive antennas for Doppler compensation. By MMSE-filtering/interpolation they generate a receive signal which seemingly has been received over a slowly time-varying channel. The authors of [8] demonstrate that directional antennas can effectively reduce the fading rate of the channel. These antennas slice the horizontal reception space into wedgeshaped sectors. This approach then allows for separating incoming paths according to their position in the Doppler spectrum. Thereby, each sector experiences only a fraction of the original Doppler spread. In [9] this effect is further investigated and it is shown that the ultimate intercarrier interference is reduced. To our best knowledge literature so far lacks a thorough study of the effect of directional antenna reception on the achievable bit error rate. We are aware of one paper, [10], where the unrealistic case of perfect channel state information at the receiver and a flat channel was assumed.

## 2. SYSTEM MODEL

Fig. 1 depicts the OFDM-transmitter with DPSK which allows for noncoherent reception. Throughout the paper we assume the equivalent complex baseband. Information bits $b(\xi)$ are convolutionally encoded (CC) and bitwise randomly interleaved ($\Pi$). The interleaved code bits $c(\xi')$ are then mapped to an $M$-PSK signal constellation by the mapping function $\mathcal{M}$, yielding the symbols $\Delta d_n(i)$ with subcarrier index $n$ and OFDM symbol index $i$. The differential modulation (DPSK) can be performed either in time-direction

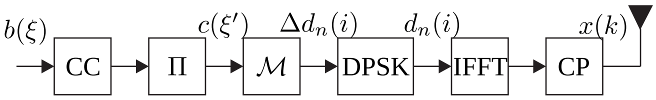


**Fig. 1**. OFDM-transmitter allowing for noncoherent reception

$$d_n(i) = \Delta d_n(i) \cdot d_n(i-1) \tag{1}$$

or in frequency-direction

$$d_n(i) = \Delta d_n(i) \cdot d_{n-1}(i) \tag{2}$$

depending on the channel properties. Due to our proposed technique of reducing the effective Doppler spread we will preferably apply differential modulation in time-direction (1). The OFDM time-domain signal is then computed by the IFFT. Prepending the cyclic prefix (CP) then produces the transmit signal

$$x(k) = \sqrt{\frac{E_\mathrm{s}}{N}} \sum_{i=-\infty}^{\infty} \sum_{\nu=0}^{N-1} d_\nu(i) \cdot \mathrm{e}^{\mathrm{j}2\pi\nu(k-i(N+N_\mathrm{g}))/N} \tag{3}$$

with the number of subcarriers $N$, the number of guard taps $N_g$, and the signal energy $E_\mathrm{s}$.

### 2.1. Sectorized Receive Antenna

Let us first review the model for a wide-sense stationary channel with uncorrelated scattering (WSSUS-channel), which we will assume in the following. Its discrete-time impulse response at time $k$ and delay $\ell$ reads [11]

$$h_\ell(k) = \frac{1}{\sqrt{N_e}} \sum_{\mu=0}^{N_e-1} a(\mu) \mathrm{e}^{\mathrm{j}(\theta(\mu)+2\pi f_\mathrm{D}(\mu)Tk)} \delta(\ell - \ell(\mu)), \tag{4}$$

where $a(\mu)$ and $\ell(\mu)$ are the $N_e$ path amplitudes, and delays, respectively. The sampling period is denoted by $T$. The phases $\theta(\mu)$ are uniformly distributed between $0$ and $2\pi$. The distribution of the Doppler frequencies $f_\mathrm{D}(\mu)$ determines the channel correlation in time. The common spectrum due to Jakes emerges if

$$f_\mathrm{D}(\mu) = f_{\mathrm{D,max}} \cos(\phi(\mu)) \,. \tag{5}$$

The phases $\phi(\mu)$ are the angle of incidence relative to the direction of motion. They are equally distributed between $0$ and $2\pi$. The maximal Doppler frequency is denoted by $f_{\mathrm{D,max}}$. We will assume this model through out the paper. Eq. (4) models omnidirectional reception of a moving antenna in a rich scattering environment.

Let us now consider the sectorization approach. The correspondence between angle of incidence and Doppler frequency is determined by (5). Hence, if a directional antenna covers only a fractional range of all possible angles of incidence, the resulting Doppler spread will be reduced [8]. We are interested in splitting the Doppler spectrum in equally sized partitions since then all sectors will experience identically reduced time-selectivity. However, due to the cosine function in (5) the sector angles are *not* equally sized. This effect is illustrated in Fig. 2 for a number of $S = 6$ sectors.

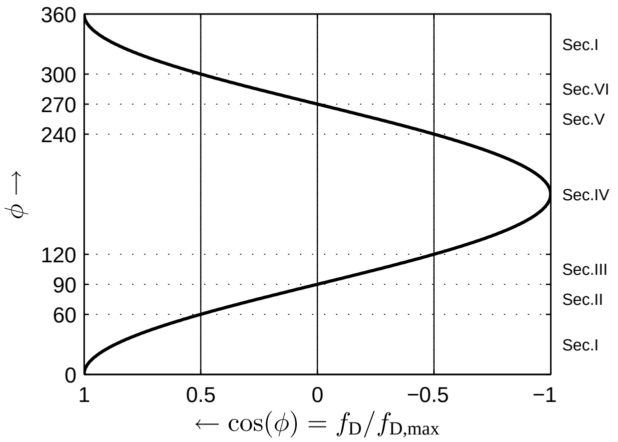


**Fig. 2**. Correspondence between angle of incidence $\phi$ (in degree) and the partitioning of the Doppler spectrum into $S = 6$ sectors

Fig. 3 illustrates the effect of the sectorization on the received Doppler spectrum. The relative direction of motion between transmitter and receiver is as indicated by the arrow. This then leads to the shown correspondence of sectors and Doppler subspectra. The effective Doppler spread of each subspectrum is smaller than the Doppler spread of a single omnidirectional antenna, i.e., the maximum Doppler spread is reduced by a factor of $1/(S/2+1)$.

In Table 1 we have collected the sector angles which lead

| $S$ | $\phi_1$ | $\phi_2$ | $\phi_3$ | $\phi_4$ | $\phi_5$ | $\phi_6$ | $\phi_7$ | $\phi_8$ |
|---|---|---|---|---|---|---|---|---|
| 2 | 90 | 270 | | | | | | |
| 4 | 71 | 110 | 251 | 290 | | | | |
| 6 | 60 | 90 | 120 | 240 | 270 | 300 | | |
| 8 | 53 | 79 | 102 | 127 | 233 | 259 | 282 | 307 |

**Table 1**. Sector angles in degree for equal Doppler partitioning (values in degree)

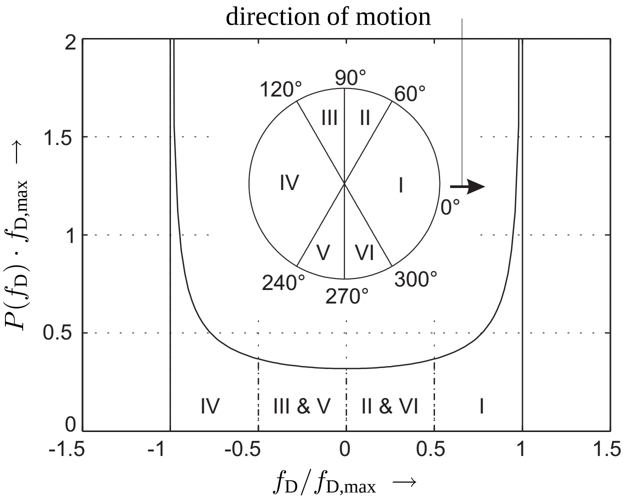


**Fig. 3**. Antenna with $S = 6$ sectors and its effect on Jakes' spectrum

to equally sized Doppler subspectra for different numbers of sectors.
Let us define the impulse response for sector $s$, $1 \leq s \leq S$, as $h_{\ell,s}(k)$. For simulations we assume ideal sectorization, i.e., we determine $h_{\ell,s}(k)$ by generating the omnidirectional impulse response (4) and picking out those incoming paths which belong to the encompassed angle of incidence.

### 2.2. Receiver

Our noncoherent receiver is depicted in Fig. 4. Each sec-

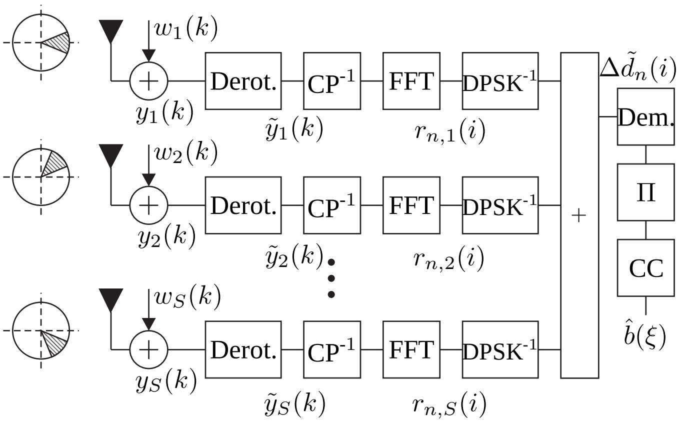


**Fig. 4**. Noncoherent OFDM-receiver for sectorized reception with differential demodulation

tor/antenna corresponds to a distinct branch

$$y_s(k) = \sum_{\ell=0}^{L-1} h_{\ell,s}(k) x(k-\ell) + w_s(k) \tag{6}$$

with the additive white noise term $w_s(k)$ and the length of the impulse response $L$.
Due to the sectorization each sector is affected not only by a Doppler spread but also by a Doppler shift. This Doppler shift requires frequency compensation ("Derot.")

$$\tilde{y}_s(k) = \mathrm{e}^{-\mathrm{j}2\pi f_\mathrm{c}(s)Tk} \cdot y_s(k)\,. \tag{7}$$

In [8] we find the approximation

$$f_\mathrm{c}(s) = \begin{cases} f_{\mathrm{D,max}} \cos(\phi_s/2)\,, & s = 1 \\ -f_{\mathrm{D,max}} \sin(\phi_s/2)\,, & s = S/2+1 \\ f_{\mathrm{D,max}} \cos((\phi_s + \phi_{s-1})/2)\,, & \text{else}\,. \end{cases} \tag{8}$$

In passing we note that (8) does not correspond to the center frequency of the Doppler subspectra (cf. Fig. 3). In Sector I, for example, Doppler frequencies towards the maximum Doppler frequency are occuring with a higher probability than those towards lower frequencies. Hence, (8) considers a bias towards the magnitude of larger Doppler frequencies.
After removing the cyclic prefix (CP$^{-1}$) from the frequency compensated receive signal the fast Fourier transform (FFT) is performed yielding the receive signal in frequency domain at the $n$-th subcarrier in the $i$-th OFDM symbol for antenna $s$

$$r_{n,s}(i) = \frac{1}{\sqrt{N}} \sum_{\mu=0}^{N-1} \tilde{y}_s(\mu + i(N+N_\mathrm{g}))\mathrm{e}^{-\mathrm{j}2\pi\mu n/N}\,. \tag{9}$$

This is followed by differential demodulation (DPSK$^{-1}$) either in frequency direction (10) or in time direction (11)

$$z_{n,s}(i) = \begin{cases} r_{n,s}(i) r^*_{n-1,s}(i)\,, & (10) \\ r_{n,s}(i) r^*_{n,s}(i-1)\,. & (11) \end{cases}$$

In order to produce a diversity gain the signals of all branches are then superimposed

$$\Delta\tilde{d}_n(i) = \sum_{s=1}^{S} z_{n,s}(i)\,. \tag{12}$$

To demodulate the resulting signal we compute an approximate softvalue

$$\begin{aligned} \mathrm{L}(c(\xi')) \approx & \min_{\forall \Delta d_n(i) \to c(\xi)=0} |\Delta\tilde{d}_n(i) - \Delta d_n(i)|^2 \\ & - \min_{\forall \Delta d_n(i) \to c(\xi)=1} |\Delta d_n(i) - \Delta d_n(i)|^2\,, \end{aligned} \tag{13}$$

i.e., we search those symbols $\Delta d_n(i)$ which are closest in Euclidean distance to the receive signal (12) and which are carrying either the codebit $c(\xi) = 0$ or $c(\xi) = 1$, respectively. This procedure implicitly generates reliability information which supports the subsequent Viterbi decoding. The softvalues $\mathrm{L}(c(\xi'))$ are eventually deinterleaved ($\Pi^{-1}$) and decoded (CC$^{-1}$) by the Viterbi algorithm.

## 3. SIMULATION RESULTS

To demonstrate the effectiveness of our approach we conducted several simulations of an OFDM-system with $N = 64$ subcarriers and $N_{\mathrm{g}} = 16$ taps for the cyclic prefix. All simulation results belong to a channel impulse response with equally distributed power delay profile. The investigated modulation schemes are gray-coded differential QPSK (QDPSK) and differential 8-PSK (8DPSK) with the standard convolutional code $(133, 171)_8$ of constraint length $L_c = 7$. The codebits were randomly interleaved at bit-level. Decoding was performed frame-based for a length of $10^4$ information bits. The parameter $\gamma$ denotes the maximum Doppler frequency normalized to the subcarrier spacing. We assume that the receiver has perfect knowledge about the maximum Doppler frequency.

### 3.1. Single Antenna Performance

In Fig. 5 we show the limits of single antenna reception. The examples refer to a lowly frequency selective channel with differential modulation in frequency direction ("$L = 3$, freq.") and to a highly frequency selective channel with differential modulation in time direction ("$L = 10$, time").

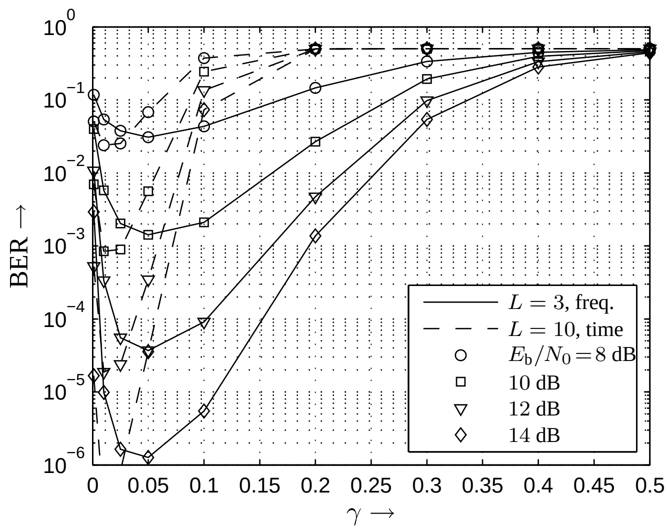


**Fig. 5**. Single antenna performance for lowly and highly frequency selective channels, QDPSK-transmission

The overall trend of all curves is an improvement of the BER from very low Doppler frequencies to moderate frequencies which is followed by a severe deterioration as soon as the Doppler frequency becomes large. The BER improvement with increasing Doppler frequency is attributed to the heightend diversity in time, whereas intercarrier interference is not a limiting factor, yet. The influence of the latter eventually leads to the drastic BER impairment for larger Doppler frequencies.

Compairing the lowly and highly frequency selective casesin detail, we see that the highly frequency selective case has a superior performance over the lowly selective case at low Doppler frequency. This can be ascribed to the larger amount of diversity collected by the larger number of paths of the impulse response. However, rapid channel variations for larger Doppler influence has a much severe influence on differential modulation in time direction. This is due to the substantial phase change between two OFDM symbols in that case.

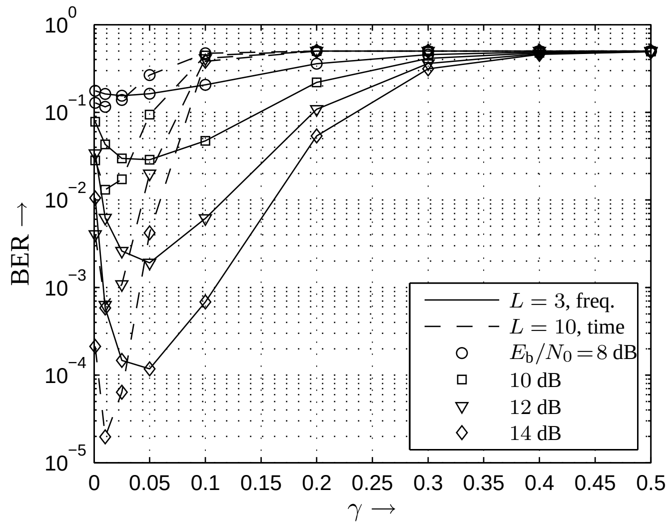


**Fig. 6**. Single antenna performance for lowly and highly frequency selective channels, 8DPSK-transmission

To complete the discussion of single antenna reception we have applied the more sensitive 8DPSK modulation. Results are depicted in Fig. 6. As is to be expected the BER impairment occurs earlier, i.e., at lower Doppler frequencies relative to the QDPSK case in Fig. 5.

### 3.2. Multiple Antenna Performance

In the previous section we have demonstrated the severe impact of rapid channel variations on the bit error rate performance. We address now the issue of multiple receive antennas. We investigate the performance of the sectorization against single antenna reception. For a fair comparison we compare the sectorized receiver with a diversity receiver, too. The latter employs the same number of antennas as the sectorized receiver, however, these antennas are omnidirectional and will experience a larger amount of ICI. Our main finding in this respect is that on the one hand we are able to overcome ICI with sectorization if the Doppler is large. On the other hand, at low Doppler frequencies the channel which is anyhow slowly time-varying will appear quasi-static after sectoriziation. Hence, the performance suffers from less diversity in time.

*3.2.1. Sectorized vs. Single Antenna Reception*

In Fig. 7 we consider a lowly frequency selective channel ($L = 3$) with a large Doppler influence of $\gamma = 0.2$. Differential modulation is performed in frequency direction. Omnidirectional reception ($S = 1$) leads to a substantial error-floor, which can be already avoided by employing two sectors ($S = 2$). However, increasing the number of sectors further ($S > 2$) leads to gains only in the high SNR regime. In the low SNR regime the BER performance is degraded by a larger number of sectors. This can be attributed to the differential demodulation. The differentially demodulated signal (12) is composed of mixed terms which are no longer Gaussian. For a larger number of sectors these mixed noise terms add up. Especially in the low SNR regime they are dominating the differential demodulation outcome and they are responsible for impairing the BER performance. The same statements hold true for 8DPSK transmission.

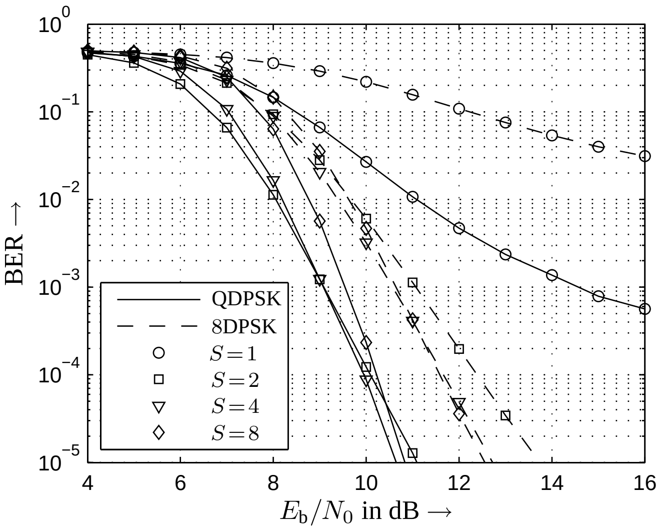


**Fig. 7**. Parameters: $\gamma = 0.2$, $L = 3$, differential modulation in frequency direction

The efficiency of sectorization is all the more apparent if we consider the highly frequency selective case in Fig.8 with differential modulation in time direction. It is obvious that the rapid channel variations for single antenna reception prevent any successful data detection. However, already the use of two sectors reduces the effective Doppler in each sector by a factor of 2 of the original maximum Doppler frequency. Unlike the prior case of low frequency selectivity (cf. Fig. 7) increasing the number of sectors to $S = 4$ yields another substantial gain. Again a refined sectorization ($S = 8$) leads to a BER impairment in the low SNR regime. Indeed gains are achieved not before the high SNR regime sets in. These gains turn out to be much larger for 8DPSK than for QDPSK.

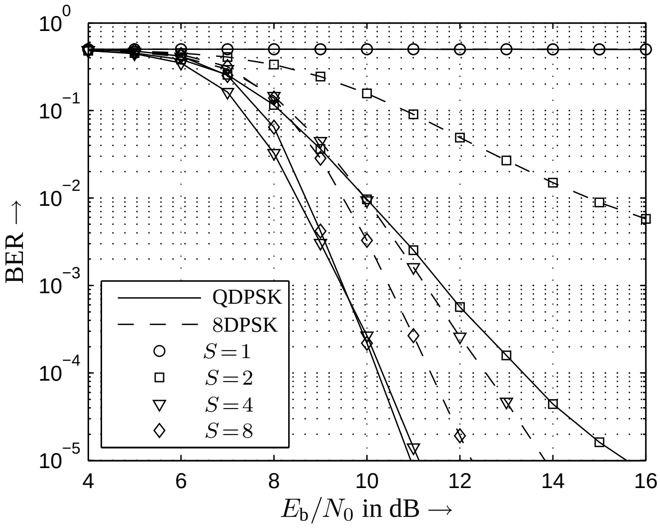


**Fig. 8**. Parameters: $\gamma = 0.2$, $L = 10$, differential modulation in time direction

*3.2.2. Diversity vs. Sectorization*

In this section we examine the performance of sectorized reception compared to diversity reception. The latter employs the same number of *omnidirectional* antennas. These are spaced at a distance large enough to receive uncorrelated signals. Unlike the sectorized case the corresponding receive signals will experience the full Doppler spectrum, i.e., the ICI influence is stronger compared to the sectorized receiver.

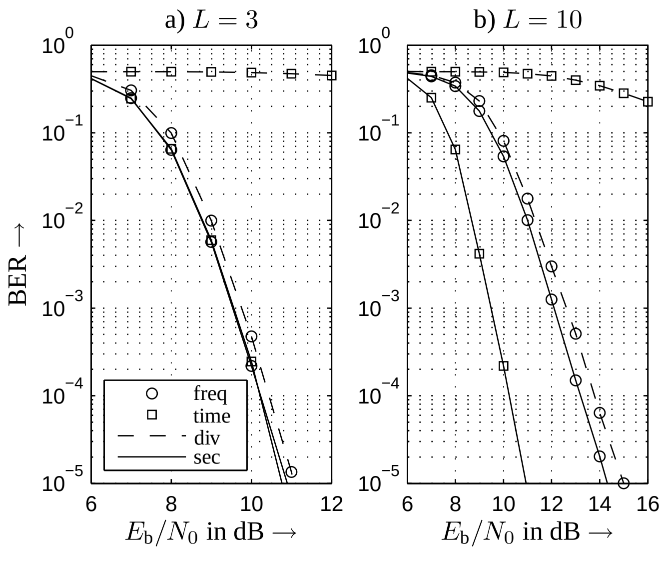


**Fig. 9**. Comparison of diversity against sectorized reception; Parameter: QPSK, $\gamma = 0.2$, $S = 8$

In Fig. 9 we consider the case of $S = 8$ receive antennas and a maximum normalized Doppler frequency of $\gamma = 0.2$. The labels `freq` and `time` denote whether differential modulation is performed in frequency or time direction, `div` and `sec` mark the performance of diversity and sectorized reception, respectively.

Let us consider Fig. 9a which shows the lowly frequency selective case with channel length $L = 3$. The diversity receiver fails miserably if differential modulation is performed in time direction. In that case large channel variations between successive OFDM symbols prevent successful data detection, which can not be overcome by multiple antennas without Doppler compensation. Differential modulation in frequency direction, however, improves the performance of diversity reception. Nevertheless, the performance of sectorized reception is superior. Although the channel is weakly frequency selective, differential modulation in time direction surpasses its counterpart in frequency direction.

Let us now turn to the strongly frequency selective ($L = 10$) case in Fig. 9b. As one might expect the performance of both schemes with differential modulation in frequency direction degrade to a large extent. A slight performance gain of sectorization over diversity is still visible which we attribute to the ICI reduction of our sectorization. Finally, performing differential modulation in time directon in combination with the sectorized receiver yields a convincing performance for these severe channel conditions.

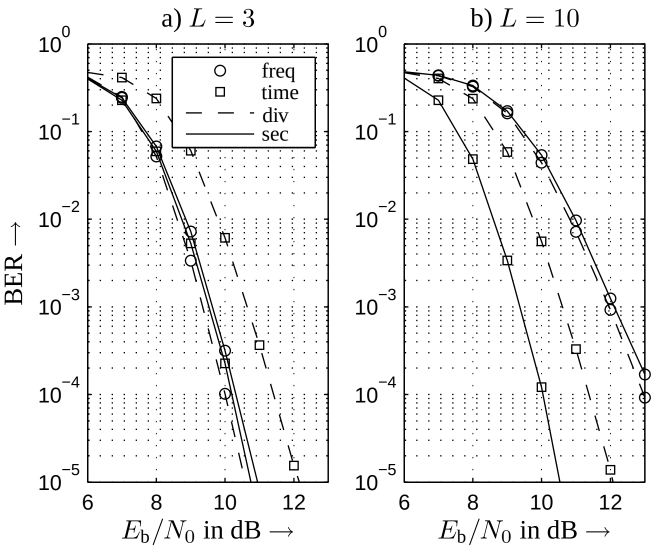


**Fig. 10**. Comparison of diversity against sectorized reception; Parameter: QPSK, $\gamma = 0.1$, $S = 8$

It begs the question how sectorization and diversity reception compare if the time selectivity of the channel is less pronounced. Fig. 10a illustrates that the performance of diversity reception improves over the sectorized approach if differential modulation is carried out in frequency direction. The explanation of this effect lies in the fact that the effective channel seen by the sectorized antennas becomes very slowly time-varying. In this case the diversity receiver benefits from diversity in time and is not yet impaired by ICI.

However, if the channel exhibits stronger frequency selectivity (cf. Fig.10b) we find differential modulation along frequency direction impaired again. Considering the diversity receiver with differential modulation in time direction, we see that its performance for the less time selective case (Fig. 10) is less degraded than for the rapidly changing channel (Fig. 9). The results of this section indicate that sectorized reception

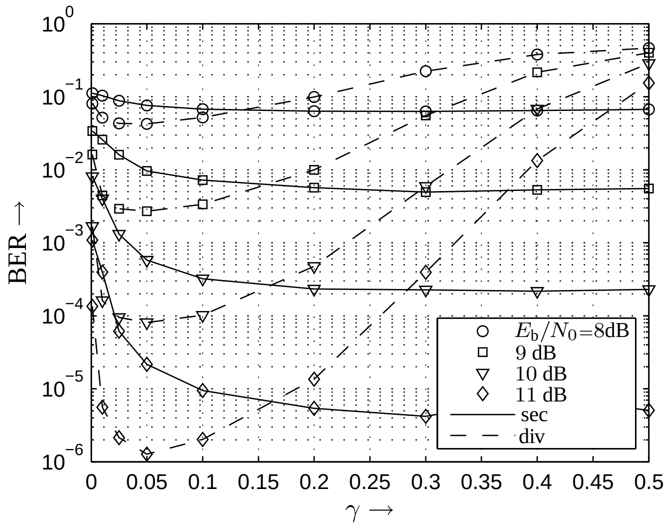


**Fig. 11**. Parameter: $L = 3$, $S = 8$, QDPSK, differential modulation in frequency direction

is beneficial and superior over diversity reception only if the channel is rapidly changing. This is supported by the following observation. The slowly fading channel provides only a small amount of diversity from which the BER performance can not benefit. If the channel variations become faster, the BER will improve since time diversity is provided. The situation changes again if the channel becomes rapidly changing. As a matter of fact ICI will be introduced, degrading the BER severely. Sectorized reception on the one hand improves robustness against large Doppler. On the other hand it will reduce channel variations for channels which are anyhow slowly changing. In this case a diversity receiver is superior because it exploits time diversity and is not impaired by ICI.

To see this more clearly we change perspective and plot the BER over the normalized Doppler frequency. Fig. 11 makes it clear that diversity reception provides better performance over the sectorized approach for small to moderate Doppler spreads. We can also see that by the way of sectorization it is possible to keep a constant BER for a large range of maximum Doppler spreads.

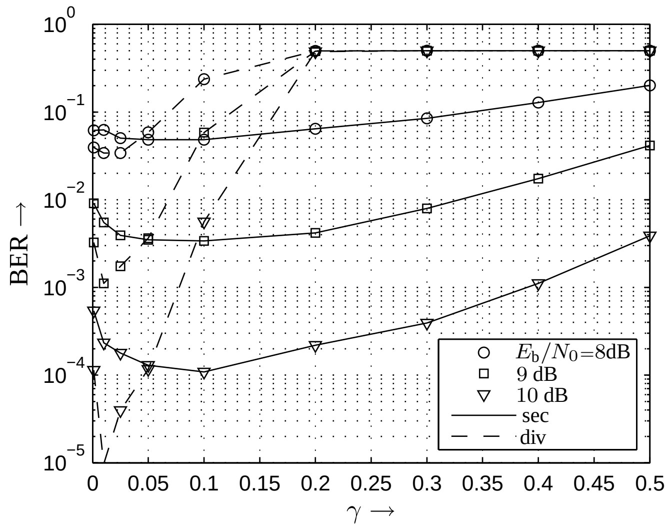


**Fig. 12**. Parameter: $L = 10$, $S = 8$, QDPSK, differential modulation in time direction

In Fig. 12 we have applied differential modulation in time direction for channels with large delay spread. The performance of the diversity receiver is superior only for small Doppler spreads, whereas the sectorized receiver proves to be resilient against much larger maximum Doppler frequencies.

## 4. CONCLUSION

We have described a noncoherent receiver which allows for reliable data reception over rapidly fading channels without channel state information. It utilizes an antenna array to sectorize the horizontal reception space such that each sector experiences only a fraction of the channel's original Doppler spread. On the downside a sectorized receiver renders an already slowly fading channel into a quasic static channel. This provides less time diversity. In this case diversity reception proves to be more robust. However, sectorized reception can effectively compensate large Doppler spreads enabling successful data transmission even with a sensitive modulation scheme such as $8$DPSK.

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