

TITLE

METHOD AND DEVICE FOR CANCELLING DOPPLER SHIFT INDUCED INTER
5 CARRIER INTERFERENCE IN AN OFDM COMMUNICATION SYSTEM BY USING
SIGNAL PRE-DISTORTION.

OFDM (Orthogonal Frequency Division Multiplexing) is a spe-
cific implementation of a multi carrier modulation method
10 which is based on the use of orthogonal carrier signals for
parallel data transmission. Different from other known multi
carrier systems, the carrier distance can be diminished sig-
nificantly through the orthogonality of the carrier func-
tions. Hence, OFDM has established itself as a bandwidth ef-
15 ficient method for data transmission. OFDM is used currently
for DAB, DVB-T, WLAN and in fourth generation (4G) mobile
phone protocols and it stands out especially in terms of ro-
bustness against multi path propagation effects and efficient
use of bandwidth.

20 US 2007/0030798 shows a Doppler frequency calculating appa-
ratus that calculates a Doppler frequency, which is the mag-
nitude of a time-dependent fluctuation of a characteristic of
the transmission path through which an orthogonal frequency-
division multiplexing (OFDM) signal is transmitted.

25 It is an object of the application to provide an improved
method of data transmission for OFDM communication systems in
the presence of a relative movement between a sending unit
and a receiving unit.

30 This and other objects are solved by the subject matter of
the application.

If a sending unit and a receiving unit of a wireless radio link move relative to each other with a velocity v and $v \ll c_0$ holds, the received signal experiences a frequency shift Δf
5 due to the Doppler effect according to

$$\Delta f = -\frac{v}{c_0} f_0,$$

wherein c_0 stands for the velocity of light in vacuum and f_0 for the signal frequency. Under the assumption of the narrow-band approximation, which states that the signal bandwidth is
10 considerably smaller than the mean frequency, the frequency shift Δf is constant for the entire signal spectrum. It is positive, if the sending unit and the receiving unit approach each other and negative if they move away from each other.

15 If sending unit and receiving unit are stationary or move slowly with respect to each other ($v \cdot f_0 \ll c_0$), there is essentially no Doppler shift. Hence, the carrier functions of received signals are orthogonal and have essentially no overlap in the frequency domain.

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If, on the other hand, the sending unit and the receiving unit move relative to each other, the Doppler shifted carrier functions are no longer orthogonal and a superposition of signals is received on the various sub-carriers (also called
25 carriers for brevity). This effect is known as inter carrier interference (ICI) and leads to a marked deterioration of the signal to noise ratio (SNR) on the various sub-carriers and causes an increased frequency of bit errors or even the interruption of the radio link.

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Herein, the carrier functions are also referred to as "SI carrier functions". In OFDM, a transmitted pulse is obtained

by modulating a sub-carrier, which is given by a rectangular pulse, with a sinusoid signal. Amplitude and phase of the sinusoid function are used to represent a symbol to be transmitted. The sub-carrier and also the transmitted pulses correspond to sinc- or SI- functions in the frequency domain. Modulation of a carrier signal may be carried out by modulation of an analog carrier signal or by digital signal processing.

10 With the subject matter of the application, it is possible to operate OFDM systems even if the maximum Doppler shift is larger than 2% of the sub-carrier distance. The application provides an increase in the transmission frequencies and the data rates and hence the carrier distance, which makes standard OFDM effectively usable for communication systems with high velocities of the participants, such as for planes, UAVs, cruise missiles and satellites.

The application discloses a transmitter for generating an OFDM signal that comprises a Doppler pre-distortion unit with an input section for receiving a data vector S . The data vector is generated from data of a data source using a symbol mapper. The data source may be provided, for example, by a camera, a microphone or another input device or also a computer readable memory in which multimedia files or other data is stored. The transmitter further comprises an OFDM modulator and a Doppler Shift memory location for readably storing a pre-determined Doppler Shift value. Herein, the Doppler shift value can be a characteristic value for the Doppler shift or also a higher-level data type such as a vector or matrix that can later be used to calculate the pre-distortion matrix. The Doppler Shift value can also be identical with the pre-distortion matrix. The Doppler pre-distortion unit is

adapted to generate a pre-distorted data vector S_{PD} from the data vector S , wherein the components of the pre-distorted vector S_{PD} and of the data vector S represent data symbols. As used herein, a data symbol does not only represent binary
5 data but also refers to data that is sent together in one time slot and/or frequency slot, for example the data that is represented by a constellation point of a QAM modulator. The pre-distorted data vector S_{PD} is a linear function of the data vector S and is dependent on the Doppler shift value.
10 The OFDM modulator is adapted to generate an OFDM signal such that sub-carrier amplitudes of the OFDM signal are based on the components of the pre-distorted data vector S_{PD} .

The linear dependence of the pre-distorted data vector S_{PD} as function of the data vector S applies to the Doppler correction itself. For other corrections, further correction
15 terms may be added, such as a constant value. This can result altogether in a non-linear function for the pre-distorted data vector S_{PD} .

20 The transmitter may further comprise a Doppler pilot signal generation unit, which is adapted to generate a Doppler pilot signal on a sub carrier. The pilot signal may be generated by setting only one input of an IDFT to a constant value and the
25 other inputs to zero.

For computational efficiency, the Doppler pre-distortion unit may be adapted to derive the linear function of the data vector S from one or more look-up tables which are selected according to the Doppler shift value.
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In a further embodiment, the Doppler pre-distortion unit is adapted to store the Doppler shift value as a pre-distortion

matrix and derive the linear function of the data vector S from the pre-distortion matrix. Herein, the pre-distortion matrix is calculated from a predetermined Doppler shift that the transmitter determines from an external input signal.

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The Doppler pre-distortion unit may further be adapted to derive the pre-distorted vector S_{PD} from a sum of the linear function and one or more non-linear correction terms in order to incorporate further corrections.

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The transmitter may further comprise a Pilot Insertion unit for inserting the Doppler Pilot signal into an OFDM data frame. Moreover, the transmitter may comprises a multiplexer and an OFDM modulator, wherein the multiplexer is connected to the Doppler pre-distortion unit and the OFDM modulator is connected to the multiplexer, the OFDM modulator comprising an IDFT calculation unit which is adapted to generate an IDFT of the pre-distorted data vector S_{PD} , and wherein the OFDM modulator is further adapted to generate an OFDM signal based on output of the IDFT calculation unit.

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The application furthermore discloses a receiver for receiving OFDM signals, which comprises an RF receiver wherein the radiofrequency RF can be an electro-magnetic wave of any frequency from a few kHz to several GHz, in principle even light. The receiver furthermore comprises a demodulator that is connected to the RF receiver, a de-multiplexer that is connected to the demodulator, and a Doppler estimation unit that is connected to the de-multiplexer. The Doppler estimation unit is adapted to generate an estimate of a Doppler shift based on amplitudes of a received OFDM signal at sub-carrier frequencies, the sub-carrier frequencies being frequencies of sub-carriers that are neighbours to a pilot sub-

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carrier frequency. Advantageously, the neighbours are next neighbours because their amplitude is higher than that of other sub-carriers, which leads to an enhanced precision. It works in principle also with the n-th next neighbours, either
5 alternatively or in addition to the next neighbours. For a good accuracy it is furthermore advantageous to use a pilot sub-carrier frequency that is at or at least close to, for example within ± 2 sub-carrier distances, the centre of an OFDM frequency band.

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The application furthermore discloses an OFDM communication unit which comprising the aforementioned transmitter according and the aforementioned receiver. Moreover, the application discloses an OFDM communication system with a first communication unit, which comprises at least the aforementioned
15 transmitter and a second communication unit that comprising at least the aforementioned receiver.

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The application furthermore discloses a method for transmitting and processing a Doppler pilot signal comprising

- generating a pilot signal with a predefined sub-carrier amplitude, wherein the pilot signal uses a pilot sub-carrier, the pilot sub-carrier being chosen from a plurality of OFDM sub-carriers;
- 25 - sending the pilot signal (via a transmitter) of a first communication unit over a communication channel to a second communication unit;
- receiving the pilot signal and evaluating signal amplitudes on sub-carrier frequencies, the sub-carrier frequencies being frequencies of neighbours, especially of
30 next neighbours, of the pilot sub carrier;
- determining a Doppler frequency shift from the signal amplitudes.

For use with OFDM frames, the method may also comprise steps of inserting a Doppler pilot symbol into an OFDM frame to be transmitted and generating the Doppler pilot symbol according to the Doppler pilot symbol.

The method for estimating a Doppler frequency shift of a relative movement between a first OFDM communication unit and a second OFDM communication unit may furthermore comprise steps of

- deriving an estimated relative velocity of the second OFDM communication unit (relative to first comm. unit);
- deriving a magnitude of a Doppler shift from the estimated relative velocity;
- transmitting the magnitude of the Doppler shift to the first OFDM communication unit over a communication channel;
- storing the magnitude of the Doppler shift into a computer readable memory of the first communication unit.

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The step of deriving the estimated velocity may furthermore comprise the aforementioned steps of transmitting and processing a Doppler pilot signal. Alternatively, the step of deriving the estimated velocity may also comprise a derivation of the estimated velocity from location signals, the location signals being received via an RF receiver of the second communication unit.

The application furthermore discloses a method for transmitting pre-distorted OFDM signals over a communication channel, the method comprising

- receiving input data from a data source;
- deriving a data vector S from the input data;

- pre-distorting the data vector S to obtain a pre-distorted data vector S_{PD} , wherein the step of pre-distorting comprises obtaining the pre-distorted data vector S_{PD} as a linear function of the data vector S wherein the linear function of the data vector S depends on a Doppler frequency shift;
- deriving an OFDM signal from the pre-distorted data vector S_{PD} , wherein sub-carrier amplitudes of the OFDM signal are based on the components of the pre-distorted data vector S_{PD} ;
- transmitting the OFDM signal via an RF antenna.

Moreover, a method for transmitting pre-distorted OFDM signals according is disclosed which further comprises deriving the Doppler frequency shift according to one of the claims 12 to 14 and using the derived Doppler frequency shift in the step of pre-distorting the data vector S .

The application furthermore discloses a computer readable program for executing one of the aforementioned methods and a computer readable memory with the computer readable program.

Moreover, the application discloses one or more signal processing units, the signal processing units each comprising a microprocessor, an instruction processor and a computer readable memory, the one or more computer readable memories comprising the computer readable program. Alternatively, the one each comprise a microprocessor and a hard-wired circuit for executing one of the aforementioned methods. The computer programs, and signal processors may located be on a first and on a second communication unit in which case the word computer program/memory refers to both the first and the second communication unit.

The subject matter is now explained in further detail with respect to the following figures in which

- 5 Fig. 1 shows sub-carrier amplitudes for a sent pilot signal and for a received pilot signal in the presence of a Doppler shift,
- Fig. 2 shows frequency-amplitude diagrams for sub-channel signals of a sent signal and of a received signal
- 10 Fig. 3 shows frequency-amplitude diagrams for sub-channel signals of a sent signal and of a received signal in the presence of a Doppler shift,
- Fig. 3 shows frequency-amplitude diagrams for sub-channel signals of a sent signal and of a received signal in the presence of a Doppler shift using a pre-distorted signal,
- 15 Fig. 4 shows a communication system according to the application,
- Fig. 5 shows quadrature coordinates derived from received signals for a Doppler shift of 0.01 sub carrier distances without the use of pre-distortion,
- 20 Fig. 6 shows quadrature coordinates derived from received signals for a Doppler shift of 0.01 sub carrier distances and using pre-distortion,
- Fig. 7 shows quadrature coordinates derived from received signals for a Doppler shift of 0.05 sub carrier
- 25 Fig. 7 shows quadrature coordinates derived from received signals for a Doppler shift of 0.05 sub carrier distances without the use of pre-distortion,
- Fig. 8 shows quadrature coordinates derived from received signals for a Doppler shift of 0.05 sub carrier distances and using pre-distortion, and
- Fig. 9 shows a simplified design of a communication unit
- 30 Fig. 9 according to the application.

According to the application, a sent signal is pre-distorted based on an estimated Doppler shift. In order to estimate the

Doppler shift, a frequency shift is determined with sufficient accuracy by using the transmission of a corresponding OFDM pilot symbol. The OFDM pilot symbol uses only one sub-carrier in the centre of the signal bandwidth, whereas the other sub-carriers are set to zero. The upper diagram of Fig. 1 shows a corresponding sub-carrier occupation for a system with 64 sub-carriers. Only the sub-carrier 33 at the centre of the bandwidth is assigned to the pilot signal.

As a consequence of the Doppler shift Δf and the loss of carrier function orthogonality, the signal energy on the receiving side is distributed over the neighbouring sub-carriers. This is seen in the lower diagram of Fig. 1. At the sub carrier frequencies, the amplitude of a received signal does not correspond to a single sub-carrier amplitude. According to the application, a Doppler shift compensation is based on the amplitude of received signals, so as to make the computations independent of phase rotations caused by the communication channel. When using SI-functions as orthogonal carriers, a proportion of an amplitude S of a left-sided neighbouring carrier (34) to an amplitude S of a right sided carrier (32) is given as

$$\frac{S_{\text{left neighbour}}}{S_{\text{right neighbour}}} = r = \frac{|si(\pi(\Delta f + 1))|}{|si(\pi(\Delta f - 1))|} = \left| -\frac{\sin(\pi\Delta f)\pi(\Delta f - 1)}{\sin(\pi\Delta f)\pi(\Delta f + 1)} \right| = \frac{1 - \Delta f}{1 + \Delta f} \quad (1), \text{ which for}$$

$\Delta f \neq 1$ can be solved for the Doppler shift Δf to give

$$\Delta f = \frac{1 - r}{1 + r} \quad (2).$$

Advantageously, the maximum Doppler shift is smaller than the frequency distance between two neighbouring sub-carriers, $\Delta f < 1$.

The relationship (1) provides a one-to-one mapping for the computation of the frequency shift from the ratio of the signal amplitudes of neighbouring carriers which is easy to implement and permits an accurate determination of the frequency shift also in the presence of additive white Gaussian noise (AWGN) or other noise.

The accuracy of the method increases with the number of used sub-carriers. For evaluating more than two sub-carriers while using the same pilot signal as above, the relation (1) can be generalized by considering the second nearest neighbours:

$$\frac{S_{m-2}}{S_{m+2}} = r_2 = \frac{|si(\pi(\Delta f + 2))|}{|si(\pi(\Delta f - 2))|} = \frac{2 - \Delta f}{2 + \Delta f}$$
 which gives $\Delta f^{(2)} = 2 \cdot \frac{1 - r_2}{1 + r_2}$, wherein m is a sub-carrier number of a sub-carrier in the centre of the bandwidth. In general $\Delta f^{(n)} = n \cdot \frac{1 - r_2}{1 + r_2}$ holds for n-th nearest

neighbours of the central sub-carrier. From this relation, the Doppler shift can be computed as a weighted sum of the ratios, $\Delta f = \sum_i w_i \Delta f^{(i)} = \sum_i w_i \cdot i \cdot \frac{1 - r_i}{1 + r_i}$, with $\sum_i w_i = 1$. In one realization, $w_i = 1/N_carriers$, wherein N_carriers is the number of sub-carriers. In another realization, the weights w_i decrease with increasing distance from the central sub-carrier m.

According to a first method of determining a Doppler shift Δf for generating a pre-distortion matrix, a pilot signal is sent via a transmitter of a sending unit A to a receiver of a receiving unit B. The pilot signal uses a sub-carrier in the centre of the OFDM band and a predetermined sub-carrier amplitude, as shown in the upper diagram of Fig. 1. The receiving unit B receives a signal that is distributed over several

sub-channels, as shown in the lower diagram of Fig. 1. From the ratio r of the amplitude $S_{\text{left neighbour}}$ of the left neighbouring sub-carrier to the amplitude $S_{\text{right neighbour}}$ of the right neighbouring sub-carrier, the receiving unit B determines the Doppler shift Δf according to equation (2) and sends this information back to the sending unit A. According to a second method, the pilot signal is generated by the receiving unit B after a communication with the sending unit B has been initiated, and the ratio r is evaluated by the sending unit A.

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According to the application, a pilot signal for determination of the Doppler shift is itself not pre-distorted but, rather, the Doppler shift is determined from the distortion of the pilot signal, which is known to the receiving unit or can be computed from values that are accessible to the receiving unit.

Advantageously, the pilot symbol is transmitted regularly between the communication units for determining an accurate frequency shift. In a specific embodiment, the pilot symbol is inserted into each OFDM frame to be transmitted. According to a method for transmitting OFDM message from a sending unit A to a receiving unit B, the sending unit A sends a first message, for example a first OFDM frame, without pre-distortion. Hence, the first message may lead to a higher bit error rate than the following messages. The receiving unit B receives the first message and determines a Doppler shift from a pilot symbol that is included in the first message. The receiving unit B sends a response message, which includes the determined Doppler shift. The response message from the receiving unit B may be pre-distorted using the determined Doppler shift. The sending unit A receives the response message from the receiving unit B, stores the Doppler shift in a

computer readable memory and uses the Doppler shift to pre-distort further messages according to the Doppler shift.

In a further modification, the pilot symbol may be included
 5 only in only some of the messages. For example, the pilot symbol may be sent after a pre-determined expiry time. In another embodiment, a new determination of the Doppler-shift is started when one of the communication units determines a significant change of its movement. To determine a velocity
 10 change, position determination via a GPS, phone cell locations, acceleration sensors or other means may be used.

The first communication unit then uses the Doppler shift Δf
 15 to pre-distort a signal to be sent. In an implementation of a pre-distortion method for an OFDM communication system using IDFT/DFT (inverse discrete Fourier transform/discrete Fourier transform) according to the application, the SI-functions are replaced with the expression

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$$\frac{\sin(\pi(l-k+\Delta f))}{N \sin\left(\frac{\pi}{N}(l-k+\Delta f)\right)} \quad (3), \text{ wherein } k \text{ and } l \text{ are sub-carrier numbers}$$

and N is the number of sub-carriers. The abovementioned relation (1), which applies to the continuous Fourier transform, corresponds to the special case in which $l - k = 1$. Taking

25 into account the approximation $si(x) \approx \frac{\sin(x)}{N \sin\left(\frac{x}{N}\right)}$ for $N \gg x$ for

the sinc function $si(x)$, the abovementioned relation is also valid in the DFT case, provided the number N of sub-carriers is large enough.

According to the application, a frequency shift is determined with sufficient accuracy prior to a pre distortion of a signal to be transmitted. In one embodiment, the frequency shift is determined by using a reception of the abovementioned pilot symbol. Further embodiments comprise the use of other system information to derive a relative movement such as the computation of a relative velocity from GPS data, especially from GPS data of the receiving unit or from other position data.

By determining a relative velocity and/or Doppler shift according one of the abovementioned frequency estimation methods, the sending unit computes a pre-distorted signal.

The distortion of a signal due to the Doppler shift can be represented by an interference matrix Ξ of the size $[N \times N]$, wherein N is the number of OFDM sub-carriers, which takes the form

$$\Xi = \begin{bmatrix} \xi_{1,1} & \xi_{1,2} & \cdots & \xi_{1,N} \\ \xi_{2,1} & \xi_{2,2} & \cdots & \xi_{2,N} \\ \vdots & \vdots & \ddots & \vdots \\ \xi_{N,1} & \xi_{N,2} & \cdots & \xi_{N,N} \end{bmatrix}.$$

Herein, the elements ξ_{kl} of the interference matrix determine the interference component of the l -th sub-carrier on the k -th sub-carrier, or, in other words, the proportion of the signal from the sub-carrier l , which appears on sub-carrier k on the receiving side. When using SI-carrier functions and for a time continuous system, the components of the interference matrix Ξ and a given frequency shift Δf is computed according to

$$\xi_{k,l} = \text{si}(\pi(k-l+\Delta f)) \quad (4).$$

According to the application, the inverse $\mathbf{E}^{-1}$ of the distortion matrix $\mathbf{E}$ is computed and a data vector $\mathbf{S}$ to be sent is multiplied with the inverse matrix $\mathbf{E}^{-1}$ to obtain a pre-distorted data vector $\mathbf{S}_{PD}$, $\mathbf{S}_{PD} = \mathbf{E}^{-1} \cdot \mathbf{S}$. The inverse may be obtained by direct numerical calculation such as a variant of the Gaussian elimination algorithm or also by an iterative method, such as Jacobi iteration, conjugate gradient or others.

A modulating means of the receiving unit modulates the sub-carrier according to the pre-distorted data vector and transmits the signal over a communication channel. At the receiving unit, a corresponding signal is received. The corresponding signal can be represented as a function of the pre-distorted signal, which represents the properties of the communication channel. The receiving unit demodulates the received signal. In an idealized case in which only the Doppler shift is present or in the case in which other signal distortions are at least sufficiently small, the channel can be represented with sufficient accuracy by the distortion matrix $\mathbf{E}$, and the reconstructed data vector $\mathbf{R}$ at the receiving side is equal to the original data vector $\mathbf{S}$, $\mathbf{R} = \mathbf{E} \cdot \mathbf{S}_{PD} = \mathbf{S}$.

The sending unit and the receiving unit may comprise additional units which are not shown in Fig. 4 for simplicity, such as scrambler/descrambler, an interleaver/deinterleaver, a channel coding/decoding unit, digital analog converters (DACs), analog digital converters (ADCs), low pass filters, oscillators for generating a carrier frequency and also fur-

ther error correction means, such as the channel coding indicated in Fig. 4.

A signal pre-distortion and recovery according to the application is now illustrated with reference to the Figures 2 and 3, wherein Fig. 3 shows the use of a pre-distortion according to the application. In the examples of Fig. 2 and 3, the OFDM system uses four sub-carriers and the data symbols are modulated by an amplitude modulation. The components of the data symbol S can also be used as the in-phase or quadrature components of QAM modulations. In this case, the data symbol S represents only half of the information while the other half is transmitted via the respective other components of the QAM modulation. In the example shown in Figs. 2 and 3, the relative movement is such that a Doppler shift of 0.4 sub-carrier distances results. The amplitudes of the sent and of the received signal at the sub channels are indicated by arrows.

By way of example it is assumed that the data symbol $S = [3 \ 1 \ 1 \ 3]'$ is to be transmitted, in which the components correspond to sub carrier amplitudes, which are numbered by the indices 0, 1, 2, 3. Amplitudes of the amplitude modulation corresponding to discrete values are indicated in Figs. 2 and 3 in arbitrary units on the Y-axis and by corresponding horizontal lines. Likewise, the sub-carrier frequencies are indicated in arbitrary units on the X-axis and by corresponding vertical lines. A signal is represented by the sum of the four frequency curves as shown in the lower diagrams of Figs. 2 and 3.

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For comparison, the communication system without use of the pre-distortion is considered first. Under the assumption that

there is substantially only the Doppler shift $\Delta f = 0.4$, the interference between sub-carrier signals can be represented by an interference matrix $\mathbf{E}$ with the following components:

$$\mathbf{E} = \begin{bmatrix} 0.67 & 0.50 & -0.19 & 0.12 \\ -0.22 & 0.76 & 0.50 & -0.19 \\ 0.13 & -0.22 & 0.76 & 0.50 \\ -0.09 & 0.13 & -0.22 & 0.76 \end{bmatrix}$$

The resulting received signal is shown in the lower diagram of Fig. 2 in which the received signal, which is given by the sum of the individual signals from the four carriers, is indicated by a thick line. Accordingly, the following distorted data vector is derived from the demodulated signal:

$$\mathbf{S} = [2.93 \quad 0.05 \quad 2.43 \quad 1.91]'$$

It can be seen in Fig. 2 and also in the Fig. 7 that a reconstruction of the original data vector becomes difficult to impossible for Doppler shifts of this size if the frequency shift Δf is not determined: the positions at which one of the sub-carrier signals has the maximum amplitude and the other three sub-carrier signals are zero are shifted by the frequency shift Δf which is not known to the receiving unit. Hence, a receiving unit will still evaluate the sum signal at the sub-carrier frequencies at which the amplitude cannot be attributed uniquely to a sub-carrier signal.

According to the application, the sending unit generates a pre-distorted symbol by multiplying the symbol to be sent with the inverse of the interference matrix. Thereby, a symbol $\mathbf{S}_{PD} = [1.39 \quad 2.89 \quad -0.43 \quad 3.52]'$ is obtained which is modulated and sent over the communication channel via a transmission antenna. The communication channel is assumed to be the same

Doppler channel as above, which is characterized by the interference matrix Ξ . The upper diagram of Fig. 3 shows a frequency-amplitude diagram that represents the sent signal and the lower diagram shows a frequency-amplitude diagram that represents the received signal. As can be seen in the upper diagram, the amplitudes of the received signal coincide with amplitudes of the original signal at the positions of the four sub-carrier frequencies. The receiving unit uses the detected amplitudes at the sub-carrier frequencies to recover the original data vector $\mathbf{S}$.

In contrast to an alternative method that uses a reverse shift by Δf of the sent signal by the frequency shift, a method according to the application is technically easier to realize as it can be done by simply adjusting the signal amplitude at the sending unit and it does not require a rescaling of pulse lengths or a tuning of oscillator frequencies.

In a further embodiment, a system according to the application comprises a digital (time discrete) signal processing system. The sender comprises an IDFT unit for executing an inverse discrete Fourier transform and the receiving unit comprises a DFT unit for executing a discrete Fourier transform. In a QAM realization of OFDM, the real part and imaginary parts of the IDFT input values and the DFT output values represent in-phase and quadrature amplitudes. As is known for OFDM, the IDFT is used to transform the QAM components for the N sub-carriers into a time dependent complex valued signal, the real and imaginary part are converted into analog signals and up-converted into two 90° phase shifted signals. Herein, complex values are interpreted in the usual way by identifying phase and amplitude in the complex plane as phase and amplitude of a signal or of a digital representation of

the signal. In a known way, the process is reversed at the receiver.

The DFT is represented with complex valued exponential functions $\exp(x + jy)$, wherein $\exp(x + jy) = \exp(x) * (\cos(y) + j \sin(y))$ and $j = \sqrt{-1}$. Correspondingly, the interference matrix also comprises complex valued exponential functions. More specifically, the elements of the interference matrix are given by the sinc function or by the function (3) as before, but in addition they are multiplied by a complex exponential function. This is explained below in further detail.

By way of example, a data vector to be sent is given by the vector $s = [s_0 \ s_1 \ \dots \ s_{N-1}]'$. The DFT is represented by the matrix

$$\mathbf{F} = \begin{bmatrix} e^{-j2\pi \frac{0 \cdot 0}{N}} & e^{-j2\pi \frac{0 \cdot 1}{N}} & \dots & e^{-j2\pi \frac{0 \cdot (N-1)}{N}} \\ e^{-j2\pi \frac{1 \cdot 0}{N}} & e^{-j2\pi \frac{1 \cdot 1}{N}} & \dots & e^{-j2\pi \frac{1 \cdot (N-1)}{N}} \\ \vdots & \vdots & \ddots & \vdots \\ e^{-j2\pi \frac{(N-1) \cdot 0}{N}} & e^{-j2\pi \frac{(N-1) \cdot 1}{N}} & \dots & e^{-j2\pi \frac{(N-1) \cdot (N-1)}{N}} \end{bmatrix} \quad \text{and the IDFT is represent-}$$

ed by the Hermitian transpose $\mathbf{F}^*$ (complex conjugate transpose) of the matrix $\mathbf{F}$. A signal $\mathbf{t}$ to be transmitted is represented by the relation $\mathbf{t} = \mathbf{F}^* \cdot \mathbf{S}$, wherein the N components of $\mathbf{t}$ define modulation parameters for the N sub-carriers. For the DFT, the matrix $\mathbf{F}$ is multiplied by a normalization factor of $1/N$. The normalization factor $1/N$ can also be attributed to the IDFT or a normalization factor of $1/\sqrt{N}$ can be attributed to both the DFT and the IDFT.

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Under the assumption that the communication channel causes a phase rotation θ and a Doppler frequency shift of Δf to a signal, wherein the Doppler shift is represented in units of

the sub-carrier distance, the communication channel can be represented by a diagonal channel matrix $\mathbf{H}$ with the following elements

$$\mathbf{H} = \begin{bmatrix} e^{-j2\pi\left(\frac{0\Delta f}{N}+\theta\right)} & 0 & \dots & 0 \\ 0 & e^{-j2\pi\left(\frac{1\Delta f}{N}+\theta\right)} & \dots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \dots & e^{-j2\pi\left(\frac{(N-1)\Delta f}{N}+\theta\right)} \end{bmatrix}$$

$$= \text{diag}\left(e^{-j2\pi\left(\frac{0\Delta f}{N}+\theta\right)} \quad e^{-j2\pi\left(\frac{1\Delta f}{N}+\theta\right)} \quad \dots \quad e^{-j2\pi\left(\frac{(N-1)\Delta f}{N}+\theta\right)}\right)$$

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The diagonal channel matrix $\mathbf{H}$ can be represented as a product of a diagonal matrix $\mathbf{H}_D$ and a diagonal matrix $\mathbf{H}_P$ which represent the Doppler shift and the phase shift, respectively, and which have the following elements:

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$$\mathbf{H}_D = \begin{bmatrix} e^{-j2\pi\left(\frac{0\Delta f}{N}\right)} & 0 & \dots & 0 \\ 0 & e^{-j2\pi\left(\frac{1\Delta f}{N}\right)} & \dots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \dots & e^{-j2\pi\left(\frac{(N-1)\Delta f}{N}\right)} \end{bmatrix}$$

$$= \text{diag}\left(e^{-j2\pi\left(\frac{0\Delta f}{N}\right)} \quad e^{-j2\pi\left(\frac{1\Delta f}{N}\right)} \quad \dots \quad e^{-j2\pi\left(\frac{(N-1)\Delta f}{N}\right)}\right)$$

$$\mathbf{H}_P = \begin{bmatrix} e^{j2\pi\theta} & 0 & \dots & 0 \\ 0 & e^{j2\pi\theta} & \dots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \dots & e^{j2\pi\theta} \end{bmatrix} = e^{j2\pi\theta} \mathbf{1}.$$

The received signal $\mathbf{r}$ is given by the relation

15 $\mathbf{r} = \mathbf{H}_D \cdot \mathbf{t} \cdot e^{j2\pi\theta} = \mathbf{H}_D \cdot \mathbf{F}^* \cdot \mathbf{S} \cdot e^{j2\pi\theta}$ and the received symbol is given by

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$\mathbf{R} = \frac{1}{N} \mathbf{F} \cdot \mathbf{r} = \mathbf{S} \cdot \frac{1}{N} \cdot \mathbf{F} \cdot \mathbf{H}_D \cdot \mathbf{F}^* e^{j2\pi\theta}$. Hence, the interference matrix Ξ

is given by the product $\Xi = \frac{1}{N} \cdot \mathbf{F} \cdot \mathbf{H}_D \cdot \mathbf{F}^*$.

The components $\xi_{m,n}$ von Ξ are computed according to

$$\xi_{k,l} = \frac{1}{N} \cdot \sum_{n=0}^{N-1} e^{j2\pi \frac{n}{N}(k-l+\Delta f)} = \frac{\sin(\pi(l-k+\Delta f))}{N \sin\left(\frac{\pi}{N}(l-k+\Delta f)\right)} e^{j\pi\left(1-\frac{1}{N}\right)(l-k+\Delta f)} \quad (5)$$

- 5 With the definition of m as carrier distance $l-k$, the interference can be brought into the symmetric form:

$$\Xi = \begin{bmatrix} \xi_0 & \xi_1 & \cdots & \xi_{N-1} \\ \xi_{-1} & \xi_0 & \cdots & \xi_{N-2} \\ \vdots & \vdots & \ddots & \vdots \\ \xi_{-N+1} & \xi_{-N+2} & \cdots & \xi_0 \end{bmatrix}, \text{ wherein}$$

$$\xi_m = \frac{1}{N} \cdot \sum_{n=0}^{N-1} e^{j2\pi \frac{n}{N}(m+\Delta f)} = \frac{\sin(\pi(m+\Delta f))}{N \sin\left(\frac{\pi}{N}(m+\Delta f)\right)} e^{j\pi\left(1-\frac{1}{N}\right)(m+\Delta f)} \quad (6).$$

10

The receiving unit computes the pre-distorted data vector using the interference matrix according to the relation

$\mathbf{S}_{PD} = \Xi^{-1} \cdot \mathbf{S}$. Under the abovementioned assumption that the communication channel causes only a Doppler distortion and a

- 15 phase shift and provided that the relative velocity has not changed significantly since the last determination, the reconstructed data vector $\mathbf{R}$ is equal to the sent data vector $\mathbf{S}$ times a phase factor $\exp(j 2\pi\theta)$ that is due to a phase rotation $2\pi\theta$,

20

$$\mathbf{R} = \mathbf{S}_{PD} \cdot \mathbf{H} = \Xi^{-1} \cdot \mathbf{S} \cdot \mathbf{F} \cdot \mathbf{H} \cdot \mathbf{F}^* = \mathbf{S} \cdot e^{j2\pi\theta}.$$

The phase rotation is corrected for using a known method, for example based on pilot sub-carriers. The term "pilot sub-carrier" refers to the sub-carrier that is used for sending a pilot signal to determine the phase shift. The pilot sub-carrier may also be used for sending a pilot signal to determine the Doppler shift according to the invention.

Fig. 4 shows a flow diagram of an OFDM communication unit 10 according to the application. The communication unit 10 comprises a transmitter 11 and a receiver 12 for sending and receiving messages via a communication channel 13 to another communication unit, which is not shown in Fig. 4. The other communication unit may be of the type shown in Fig. 4 or also of the simpler type shown in Fig. 9, for example.

In the transmitter 11, a data source 14 is connected to an input of a channel coding and interleaving unit 15. An output of the channel coding and interleaving unit 15 is connected to an input of a symbol mapper 16. An output of the symbol mapper 16 is connected to an input of a channel estimation and pilot signal insertion unit 17 and an output of the channel estimation and pilot signal estimation unit 17 is connected to a Doppler pre-distortion unit 18. An output of the Doppler pre-distortion unit 18 is connected to an input of a multiplexer 19. A further input of the multiplexer 19 is connected to a Doppler pilot signal generation unit 20. An output of the multiplexer 19 is connected to an input of an OFDM modulator 21 and an output of the OFDM modulator 21 is connected to an input of an RF transmitter 22, which comprises a RF transmitter antenna.

In the receiver 12 of the communication unit 10, an output of an RF receiver 23 is connected to an input of an OFDM demodu-

lator 24. An output of the OFDM demodulator is connected to an input of a de-multiplexer 25. An output of the de-multiplexer 25 is connected to a channel correction unit 26. A further output of the de-multiplexer 25 is connected to a Doppler estimation unit 27. An output of the channel correction unit 26 is connected to an input of a symbol demapper 28. An output of the symbol demapper 28 is connected to an input of a channel decoding and deinterleaving unit 29. An output of the channel decoding and deinterleaving unit 29 is connected to a data sink 30. The receiver 12 may comprise further components such as a phase locked loop and an adaptive equalizer.

In this embodiment, the Doppler estimation unit is connected the Doppler pre-distortion unit. However, the Doppler estimation unit may also be connected to the multiplexer for sending the value of the estimated Doppler frequency back to a second communication unit. The communication unit may also be realized without a Doppler pre-distortion unit 18 and without the Doppler pilot signal generation unit 20. This is shown in Fig. 9. The pre-distortion is then provided by a second communication unit, for example a base station, to which the communication unit 10 is connected via the channel 13.

A computation of the pre-distortion matrix E^{-1} requires the computation of an inverse of the $[N \times N]$ matrix E and in general is computationally expensive. Therefore, in a further modification, pre-computed pre-distortion matrices or elements thereof are computed for various frequency shifts and are stored in look-up tables of the sending unit. Pre-distortion matrices for intermediate values of frequency shifts may be determined by interpolation of the pre-computed pre-distortion matrices.

According to the application, the receiving unit only needs to comprise an additional functionality for estimating the Doppler shift or the relative velocity and does not need to include further additional functionality. Thus, the adaptation of existing receiving units and the use of inexpensive receiving units is facilitated. The use of pilot signals makes efficient use of the bandwidth as compared to known correction methods, such as for example the cancelling out of interferences by transmission of inverse signals on neighbouring sub-carrier frequencies.

The following Figs. 5 to 8 show data obtained from an OFDM-system with 64 sub-carriers and using a 16-QAM (quadrature amplitude) modulation of data symbols. The abovementioned pre-distortion method is based on an adaptation of the sub-carrier amplitudes. Hence, it also applies to a QAM modulation or other modulation methods using amplitude as well as phase values. The data symbols are represented preferentially by discrete values but may also comprise continuous values, as in continuous QAM.

In Figs. 5 to 8, the horizontal axis represents an "in-phase" coordinate and the vertical axis represents a "quadrature" coordinate which can be regarded as amplitudes of a sine and a cosine oscillation that are superposed to obtain a signal of an RF transmitter. Especially when many sub-carriers are used it is advantageous, however, to use QAM coordinates, that are generated by the symbol mapper 16, to derive an input signal to an IDFT calculation unit within an OFDM modulator 21, as in the embodiment of Fig. 4.

The circles in Figs. 5 to 8 represent received signals corresponding to a sent data symbol. The grid lines form a square grid around the discrete QAM amplitude and phase values. If the amplitude and phase pairs of received data symbols lie within the corresponding squares, they can be attributed uniquely to a QAM amplitude. Otherwise, bit errors will result.

It can be seen from Fig. 7 that in an OFDM system without pre-distortion or other frequency corrections, already at a Doppler shift of $\pm 5\%$ of the sub carrier distance, some of the circles lie outside the squares. Therefore, bit errors are to be expected. Especially for larger Doppler shifts, the bit errors eventually become so large that they cannot be compensated for by standard error correction methods. By contrast, the pre-distortion method according to the application allows an exact reconstruction of the sent symbol, as can be seen in Figs. 6 and 8. Even for frequency shifts as high as half the sub-carrier distance, the sent symbol will be received correctly.

Fig. 9 shows a simpler embodiment of a communication unit that does not comprise the Doppler pilot signal generation unit 20 and the Doppler pre-distortion unit 18 shown in Fig. 4. In this case, the Doppler pilot signal generation unit 20 and the Doppler pre-distortion unit 18 are provided by another communication unit, for example the communication unit 10 shown in Fig. 4. Advantageously, the other communication unit is dedicated for downlink traffic, such as a radio base station.

Fig. 10 shows a communication system comprising a first communication unit 10 and a second communication unit 10' ac-

according to the application. OFDM frames belonging to OFDM messages from communication unit 10 to communication unit 10' are indicated by rectangles 37 and OFDM frames belonging to OFDM messages from communication unit 10' to communication unit 10 are indicated by rectangles 38. The communication units 10, 10' comprise signal processing units 35, 35' respectively. The signal processing unit 35, 35' comprise components for processing and evaluating the OFDM frames, as shown in Fig. 4 or Fig. 9. In a modification, the same antenna is used as RF transmitter 22 and as RF receiver 23. If different antennas are used for transmitting and receiving, the communication units 10, 10' may be adapted not to transmit during reception of a Doppler pilot signal.

15 In an alternative embodiment, just a one way traffic of OFDM data packets 37 from the communication unit 10 to the communication unit 10' is provided and the Doppler shift estimate is transmitted back from the communication unit 10' to the communication unit 10 by other means, for example by a further modulation technique such as AM, QAM etc. and/or by a further communication channel.

20

The embodiments can also be described with the following lists of elements being organized into items. The respective combinations of features which are disclosed in the item list are regarded as independent subject matter, respectively, that can also be combined with other features of the application.

1. Transmitter for generating an OFDM signal comprising
a Doppler pre-distortion unit with an input section
10 for receiving a data vector S ,
an OFDM modulator,
a Doppler Shift memory location for readably storing a pre-determined Doppler Shift value,
wherein the Doppler pre-distortion unit is adapted to
15 generate a pre-distorted data vector S_{PD} from the data vector S ,
wherein the components of the pre-distorted vector S_{PD} and of the data vector S represent data symbols,
wherein the pre-distorted data vector S_{PD} is a linear
20 function of the data vector S ,
wherein the linear function is dependent on the Doppler shift value, and
wherein the OFDM modulator is adapted to generate an OFDM signal such that sub-carrier amplitudes of the OFDM
25 signal are based on the components of the pre-distorted data vector S_{PD} .
2. Transmitter according to item 1 further comprising
a Doppler pilot signal generation unit which is adapted
30 to generate a Doppler pilot signal on a sub carrier.
3. Transmitter according to item 1 or 2, wherein

the Doppler pre-distortion unit is adapted to derive the linear function of the data vector S from one or more look-up tables which are selected according to the Doppler shift value.

5

4. Transmitter according to one of the previous items, wherein

the Doppler pre-distortion unit is adapted to store the Doppler shift value as a pre-distortion matrix and derive the linear function of the data vector S from the pre-distortion matrix.

10

5. Transmitter according to one of the previous items, wherein

the Doppler pre-distortion unit is adapted to derive the pre-distorted vector S_{PD} from a sum of the linear function and one or more non-linear correction terms.

15

6. Transmitter according to one of the previous items further comprising
a Pilot Insertion unit for inserting the Doppler Pilot signal into an OFDM data frame.

20

7. Transmitter according to one of the previous items further comprising

25

a multiplexer and
an OFDM modulator,

30

wherein the multiplexer is connected to the Doppler pre-distortion unit and the OFDM modulator is connected to the multiplexer, the OFDM modulator comprising an IDFT calculation unit which is adapted to generate an IDFT of the pre-distorted data vector S_{PD} , and

wherein the OFDM modulator is further adapted to generate an OFDM signal based on output of the IDFT calculation unit.

- 5 8. Receiver for receiving OFDM signals comprising
 an RF receiver,
 a demodulator that is connected to the RF receiver,
 a demultiplexer that is connected to the demodulator, and
10 a Doppler estimation unit that is connected to the demultiplexer,
 wherein the Doppler estimation unit is adapted to generate an estimate of a Doppler shift based on amplitudes of a received OFDM signal at sub-carrier frequencies,
15 the sub-carrier frequencies being frequencies of sub-carriers that are neighbours to a pilot sub-carrier frequency.
9. Receiver according to item 8, wherein
20 the pilot sub-carrier frequency is at the centre of an OFDM frequency band.
10. OFDM communication unit comprising
 a transmitter according to one of items 1 to 7 and
25 a receiver according to one of items 8 to 9.
11. OFDM communication system comprising
 a first communication unit which comprises at least
 a transmitter according to one of the item 1 to 7 and
30 a second communication unit comprising at least a receiver according to one of the items 8 to 9.

12. Method for transmitting and processing a Doppler pilot signal comprising
- generating a pilot signal with a predefined sub-carrier amplitude, wherein the pilot signal uses a pilot sub-carrier, the pilot sub-carrier being chosen from a plurality of OFDM sub-carriers,
 - sending the pilot signal of a first communication unit over a communication channel to a second communication unit,
 - receiving the pilot signal and evaluating signal amplitudes on sub-carrier frequencies, the sub-carrier frequencies being frequencies of neighbours of the pilot sub carrier, and
 - determining a Doppler frequency shift from the signal amplitudes.
13. Method for transmitting and processing a Doppler pilot signal according to item 12, the generation of the pilot signal further comprising
- inserting a Doppler pilot symbol into an OFDM frame to be transmitted, and
 - generating the Doppler pilot symbol according to the Doppler pilot symbol.
14. Method for estimating a Doppler frequency shift of a relative movement between a first OFDM communication unit and a second OFDM communication unit, comprising
- deriving an estimated relative velocity of the second OFDM communication unit,
 - deriving a magnitude of a Doppler shift from the estimated relative velocity,

- transmitting the magnitude of the Doppler shift to the first OFDM communication unit over a communication channel, and
 - storing the magnitude of the Doppler shift into a computer readable memory of the first communication unit.
- 5
15. Method for estimating a Doppler frequency shift according to item 14, wherein
- 10 the step of deriving the estimated velocity comprises the steps of transmitting and processing a Doppler pilot signal according to one of the items 12 to 13.
16. Method for estimating a Doppler frequency shift according to item 14, wherein
- 15 the step of deriving the estimated velocity comprises deriving the estimated velocity from location signals, the location signals being received via an RF receiver of the second communication unit.
- 20
17. Method for transmitting pre-distorted OFDM signals over a communication channel, the method comprising
- receiving input data from a data source,
 - deriving a data vector S from the input data,
 - pre-distorting the data vector S to obtain a pre-distorted data vector S_{PD} , wherein the step of pre-distorting comprises obtaining the pre-distorted data vector S_{PD} as a linear function of the data vector wherein the linear function of the data vector S depends on a Doppler frequency shift,
 - deriving an OFDM signal from the pre-distorted data vector S_{PD} , wherein sub-carrier amplitudes of the
- 25
- 30

OFDM signal are based on the components of the pre-distorted data vector S_{PD} , and

- transmitting the OFDM signal via an RF antenna.

- 5 18. Method for transmitting pre-distorted OFDM signals according to item 17 further comprising
- deriving the Doppler frequency shift according to one of the items 12 to 14 and
 - using the derived Doppler frequency shift in the
- 10 step of pre-distorting the data vector S .
19. Computer readable program for executing a method according to one of the items 12 to 18.
- 15 20. Computer readable memory with a computer readable program according to item 19.
21. One or more signal processing units, the signal processing units each comprising
- 20
- a microprocessor,
 - an instruction processor, and
 - a computer readable memory, the one or more computer readable memories comprising a computer readable program according to item 19.
- 25
22. One or more signal processing units, the signal processing units each comprising
- a microprocessor and
 - a hard-wired circuit for executing a method according to one of the items 12 to 18.
- 30

Patent claims

1. Transmitter for generating an OFDM signal comprising
5 a Doppler pre-distortion unit with an input section
 for receiving a data vector S ,
 an OFDM modulator,
 a Doppler Shift memory location for readably storing
 a pre-determined Doppler Shift value,
10 wherein the Doppler pre-distortion unit is adapted to
 generate a pre-distorted data vector S_{PD} from the data
 vector S ,
 wherein the components of the pre-distorted vector S_{PD}
 and of the data vector S represent data symbols,
15 wherein the pre-distorted data vector S_{PD} is a linear
 function of the data vector S ,
 wherein the linear function is dependent on the Doppler
 shift value, and
 wherein the OFDM modulator is adapted to generate an
20 OFDM signal such that sub-carrier amplitudes of the OFDM
 signal are based on the components of the pre-distorted
 data vector S_{PD} .
2. Transmitter according to claim 1 further comprising
25 a Doppler pilot signal generation unit which is adapted
 to generate a Doppler pilot signal on a sub carrier.
3. Transmitter according to claim 1, wherein
30 the Doppler pre-distortion unit is adapted to derive the
 linear function of the data vector S from one or more
 look-up tables which are selected according to the Dop-
 pler shift value.

4. Transmitter according to claim 1, wherein
the Doppler pre-distortion unit is adapted to store the
Doppler shift value as a pre-distortion matrix and de-
rive the linear function of the data vector S from the
pre-distortion matrix.
5. Transmitter according to claim 1, wherein
the Doppler pre-distortion unit is adapted to derive the
pre-distorted vector S_{PD} from a sum of the linear func-
tion and one or more non-linear correction terms.
6. Transmitter according to claim 1 further comprising
a Pilot Insertion unit for inserting the Doppler Pilot
signal into an OFDM data frame.
7. Transmitter according to claim 1 comprising
a multiplexer and
an OFDM modulator,
wherein the multiplexer is connected to the Doppler pre-
distortion unit and the OFDM modulator is connected to
the multiplexer, the OFDM modulator comprising an IDFT
calculation unit which is adapted to generate an IDFT of
the pre-distorted data vector S_{PD} , and
wherein the OFDM modulator is further adapted to gener-
ate an OFDM signal based on output of the IDFT calcula-
tion unit.
8. Receiver for receiving OFDM signals comprising
an RF receiver,
a demodulator that is connected to the RF receiver,
a demultiplexer that is connected to the demodula-
tor, and

a Doppler estimation unit that is connected to the demultiplexer,
wherein the Doppler estimation unit is adapted to generate an estimate of a Doppler shift based on amplitudes
5 of a received OFDM signal at sub-carrier frequencies,
the sub-carrier frequencies being frequencies of sub-carriers that are neighbours to a pilot sub-carrier frequency.

- 10 9. Receiver according to claim 8, wherein
the pilot sub-carrier frequency is at the centre of an
OFDM frequency band.
10. OFDM communication unit comprising
15 a transmitter according to claim 1 and
a receiver according to one claim 8.
11. OFDM communication system comprising
a first communication unit which comprises at least
20 a transmitter according to one of the claim 1 to 7 and
a second communication unit comprising at least a
receiver according to claim 8.
12. Method for transmitting and processing a Doppler pilot
25 signal comprising
- generating a pilot signal with a predefined sub-carrier amplitude, wherein the pilot signal uses a pilot sub-carrier, the pilot sub-carrier being chosen from a plurality of OFDM sub-carriers,
 - 30 - sending the pilot signal of a first communication unit over a communication channel to a second communication unit,

- receiving the pilot signal and evaluating signal amplitudes on sub-carrier frequencies, the sub-carrier frequencies being frequencies of neighbours of the pilot sub carrier, and
 - 5 - determining a Doppler frequency shift from the signal amplitudes.
13. Method for transmitting and processing a Doppler pilot signal according to claim 12,
- 10 the generation of the pilot signal further comprising
- inserting a Doppler pilot symbol into an OFDM frame to be transmitted, and
 - generating the Doppler pilot symbol according to the Doppler pilot symbol.
- 15
14. Method for estimating a Doppler frequency shift of a relative movement between a first OFDM communication unit and a second OFDM communication unit, comprising
- deriving an estimated relative velocity of the second OFDM communication unit,
 - 20 - deriving a magnitude of a Doppler shift from the estimated relative velocity,
 - transmitting the magnitude of the Doppler shift to the first OFDM communication unit over a communication channel, and
 - 25 - storing the magnitude of the Doppler shift into a computer readable memory of the first communication unit.
- 30 15. Method for estimating a Doppler frequency shift according to claim 14, wherein

the step of deriving the estimated velocity comprises the steps of transmitting and processing a Doppler pilot signal according to claim 12.

- 5 16. Method for estimating a Doppler frequency shift according to claim 14, wherein
the step of deriving the estimated velocity comprises deriving the estimated velocity from location signals, the location signals being received via an RF receiver
10 of the second communication unit.
17. Method for transmitting pre-distorted OFDM signals over a communication channel, the method comprising
- receiving input data from a data source,
 - 15 - deriving a data vector S from the input data,
 - pre-distorting the data vector S to obtain a pre-distorted data vector S_{PD} , wherein the step of pre-distorting comprises obtaining the pre-distorted data vector S_{PD} as a linear function of
20 the data vector wherein the linear function of the data vector S depends on a Doppler frequency shift,
 - deriving an OFDM signal from the pre-distorted data vector S_{PD} , wherein sub-carrier amplitudes of the OFDM signal are based on the components of the pre-distorted data vector S_{PD} , and
25 - transmitting the OFDM signal via an RF antenna.
18. Method for transmitting pre-distorted OFDM signals according to claim 17 further comprising
- 30 - deriving the Doppler frequency shift according to claim 12 and
 - using the derived Doppler frequency shift in the step of pre-distorting the data vector S .

19. Computer readable program for executing a method according to claim 12.
- 5 20. Computer readable memory with a computer readable program according to claim 19.
21. One or more signal processing units, the signal processing units each comprising
- 10 - a microprocessor,
- an instruction processor, and
- a computer readable memory, the one or more computer readable memories comprising a computer readable program according to claim 19.
- 15 22. One or more signal processing units, the signal processing units each comprising
- a microprocessor and
- 20 - a hard-wired circuit for executing a method according to claim 12.