



Methods and Apparatus for Receiving OFDM Signals

Field of the Invention



G00002

5 This invention relates to a receiver for Orthogonal Frequency Division Multiplexing (OFDM) signals, such as one for use in cellular wireless communication systems or wireless local area loops (WLAN). In particular, it relates to receivers employing novel methods for carrier frequency offset and channel parameter estimations over multipath fading channels. It further relates
10 to those methods, and to communication systems including the receivers.

Background of the Invention

Orthogonal Frequency Division Multiplexing (OFDM) is a promising
15 transmission technology for very high-speed information transfer. It is already used in digital television broadcasts (DTVB) and wireless local area networks (WLAN). OFDM has also been proposed for fourth generation (4G) wireless communication systems and wireless asymmetric transport mode (wireless ATM).

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A model of some components of a known OFDM communication system is shown in Fig.1. Fig. 1(a) shows the structure of an OFDM transmitter. Input data $S(n)$ (where n is an integer variable having a respective value for each symbol) to be transmitted is input (from the left of Fig. 1(a)) to a serial to parallel
25 converter 1 to generate M parallel signals $S_1(n), \dots, S_M(n)$. These signals are passed to an M -point Inverse Discrete Fourier transform (IDFT) 3. The output $f(n)$ is transmitted to a unit 7 which adds a cyclic prefix. The result is then passed to a transmission unit 9 (e.g. a radio transmission unit in the case that the signal is to be transmitted by radio). Fig. 1(b) shows schematically how the
30 transmitted signal (input from the left of Fig. 1(b)) is subject to a multipath channel, and to added noise. The result is received by a receiver (not shown in Fig. 1) as a serial signal $y(n)$.

The receiver uses a serial parallel converter to remove any cyclic prefix and convert the received signal $y(n)$ to M parallel signals $y_1(n), \dots, y_M(n)$, which we also refer to here as $\mathbf{y}(n)$. It then subjects the result to an M -point discrete
 5 Fourier transform (DFT), and then performs channel equalisation using an equaliser.

According to the principle of OFDM, the multipath channel can be modelled as M flat-fading channels in the frequency-domain after the DFT. Therefore the
 10 equalizer can equalize the equivalent channels, assuming that it knows the complex amplitudes of the equivalent channels (here called "channel parameters"). The cyclic prefix can handle the cyclic convolution effect when the signal passes through a frequency-selective multi-path channel.

15 The receiver conventionally includes two independent units for respectively estimating the "carrier frequency offset" and the channel parameters. The carrier frequency offset means the frequency difference between the Inverse Discrete Fourier Transform (IDFT) in the transmitter and the Discrete Fourier Transform (DFT) in the receiver. It has respective values for all M carriers, but
 20 all depend on a single carrier frequency offset value ϕ . The carrier frequency offset is caused by the Doppler shift during signal transmission and the different oscillators in the transmitter and receiver. The carrier frequency offset estimation provides difference information which is input to the DFT so that the errors can be removed during the DFT process.

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The channel estimator is responsible for estimating the channel parameters and providing the information to the equalizer.

We now introduce a mathematical representation of the process in the receiver.
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The received signal $\mathbf{y}(n) \in \mathbb{C}^{M \times 1}$ can be denoted as

$$\mathbf{y}(n) = \mathbf{E}\mathbf{W}\mathbf{H}\mathbf{s}(n)e^{j\phi(n+1)(M+N_c)} + \mathbf{\xi}(n) \quad (1)$$

where

$$\mathbf{E} = \text{diag}[1, e^{j\phi}, \dots, e^{j(M-1)\phi}] \in C^{M \times M} \quad (2)$$

is the carrier frequency offset matrix and ϕ is the carrier frequency offset. The term $\text{diag}[\]$ means a diagonal matrix having as its entries the elements in the square bracket. N_c is the length of cyclic prefix. $\mathbf{W}$ is the IDFT matrix. Each of its elements, corresponding to the l th row and m th column, is given by

$$e^{-j2\pi ml/M}.$$

$$\mathbf{H} = \text{diag}[h(0), \dots, h(M-1)]$$

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is the flat-fading channel parameter matrix, $\mathbf{s}(n)$ is a data transmitted in block n (i.e. the n th Serial-to-Parallel converting), and $\mathbf{\xi}(n) \in C^{M \times 1}$ is an additive Gaussian noise vector.

20 The function of the carrier frequency offset estimation is thus to estimate $\mathbf{E}$, so that its effects can be removed. Similarly, the function of the channel estimation is to estimate $\mathbf{H}$, so that its effects can be removed.

In known systems (e.g. [1], [2], [3], [4]) the carrier frequency offset is estimated without knowledge of the channel parameters, and used to estimate the channel parameters. The carrier frequency offset and channel parameters must be known before detecting the information data.

Summary of the invention

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The present invention aims to provide new and useful methods for estimating OFDM carrier frequency offset and channel parameters, and new and useful OFDM receivers.

5 In general terms, the present invention proposes that carrier frequency offset estimation and channel estimation are performed in tandem, so that the two estimations are joint-optimised with respect to the data. All of the carrier frequency offset and channel parameters are variables of a maximum likelihood cost function. If we consider them together and carry out joint estimates for
10 carrier frequency offset and channel parameters, the solution of the cost function will be the optimal solution. In other words, we can achieve an optimal estimation for carrier frequency offset and channel parameters. The performance is better than the conventional technique of estimating carrier frequency offset and using that to estimate the channel parameters.

15 Furthermore, to reduce algorithmic complexity, we propose an iterative optimisation scheme which includes repeatedly carrying out a sequence of two steps: (i) estimating the carrier frequency offset and (ii) estimating the channel parameters. In each step (i), the last estimated channel parameters are used to
20 improve the carrier frequency offset estimation. In each step (ii), the last estimated value for the carrier frequency offset is used to estimate the channel parameters. By this method, an optimal solution to both carrier frequency offset and channel parameter can be achieved, so the estimation performances for frequency offset and channel parameters are better than if they are estimated
25 independently. However, the complexity of the iterative method in each iteration is low (since there is one-dimensional searching in each iteration), so the algorithm complexity is much lower than that of multi-dimensional searching in maximum likelihood optimisation problems. A similar result can be found in [5].

30 Specifically, a first expression of the invention is a method, for use in an OFDM receiver, of estimating carrier frequency offset values and one or more

transmission channel parameters from received OFDM signals, the method including:

using the received signals to estimate a carrier frequency offset value and/or channel parameters; and

5 at least once performing the sequence of steps:

(i) using the received signals and previously estimated carrier frequency offset value to estimate the channel parameters; and

(ii) using the received signals and previously estimated channel parameters to estimate the carrier frequency offset value.

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A second expression of the invention is an OFDM receiver including:

a first portion for receiving OFDM signals and generating reconstructed messages, the first portion being arranged to employ carrier frequency offset values and one or more channel parameters;

15 a second portion for estimating carrier frequency offset values and one or more transmission channel parameters from received OFDM signals, the second portion including:

a carrier frequency offset estimation unit arranged to receive the signals and to estimate the carrier frequency offset, and

20 a channel parameters estimation unit arranged to receive the signals and an output of the carrier frequency offset estimation unit, to estimate the channel parameters, and to transmit its output to the carrier frequency offset estimation unit.

25 In either expression of the invention, the estimations may be performed based on received signals including a plurality of known training OFDM symbols (a "training sequence"). The method is suitable when the training sequence is a series of pseudo-random OFDM symbols..

30 Iterative optimisation techniques are known to be subject to convergence problems, in which for example they converge to a local minimum of a cost function, rather than to an absolute minimum. For that reason, the present

iteration method preferably includes adding random perturbations to one of the estimates obtained (preferably the estimate of the carrier frequency offset), and seeing whether the perturbed estimate actually leads to an improved cost function (i.e. on the next occasion that the cost function is calculated in the iterative scheme). If so, the perturbed estimate can be used in place of the unperturbed estimate. This perturbation feature makes it possible to speed up the algorithm, for example by escaping from a narrow local minimum in the cost function.

Note that although the invention was explained above in general terms indicating that the first offset estimation is performed before the first channel estimation, in certain embodiments, it may be acceptable, to perform the first channel estimation before the first carrier offset estimation, and to continue the iteration from these first two steps. However, this option is not preferred since it is likely that the first channel estimation would be too far from the true value, so that the total algorithm may find it difficult to converge to a global minimum of the cost function in finite steps.

Brief Description of the Figures

An embodiment of the invention will now be described for the sake of example only with reference to the following figures, in which:

Fig. 1, which is composed of Figs. 1(a) and 1(b), is a graphical representation of an OFDM communication system;

Fig. 2 shows an OFDM receiver which is an embodiment of the present invention; and

Fig. 3 is a schematic representation of the convergence process of the embodiment to the global minimum of a cost function.

Detailed Description of the Embodiment

The embodiment of the invention is illustrated schematically in Fig. 2. The embodiment is a receiver adapted to receive the signals generated and transmitted as described above with reference to Fig. 1. The receiver includes a portion 10 which may be identical to known systems. The portion 10 includes a serial to parallel converter 11 for removing the cyclic prefix from the received signal $y(n)$ and generating M parallel signals $y(n)=[y_1(n), \dots, y_M(n)]^T$. The portion 10 further includes a discrete Fourier transform (DFT) unit 13 which subjects the output of the converter 11 to an M -point discrete Fourier transform. The portion 10 further includes a channel equalisation unit 15 which performs equalisation of each of the M equivalent flat-fading channels output from the DFT unit 13, to generate an output $S(n)$ which is a reconstructed form of the input to the transmitter of Fig. 1.

The embodiment further includes a portion 20 which differs from known receivers. The portion 20 includes a carrier frequency offset estimation unit 21 and a channel estimation unit 23. The output of the carrier frequency offset estimation unit 21 is transmitted both to the DFT unit 13 (as in prior art systems) and to the channel estimation unit 23. Similarly, the output of the channel estimation unit 23 is transmitted both to the equalisation unit 15 and to the carrier frequency offset estimation unit 21. This novel structure thus permits a combined iteration of the two estimates.

Specifically, the algorithm performed by the units 21, 23 is as follows, based on an assumption that the training sequence is series of pseudo-random symbols.

1. Use the received signals to generate an initial estimate of carrier frequency offset without channel information.
2. Use the received signals and the initial estimate of carrier frequency offset to estimate channel parameters.

3. Use the improved estimate of the channel parameters to improve the estimate of the carrier frequency offset.
 4. Use the estimate of the carrier frequency offset to further improve the estimate of the channel parameters.
 5. Repeat steps 3 and 4 K times to obtain global optimization solution to carrier offset and channel parameters.
- 10 Even more specifically, the steps of the algorithm are as follows (note that the numbering of steps does not correspond to that given above):
1. Set initial values: $\mathbf{E}_{est} = \mathbf{I}, \mathbf{H}_{est} = \mathbf{I}, \mathbf{H}_{try} = \mathbf{H}_{est}, \phi_{est} = \phi_{try} = 0$ respectively, where $\mathbf{I}$ is a unit matrix. Moreover, let $\mathbf{z} = \text{diag}[1, e^{-j\phi}, \dots, e^{-j(M-1)\phi}]$
 2. Use the cost function $f = \left\| \mathbf{z} \mathbf{y} e^{-j(n-1)\phi(M+N_c)} - \mathbf{W} \mathbf{H}_{est} \mathbf{s}(n) \right\|^2$, and estimate the values of:

$$\phi_{est} = \arg \min_{\phi} \left\| \mathbf{z} \mathbf{y} e^{-j(n-1)\phi(M+N_c)} - \mathbf{W} \mathbf{H}_{est} \mathbf{s}(n) \right\|^2, \text{ and}$$

$$\phi_{try} = \arg \min_{\phi} \left\| \mathbf{z} \mathbf{y} e^{-j(n-1)\phi(M+N_c)} - \mathbf{W} \mathbf{H}_{try} \mathbf{s}(n) \right\|^2$$
 - If $\min_{\phi} \left\| \mathbf{z} \mathbf{y} e^{-j(n-1)\phi(M+N_c)} - \mathbf{W} \mathbf{H}_{est} \mathbf{s}(n) \right\|^2 > \min_{\phi} \left\| \mathbf{z} \mathbf{y} e^{-j(n-1)\phi(M+N_c)} - \mathbf{W} \mathbf{H}_{try} \mathbf{s}(n) \right\|^2$, then set $\mathbf{E}_{est} = \mathbf{E}(\phi_{try})$, or else set $\mathbf{E}_{est} = \mathbf{E}(\phi_{est})$.

3. Let $\mathbf{E}_{try} = \mathbf{E}(\phi_{est} + \varsigma)$, where ς is a small random number (perturbation).
4. Set $\mathbf{H}_{est} = diag\left[\frac{1}{M} \mathbf{W}^H \mathbf{E}_{est}^{-1} \mathbf{y} e^{j(n-1)(\phi_{est} + \varsigma)(M+N_c)} ./ \underline{\mathbf{s}}(n) \right]$, where $./$ denotes that the elements in the former matrix are divided by the corresponding elements in the latter matrix, respectively. $\mathbf{W}^H$ means the conjugate transpose of $\mathbf{W}$, and $\mathbf{E}_{est}^{-1}$ means the inverse of $\mathbf{E}$.
5. Set $\mathbf{H}_{try} = diag\left[\frac{1}{M} \mathbf{W}^H \mathbf{E}_{try}^{-1} \mathbf{y} e^{-j(n-1)(\phi_{est} + \varsigma)(M+N_c)} ./ \underline{\mathbf{s}}(n) \right]$
6. Set $n = n + 1$. Repeat step 2 to step 5 K times for optimal $\mathbf{E}_{est}$ and $\mathbf{H}_{est}$. There is one iteration, i.e. one estimation of both $\mathbf{E}$ and $\mathbf{H}$, for each value of n .

In the training period, $\underline{\mathbf{s}}(n)$ is assumed to be known training symbols.

- 15 Preferably, $\underline{\mathbf{s}}(n)$ is a series of pseudo-random symbols.

Fig. 3 is a schematic view of the convergence, in which for simplicity a single direction (the horizontal direction) is used to represent the multi-dimensional (specifically M-dimensional) space in which the optimisation is actually occurring. The value of the cost function for each point is illustrated for simplicity as a line whose height at each of a number of horizontal positions corresponds to the value of the cost function. The cost function shown in Fig. 3 has a single local minimum and a single global minimum.

- 25 The points marked 1, 2 and 3 mark the values of the cost function after each of the first three iterations of the present method for this particular cost function. Point 3 is near the local minimum of the cost function. In iteration 3, however, it is found (at the end of step 2) that the perturbed cost function derived from the perturbed values $\mathbf{E}_{try}$, $\mathbf{H}_{try}$ (shown in Fig. 3 in the horizontal position marked "trial

3") actually leads to a lower value for the cost function than point 3. Thus, the next value of $\mathbf{E}_{\text{est}}$ is generated based on $\mathbf{E}_{\text{try}}$, $\mathbf{H}_{\text{try}}$. In the next two iterations, points 4 and 5 are generated respectively. Point 5 is near the global minimum of the cost function. In summary, from Fig 3, we can see how the algorithm jumps
 5 out from the local minimum to the global minimum.

By the new iterative algorithm, one can obtain good estimations for carrier frequency offset and channel parameters. These results are directly used to detect the OFDM symbols. Therefore, a better receiving performance can be
 10 achieved by adopting the proposed structure for the OFDM signal receiver. In summary, the new methods can improve the receiving performance of the OFDM receiver in DTVB, WLAN and wireless ATM.

Although the invention has been described above in relation to a single
 15 embodiment, many variations are possible within the scope of the invention as will be clear to a skilled reader. For example, although the text above refers to the receiver having various "units", the invention is not limited to receivers in which these are separate physical units. Rather they may be portions of software, which runs on any number of processors.

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References

The disclosure contained in the following references is incorporated herein in its entirety by reference:

- [1] Hui Liu and Ufuk Tureli, "A High-Efficiency Carrier Estimator for OFDM
 25 Communications." IEEE Communications Letter, vol.2, no.4, April 1998.
- [2] Ufuk Tureli, Hui Liu and Michael D. Zoltowski, "OFDM Blind Carrier Offset Estimation: ESPRIT." IEEE Transactions on Communications, vol.48, no.9, Sept.2000.
- [3] Robert W. Heath, Jr and Georgios B. Giannakis, "Exploiting Input
 30 Cyclostationarity for Blind Channel Identification in OFDM Systems." IEEE Transactions on Signal Processing, vol.47, no.3, March 1999.

- [4] Ove Edfors, Magnus Sandell, et al, "OFDM Channel Estimation by Singular Value Decomposition." IEEE Transactions on Communications, vol.46, no.7, July 1998.
- [5] Jian Li and Renbiao Wu, "An efficient Algorithm for Time Delay Estimation." IEEE Transactions on Signal Processing, vol.46, no.8, Aug.1998.
- [6] Jian Li, Guoqing Liu and Georgios B. Giannakis, "Carrier Frequency Offset Estimation for OFDM-Based WLANs." IEEE Signal Processing Letters, vol..8, no.3, March 2001.

Claims

1. A method, for use in an OFDM receiver, of estimating carrier frequency offset values and one or more transmission channel parameters from received
5 OFDM signals, the method including:
 using the received signals to estimate an carrier frequency offset value and/or channel parameters; and
 at least once performing the sequence of steps:
 (i) using the received signals and previously estimated carrier frequency
10 offset value to estimate the channel parameters; and
 (ii) using the received signals and previously estimated channel parameters to estimate the carrier frequency offset value.
2. A method according to claim 1 in which said sequence of steps is
15 performed K times, where K is an integer greater than 1.
3. A method according to claim 1 or claim 2 in which the carrier frequency offset values are estimated by minimising a cost function.
- 20 4. A method according to claim 3 in which said sequence of steps includes adding a random perturbation to an previous estimate and determining whether the perturbed estimate leads to an improved value of the cost function, and in this case using the perturbed estimate in place of the original estimate in a subsequent estimation.
- 25 5. A method according to any preceding claim in which the received signal is based on a pseudo-random pilot signal.
6. A method according to any preceding claim in which the sequence of
30 steps is performed for each of a plurality of respective training symbols in the received message.

7. An OFDM receiver including:
 - a first portion for receiving OFDM signals and generating reconstructed messages, the first portion being arranged to employ carrier frequency offset values and one or more channel parameters;
 - 5 a second portion for estimating carrier frequency offset values and one or more transmission channel parameters from received OFDM signals, the second portion including:
 - a carrier frequency offset estimation unit arranged to receive the signals and to estimate the carrier frequency offset, and
 - 10 a channel parameters estimation unit arranged to receive the signals and an output of the carrier frequency offset estimation unit, to estimate the channel parameters, and to transmit its output to the carrier frequency offset estimation unit.
- 15 8. A receiver according to claim 7 in which the first portion includes:
 - a reception unit for receiving an OFDM signal;
 - a serial-to-parallel converter receiving the output of the reception unit,
 - a discrete Fourier transform unit receiving the output of the serial-to-parallel converter and of the carrier frequency offset estimation unit; and
 - 20 an equalisation unit receiving the output of the discrete Fourier transform unit and the channel parameters estimation unit.
9. A receiver according to claim 7 or claim 8 in which the carrier frequency offset estimation unit is arranged to estimate carrier frequency offset values by
 - 25 minimising a cost function.
10. A receiver according to claim 9 in which the second portion is arranged to generate a perturbed estimate value by adding a random perturbation to a previous estimate and determining whether the perturbed estimate value leads
 - 30 to an improved value of the cost function, and in this case to perform a subsequent estimate using the perturbed estimate value in place of the original estimate.

11. An OFDM signal communication system including an OFDM signal transmission unit and a receiver according to any of claims 7 to 10.