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Methods and Apparatus for Receiving OFDM Signals



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Field of the Invention

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 over multipath fading channels. It further relates to those methods, and to communication systems including the receivers.

Background of the Invention

Orthogonal Frequency Division Multiplexing (OFDM) is a promising 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).

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 converter 1 to generate M parallel signals $S_1(n), \ldots, S_M(n)$. 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 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 $y_1(n), \ldots, y_M(n)$, which we also refer to here as $\mathbf{y}(n)$. It then subjects the result to an *M*-point discrete 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 equalizer can equalize the equivalent channels, assuming that it knows the properties of the channel (here called "channel parameters"). The cyclic prefix can handle the cyclic convolution effect when the signal passes through a frequency-selective multi-path channel.

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 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.

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.

The received signal $\mathbf{y}(n) \in C^{Mx1}$ can be denoted as

$$\mathbf{y}(n) = \mathbf{EWHs}(n)e^{j\phi(n-1)(M+N_c)} + \boldsymbol{\xi}(n) \qquad (1)$$

where

$$\mathbf{E} = diag\left[1, e^{j\phi}, \cdots, e^{j(M-1)\phi}\right] \in C^{MxM} \qquad (2)$$

is the carrier frequency offset matrix and ϕ is the carrier frequency offset. The term $diag[\ ]$ means a diagonal matrix having as its entries the elements of the vector in the square bracket. N_c is the length of cyclic prefix. **W** is the IDFT matrix. Each of its elements, corresponding to the l th row and m th column, is given by $e^{-j2\pi ml/M}$.

$$H = diag[h(0), \cdots, h(M-1)]$$

is the flat-fading channel parameter matrix, $\underline{\mathbf{s}}(n)$ is a data transmitted in block n (i.e. the n th Serial-to-Parallel converting), and $\boldsymbol{\xi}(n) \in C^{Mx1}$ is an additive Gaussian noise vector.

The function of the carrier frequency offset estimation is thus to estimate **E**, so that its effects can be removed. Similarly, the function of the channel estimation is to estimate **H**, so that its effects can be removed. The estimations are performed based on received signals including a plurality of known training OFDM symbols (a "training sequence").

In some systems, for example WLAN systems, the training sequence is a series of identical OFDM symbols. In this case, the received signal in respect of each symbol can be treated as a "sample" from the same distribution. [6] proposed a carrier frequency offset estimation using a non-linear least-square (NLS)

technique, based on a cost function which is a sum over each of the training symbols (except the last) of a function of (i) the received signal for that training symbol and (ii) the received signal for the consecutively next training symbol. In other words, the cost function is generated based on relationships between "nearest neighbours" in the series of training symbols. In this way, one can estimate carrier frequency offset by N-1 statistics, where N is the number of OFDM block symbols used for the training.

Summary of the invention

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

In general terms, the present invention proposes that the carrier frequency offset is estimated using a cost function which includes terms generated from the received signal at a (predetermined) set of pairs of samples which are not just nearest-neighbours in the symbols sequence. For example, the cost function can include terms generated not only between the nearest neighbour symbols, but also between all pairs of symbols.

Thus, the invention makes it possible to obtain many more statistics than in conventional methods from the same number of observation samples. This can increase signal-to-noise ratio (SNR) as compared to prior art systems. Accordingly, more accurate estimate of carrier frequency offset can be achieved.

This method is suitable when the training sequence is a series of identical OFDM symbols.

The present invention is especially valuable for a burst packet switch communications system such as a WLAN system, because the number of

training symbols available for estimation in this kind of communication systems is very small. Using the limited samples efficiently is very important to achieve a good performance.

Specifically, a first expression of the invention is a method, for use in an OFDM receiver, of estimating a carrier frequency offset value, the method including:

receiving an OFDM signal including a received signal for each of a series of N symbols;

deriving a cost function which is a sum, over a set of pairs of said symbols, of a correlation function of

(i) a carrier frequency offset value, and

(ii) the received signals for that pair of symbols;

determining the carrier frequency offset value which minimises the cost function;

wherein said pairs of symbols comprise pairs of symbols which are not consecutive within said series.

An alternative 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;

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

a channel parameters estimation unit;

the carrier frequency offset estimation unit being arranged to estimate the carrier offset upon receiving a training sequence of N symbols by;

deriving a cost function which is a sum, over a set of pairs of said symbols, of a correlation function of

(i) a carrier frequency offset value, and

(ii) the received signals for that pair of symbols;

determining the carrier frequency offset value which minimises the cost function;

wherein said pairs of symbols comprise pairs of symbols which are not consecutive within said series.

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;

Fig. 3, which is composed of Figs. 3(a) and 3(b), is a schematic comparison of the definition of the cost function in a prior art method and in the embodiment; and

Fig. 4 is a comparison of the mean-square error performance for carrier frequency offset estimation of the prior art method and the embodiment.

Detailed description of the embodiments

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 $\boldsymbol{y}(n)$ and generating M parallel signals $\mathbf{y}(n)=[y_1(n), \ldots, y_M(n)]^T$. 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 and to the channel estimation unit 23. The output of the channel estimation unit 23 is transmitted to the equalisation unit 15. In training period, $\underline{\mathbf{s}}(n)$ is assumed to be known as training sequence which is a series of identical OFDM symbols.

The cost function utilised by the carrier frequency offset estimation unit 21 within the scope of the invention is formed as follows:

$$f(\phi) = \sum_{l=1}^{N} \sum_{i=1}^{N-l} \frac{\left\| \mathbf{y}(i+l)e^{-jl\phi(M+N_c)} - \mathbf{y}(i) \right\|^2}{\left\| \mathbf{y}(i) \right\|^2} \qquad (1)$$

In other words, the cost function $f(\phi)$ is the sum, over all possible pairs of the samples (symbols), of a correlation function for a given pair given by:

$$\frac{\left\| \mathbf{y}(i+l)e^{-jl\phi(N+N_c)} - \mathbf{y}(i) \right\|^2}{\left\| \mathbf{y}(i) \right\|^2} \qquad (2)$$

The estimate for the carrier frequency offset is generated as

$$\phi_{est} = \arg\min_{\phi} f(\phi) \qquad (3)$$

Equation (1) is a sum of C_N^2 statistics, where $C_N^2 = \frac{N!}{2!(N-2)!}$. By contrast, as discussed above, the NLS estimator in [6] can only obtain a sum of N-1 statistics. This difference is illustrated in Fig. 3. Fig. 3(a) illustrates how in [6] a series of N symbols ("samples") is used to generate a cost function as a sum over the (N-1) pairs of nearest neighbours in the series. By contrast, as shown in Fig. 3(b), the embodiment generates the cost function as a sum of C_N^2 between all possible combinations of two samples.

Due to this difference, the proposed estimator can smooth much stronger noise and obtain more accurate carrier frequency offset estimation. This is illustrated in Fig. 4, which shows the mean square error performance of the prior art method of [6] and of the embodiment. This figure was generated as a simulation result using N=9. An improvement of roughly an order of magnitude can be seen.

Note that the method in [6] approaches the performance lower bound (Cramer-Rao bound) when the signal to noise ratio is large. However the Cramer-Rao bound (CRB) in [6] is associated with N-1 statistics. The embodiment employs many more statistics. This is the reason for the better performance achieved by the embodiment.

After carrier frequency offset estimation, the channel estimation can be achieved using carrier frequency information and the training sequence as follows:

$$\mathbf{H}_{est} = diag\left[\frac{1}{MN} \mathbf{W}^{H} \mathbf{E}_{est}^{-1} \mathbf{y} e^{j(n-1)(\phi_{est}+\zeta)(M+N_c)} ./ \underline{\mathbf{s}}(n) \right] \qquad (4)$$

In Eqn. (4), ./ 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 **W**, and $\mathbf{E}_{est}^{-1}$ means the inverse of **E**.

Note that, although in the embodiment the cost function of Eqn. (1) includes terms from **all** of the C_N^2 possible pairs of samples, the invention is not limited in this respect. For example, in practical applications, only a proportion of these terms (e.g. up to a half, or up to a quarter) may be included in the expression for the cost function. Provided the number of statistics generated is significantly higher than (N-1) (for example, N or at least 2N) a significant improvement in estimation can be achieved.

In fact, one can flexibly choose the numbers of statistics up to C_N^2 according to the estimation precision required.

Embodiments of the invention make it possible to estimate the carrier frequency offset and channel parameters better than by conventional methods by a special cost function. This is achieived without a great increase in complexity. Thus, the embodiments 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 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.

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 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 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 a carrier frequency offset value, the method including:

receiving an OFDM signal including a received signal for each of a series of N symbols;

deriving a cost function which is a sum, over a set of pairs of said symbols, of a correlation function of

(i) a carrier frequency offset value, and

(ii) the received signals for that pair of symbols;

determining the carrier frequency offset value which minimises the cost function;

wherein said pairs of symbols comprise pairs of symbols which are not consecutive within said series.

2. A method according to claim 1 in which the pairs of symbols comprise substantially all possible pairs of the N symbols.

3. A method according to claim 1 in which the number of said pairs of symbols is greater than N.

4. A method according to claim 1 in which the number of pairs of symbols is at least half $\frac{N!}{2!(N-2)!}$.

5. A method according to any preceding claim in which for a given one of said pairs, said correlation function depends on the normalised magnitude of a sum over the channels of the received signals, of the difference between (i) that channel of the first symbol of the pair multiplied by a complex value dependent upon the carrier frequency offset, and (ii) that channel of the second symbol of the pair.

6. A method according to claim 5 in which the received signals are generated from a transmitted signal including a cyclic prefix of N_c, and said correlation function can be written, for a pair of symbols which is the i-th one of said symbols and another symbol l places later in the series, as

$$\frac{\left\|\mathbf{y}(i+l)e^{-jl\phi(N+N_c)}-\mathbf{y}(i)\right\|^2}{\left\|\mathbf{y}(i)\right\|^2}$$, where j is a complex number.

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;

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

a channel parameters estimation unit;

the carrier frequency offset estimation unit being arranged to estimate the carrier offset upon receiving a training sequence of N symbols by;

deriving a cost function which is a sum, over a set of pairs of said symbols, of a correlation function of

(i) a carrier frequency offset value, and

(ii) the received signals for that pair of symbols;

determining the carrier frequency offset value which minimises the cost function;

wherein said pairs of symbols comprise pairs of symbols which are not consecutive within said series.

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

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 pairs of symbols comprise substantially all possible pairs of the N symbols.

10. A receiver according to claim 7 or claim 8 in which the number of said pairs of symbols is greater than N.

11. A receiver according to claim 7 or claim 8 in which the number of pairs of symbols is at least half $\frac{N!}{2!(N-2)!}$.

12. A receiver according to any of claims 7 to 11 in which for a given one of said pairs, said correlation function depends on the normalised magnitude of a sum over the channels of the received signals, of the difference between (i) that channel of the first symbol of the pair multiplied by a complex value dependent upon the carrier frequency offset, and (ii) that channel of the second symbol of the pair.

13. A receiver according to claim 12 in which the received signals are generated from a transmitted signal including a cyclic prefix of N_c, and said correlation function can be written, for a pair of symbols which is the i-th one of said symbols and another symbol l places later in the series, as

$$\frac{\left\|\mathbf{y}(i+l)e^{-jl\phi(N+N_c)}-\mathbf{y}(i)\right\|^2}{\left\|\mathbf{y}(i)\right\|^2}$$, where j is a complex number

14. An OFDM signal communication system including an ODFM signal transmission unit and a receiver according to any of claims 7 to 13.