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METHOD AND/OR SYSTEM FOR FREQUENCY SYNCHRONISATION

FIELD

5 The present invention relates to a method and/or system for frequency synchronisation, particularly though not exclusively to carrier frequency offset estimation for a communication system that uses orthogonal frequency division multiplexing.

10 BACKGROUND

 There are many forms of modulation used in communication systems. For example in cellular and wireless computer networks, Orthogonal Frequency Division Multiplexing (OFDM) has become popular for its ability to efficiently use
15 the frequency spectrum. OFDM is a type of frequency division modulation where the frequencies are chosen so that the modulated data streams are orthogonal to each other.

 An OFDM signal is composed of multiple sub-carriers and narrow band
20 signals, eg: 64QAM. Because of this an OFDM system requires more accurate carrier frequency estimation and compensation than single carrier communication system. Thus the Carrier Frequency Offset (CFO) is one factor affecting OFDM system performance.

25 A prior art method to estimate the CFO used in wireless modems uses a training preamble for initial frequency synchronisation and channel estimation. Standards such as IEEE802.11a/g/n and HIPERLAN/2 specify a short training sequence in which a short symbol (L-STF) is repeated 10 times and a long training sequence in which a long symbol (L-LTF) is repeated twice. The
30 corresponding estimation of the CFO is also carried out in two steps. Firstly, a coarse CFO estimation is obtained using the short training sequence. Secondly, a fine CFO estimation is obtained using the long training sequence. However this requires a large buffer and two correlators. Moreover the



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subsequent step of channel estimation occurs during the long training sequence, and therefore relies on the less accurate coarsely estimated CFO.

For example in US Patent 7,068,593 an OFDM system is proposed
5 which includes separate processes and separate hardware for coarse and fine CFO estimation.

SUMMARY

10 In general terms, it is proposed that a plurality of short training symbols is used to estimate the CFO. The autocorrelation of the received signal is filtered over the period of the plurality of short training symbols. The filtered autocorrelation result is used to estimate the CFO. This may have the advantage that CFO estimation is faster, more accurate, require less hardware
15 and/or allows the subsequent channel estimation to be more accurate.

In a first specific expression there is provided a method of estimating the Carrier Frequency Offset (CFO) in a communications signal comprising:
performing an autocorrelation on the communications signal,
20 detecting the beginning of a plurality of short training symbols based on at least the autocorrelation,
filtering the autocorrelation signal after the beginning of the plurality of short training symbols, and
estimating the CFO based on at least the filtered autocorrelation signal.

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BRIEF DESCRIPTION OF THE DRAWINGS

One or more exemplary embodiments will now be described, with reference to the following figures, in which:

30 Figure 1 is a block diagram of an OFDM system according to an exemplary embodiment.

Figure 2 is a flow diagram of a method of demodulation using the system in Figure 1.

Figure 3 is a flow diagram of the frequency synchronisation in Figure 2.

Figure 4 is a graph of signal correlation and signal energy using the
5 method in Figure 2.

Figure 5 is a graph showing the time taken for frequency synchronisation using the method in Figure 2.

DETAILED DESCRIPTION OF EXEMPLARY EMBODIMENTS

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A frequency synchronisation apparatus for an OFDM communication system according to an exemplary embodiment is shown in Figure 1. In particular a receiver system 100 includes a radio frequency (RF) receiving module 102, an analogue/digital converter (ADC) 104, a synchronisation
15 module 106, a Fast Fourier Transform (FFT) module 108, a channel estimation and equalisation module 110, and a demodulator 112. Some modules may be implemented in a Digital Signal Processor (DSP) as is known in the art.

A method 200 is shown in Figure 2, for demodulating the signal received
20 by the system 100 in Figure 1. An OFDM signal is received at the RF receiving module 102, for example using the IEEE 802.11g protocol (receiving 202). The IEEE 802.11g protocol signal includes a training preamble to allow synchronisation. The OFDM signal is converted to a digital signal by the ADC 104 (digital conversion 204). The training preamble is simultaneously used to
25 synchronise the digital signal in frequency (frequency synchronisation 206) and in time (timing synchronising 208) by the synchronisation module 106. The synchronised signal is converted to the frequency domain by the FFT module 108 (frequency conversion 210). Each channel in the frequency domain signal is estimated and each estimated channel equalised (channel estimation and
30 equalisation 212). The estimated and equalised channels are then demodulated (demodulation 214).

Referring to Figure 3, the frequency synchronisation portion of synchronising 206 is shown in more detail. The instantaneous signal energy is calculated (energy calculation 206A) and scaled according to a predetermined scaling factor (scaling 206B). The signal energy is compared to a threshold to
 5 detect whether any signal is present (threshold 206C).

Simultaneously an autocorrelation result is calculated from the digital signal (autocorrelation 206D).

10 If a signal is detected, the scaled signal energy is compared to the autocorrelation result to detect the start of the short training symbols (L-STF detection 206E). The L-STF starts when the magnitude of the autocorrelation result is greater than the magnitude of the scaled signal energy and ends when the magnitude of the autocorrelation result is less than the magnitude of the
 15 scaled signal energy. If the L-STF is detected, the autocorrelation result from the start to the end of the L-STF is filtered (filtering 206F). The filtered autocorrelation result is used to estimate the phase shift in the signal (phase estimation 206G). The estimated phase shift is used to compensate for the CFO (phase compensation 206H).

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Receiving 202 may be implemented by sampling the received signals at an over-sampling rate, and saved into a buffer.

Energy calculation 206A may be implemented by measuring the energy
 25 or power of received signals and summing the measured energy over the duration of T_w . If the sample interval is T , $T_w = WT$, i.e. W samples are processed to calculate the energy. The energy $R(d)$ can be calculated according to Equation (1):

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$$R(d) = \sum_{m=0}^{w-1} |r_a(d+m)|^2 \quad (1)$$

In Equation (1) W is window length, which represents the number of samples used to compute the signal energy within the window; d is a time index corresponding to the first sample in a window of W samples; and m the sample index of the window.

5

In order to simplify the processing requirements $R(d)$ can be estimated using equation (2):

$$R(d+1) = R(d) + |r(d+w)|^2 - |r(d)|^2 \quad (2)$$

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Scaling 206B may be implemented by providing the calculated signal energy R to one input of a multiplier, R being multiplied by a constant scale factor value, μ . μ is selected to provide a sufficient margin relative to the instantaneous noise level. The multiplier asserts an energy threshold signal at its output.

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Autocorrelation 206D may be implemented by calculating the auto-correlation of received signal samples according to Equation (3):

$$AC(d) = \sum_{m=0}^{W-1} (r^*(d+m)r(d+m+D)) \quad (3)$$

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In Equation (3) D is the number of delay samples and W is the number of samples for the length of the correlation window. The window moves along in time as the receiver searches for the Legacy Short Training Field (L-STF). If T is denoted as a sample interval, then delay time $T_d = DT$ and the length of the integration window $T_w = WT$. For signal detection, the delay time T_d is normally set to be one or two short symbols, and the integration window length T_w is set to be one short symbol.

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L-STF detection 206E may be implemented by comparing the absolute value of the calculated auto-correlation, $|AC|$, with the absolute value of the

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energy threshold $|\mu \cdot R|$ to detect the L-STF. In order to simplify the processing requirements, $|AC|$ can be replaced with $|real(AC)| + |imag(AC)|$. As shown in Figure 4 when $|AC| > |\mu \cdot R|$ this indicates the start 402 of the L-STF and when $|AC| < |\mu \cdot R|$ this indicates the end 404 of the L-STF.

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As shown in Figure 4, after the preamble is detected, the $|AC|$ becomes stable and forms a plateau 400. Within this plateau, AC has almost the same phase and amplitude value except for the noise because of the iterative property of multiple identical symbol correlation. In Equation 3, when two
 10 identical symbols are received completely and correlated with each other, the $|AC|$ will be equal to the plateau level. When more identical symbols are received, during this period the $|AC|$ has almost the same level. The noise effect is one of the factors affecting CFO estimation performance.

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Filtering 206F may be implemented by using a Low Pass Filter (LPF) to average the AC over the L-STF. A Finite Impulse Response (FIR) or Infinite Impulse Response (IIR) LPF, can be used. For example, a first order IIR filter can be used. The output of the first order IIR filter can be expressed according to Equation (4):

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$$iir_{AC}(n) = (1 - \beta) \cdot iir_{AC}(n-1) + \beta \cdot AC(n) \quad (4)$$

In Equation (4) β is the tap coefficient.

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Phase estimation 206G may be implemented by estimating the phase shift in received signal samples. If the conjugate of a signal sample from the first symbol is multiplied by the corresponding sample from the second identical symbol (delay time T_d later), the effect of the channel should cancel. The channel affects the transmitted signal in amplitude and phase according to the
 30 channel factor in Equation (5):

$$R_x = T_x \cdot A_{channel} \cdot \exp(j \cdot \text{phase}_{channel}) \quad (5)$$

In Equation 5, R_x is the received signal, T_x is the transmitted signal, A_{channel} is the amplitude factor and $\text{phase}_{\text{channel}}$ is the phase factor. The autocorrelation operation may remove the channel effect, so that phase estimation is
 5 determined according to Equation (6):

$$\phi = 2\pi T_d \Delta f \quad (6)$$

In Equation (6) Δf is the frequency offset. The phase shift can be estimated by
 10 calculating the arctangent of the auto-correlation result from Equation (3) according to Equation (7):

$$\hat{\phi} = \arg(AC(d)) \quad (7)$$

15 Phase compensation 206H includes compensating the incoming data signals using the phase shift. The phase-corrected signal is then output to the FFT module 110. Because of the 2π ambiguity of the phase, the estimated phase $|\hat{\phi}|$ should be less than π . The frequency offset estimate may then be calculated according to Equation (8):

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$$\hat{\Delta f} = \frac{\hat{\phi}}{2\pi T_d} \quad (8)$$

In order to ensure an unambiguous frequency offset estimate, the CFO estimation may be limited to a range of smaller than $1/2T_d$ which should cover
 25 the maximum frequency offset.

In WLAN standards IEEE802.11a/g/n, the transmitter and receiver centre frequency tolerance shall be ± 20 ppm maximum. This means that the worst case offset as seen by a receiver can be up to ± 40 ppm, as it experiences the
 30 sum of the frequency offsets from both transmitter and receiver. Consider a

carrier frequency of 5.2GHz, the frequency offset could be up to $5.2 \times 10^9 \times 40 \times 10^{-6} = \pm 208 \text{ kHz}$. The CFO estimation range can be adjusted by changing T_d . For example, by setting T_d to be two short symbols, i.e. $1.6 \mu\text{s}$, the maximum estimated frequency offset is $1/(2 \times 1.6 \times 10^{-6}) = \pm 312.5 \text{ kHz}$, which meets the standard. This means the frequency estimation range is from -312.5 kHz to $+312.5 \text{ kHz}$, and therefore a 208 kHz frequency offset can be estimated. It is feasible to set T_d to be one short symbol to double the CFO estimation range. If T_d is one short symbol, i.e. $0.8 \mu\text{s}$, then the estimation range is $1/(2 \times 0.8 \times 10^{-6}) = \pm 625 \text{ kHz}$.

One or more embodiments may have any of the following advantages. Firstly at least one embodiment may have better CFO accuracy. The IIR filter is applied to remove noise in the CFO. At low SNR (e.g. 10 dB), the CFO may be reduced to less than 600 Hz while conventional methods may be about 3 kHz residual CFO. And at high SNR (e.g. 30 dB), the CFO can be reduced to less than 50 Hz while conventional methods may be about 1 kHz residual CFO. This is shown in Figure 5 where a prior art estimate 500 of the CFO is higher than that estimated 502 using an embodiment described above.

Secondly at least one embodiment may be faster at estimating the CFO. In Figure 5 a prior art coarse CFO estimation and fine CFO estimation takes time t_p . An embodiment described above takes a shorter time t_i . For example this may allow the frequency synchronisation process to be completed using only the short training sequence, or it may even be only a portion of the short training sequence. This has the added advantage of making the subsequent channel estimation, which relies on the CFO, more accurate.

Thirdly at least one embodiment may require less hardware. As conventional methods require a coarse estimation and a fine estimation to do frequency synchronisation, a large buffer and two correlators are required. An embodiment described above uses only the short training sequence, so the buffer requirement is lower and only one correlator is required.

Many variations of the above example embodiments are possible within the scope of the following claims, as will be clear to a skilled reader. For example the communications may not be OFDM, but may be a communications signal
5 which requires CFO synchronisation.

CLAIMS

1. A method of estimating the Carrier Frequency Offset (CFO) in a communications signal comprising:
 - 5 performing an autocorrelation on the communications signal,
 - detecting the beginning of a plurality of short training symbols based on at least the autocorrelation,
 - filtering the autocorrelation signal after the beginning of the plurality of short training symbols, and
 - 10 estimating the CFO based on at least the filtered autocorrelation signal.
2. The method in claim 1 further comprising detecting the end of the plurality of short training symbols based on at least the autocorrelation and wherein the autocorrelation signal is filtered between the beginning and the end
15 of the plurality of short training symbols.
3. The method in claim 2 further comprising determining a parameter indicative of the signal energy and if the parameter is over a threshold detecting the beginning of the plurality of short training symbols based on at least the
20 autocorrelation and the parameter.
4. The method in claim 3 wherein the beginning of the plurality of short training symbols is detected based on when the magnitude of the autocorrelation is greater than a predetermined proportion of the signal energy
25 and the end of the plurality of short training symbols is detected based on when the magnitude of the autocorrelation is less than a predetermined proportion of the signal energy.
5. The method as claimed in any of the preceding claims wherein filtering
30 the autocorrelation signal comprises passing the autocorrelation signal through a first order, or greater, Infinite Impulse Response (IIR) Low Pass Filter (LPF).

6. The method as claimed in claim 5 wherein the low pass filter has a transfer function:

$$\text{iir}_{AC}(n) = (1-\beta) \cdot \text{iir}_{AC}(n-1) + \beta \cdot AC(n)$$

5 7. The method as claimed in any of the preceding claims wherein performing the autocorrelation comprises:

$$AC(d) = \sum_{m=0}^{W-1} (r^*(d+m)r(d+m+D))$$

8. The method as claimed in claim 7 wherein estimating the CFO
10 comprises:

$$\Delta f = \arg(AC(d)) / 2\pi T_d$$

9. The method as claimed in any of the preceding claims the
communications signal is an Orthogonal Frequency Division Multiplexed
15 (OFDM) signal.

10. A method of synchronising an Orthogonal Frequency Division
Multiplexed (OFDM) signal comprising:

receiving the OFDM signal,
20 converting the received OFDM signal to a digitised signal,
estimating the Carrier Frequency Offset (CFO) according to the method
in any of the preceding claims,
compensating the digitised signal based on at least the estimated CFO,
performing a Fast Fourier Transform (FFT) on the compensated signal,
25 and
demodulating the FFT signal.