

A METHOD OF DETERMINING A CARRIER FREQUENCY OFFSET BETWEEN A TRANSMITTER AND A RECEIVER

- 5 The present application claims the benefit of United States provisional application 60/883,645 (filed on 5 January, 2007), the entire contents of which are incorporated herein by reference for all purposes.

10 **FIELD OF THE INVENTION**

Embodiments of the invention relate to the field of wireless communications. By way of example, embodiments of the invention relate to a method of determining a first carrier frequency offset between a transmitter and a receiver for a first frequency band and a second carrier frequency offset between the transmitter and the receiver for a second frequency band, a method of compensating a first carrier frequency offset between a transmitter and a receiver for a first frequency band and a second carrier frequency offset between the transmitter and the receiver for a second frequency band, and a method of compensating a sampling interval offset between a transmitter and a receiver, a first carrier frequency offset between the transmitter and the receiver for a first frequency band and a second carrier frequency offset between the transmitter and the receiver for a second frequency band, as well as corresponding communication devices.

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BACKGROUND OF THE INVENTION

In wireless communication, it is common to encounter the problem of carrier frequency offset (or frequency difference) between a transmitter and a receiver. In the case of high speed wireless communications, where higher bandwidths and higher carrier frequencies are typically used, the

corresponding effect on the carrier frequency offset between the transmitter and the receiver on the system performance is even greater.

As used herein, the term "carrier frequency offset" refers to the frequency
5 difference between the carrier of a received signal at a receiver and a demodulation signal generated at the receiver (from its own clock crystal oscillator) in order to demodulate the received signal.

There are already a number of known methods to solve problem of the carrier
10 frequency offset between the transmitter and the receiver.

A first conventional method [1] would be to first estimate the carrier frequency offset using the transmitted pilot symbols, and then to carry out the compensation of carrier frequency offset based on the estimated carrier
15 frequency offset, for example.

In more detail, for each OFDM symbol, the angle of the phase ramp is estimated using the four pilot tones embedded in each OFDM symbol. The effect of the sampling interval offset is then compensated by multiplying the
20 OFDM symbol with the inverse of the phase ramp.

A second conventional method [2] would be to use a best fit method to estimate the slope of the phase angle change with respect to symbol time. In more detail, the best fit method used is a weighted least squares best fit
25 straight line.

A third conventional method [3] would be to jointly estimate the carrier frequency offset and the sampling interval offset. This method involves using a specially designed preamble to estimate the carrier frequency offset and
30 then compensate the said preamble in the time domain first. Following which, the compensated preamble is transformed into the frequency domain and then used to estimate the sampling interval offset.

However, there are disadvantages with all the above discussed conventional methods. For example, with the first conventional method, in the case when the packet size of the transmitted data large, the solution suffers from the phase wrapping effect.

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In this document, a new method to overcome the problem of carrier frequency offset between the transmitter and the receiver is provided.

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SUMMARY OF THE INVENTION

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In one embodiment of the invention, a method of determining a first carrier frequency offset between a transmitter and a receiver for a first frequency band and a second carrier frequency offset between the transmitter and the receiver for a second frequency band is provided. The method provided includes determining an estimate of the first carrier frequency offset, determining an estimate of the second carrier frequency offset, determining an estimate of a first sampling interval offset between the transmitter and the receiver for the first frequency band based on the determined estimate of the first carrier frequency offset, and determining an estimate of a second sampling interval offset between the transmitter and the receiver for the second frequency band based on the determined estimate of the second carrier frequency offset. The method provided further includes determining an averaged sampling interval offset based on the calculation of an average of the determined estimate of the first sampling interval offset and the determined estimate of the second sampling interval offset, and determining the first carrier frequency offset and the second carrier frequency offset based on the determined averaged sampling interval offset.

BRIEF DESCRIPTION OF THE DRAWINGS

In the drawings, like reference characters generally refer to the same parts throughout the different views. The drawings are not necessarily to scale, emphasis instead generally being placed upon illustrating the principles of the invention. In the following description, various embodiments of the invention
5 are described with reference to the following drawings, in which:

Figure 1 shows a communication device according to one embodiment of the invention.

10 Figure 2 shows an illustration of how frequency ranges may be used by the communication system shown in Figure 1 according to one embodiment of the invention.

Figure 3 shows an illustration of the preamble structure used by the
15 communication device shown in Figure 1 according to one embodiment of the invention.

Figure 4 shows a block diagram illustrating the implementation of one
20 embodiment of the invention, where the sampling interval compensation is performed in the frequency domain.

Figure 5 shows a block diagram illustrating the implementation of one
25 embodiment of the invention, where the sampling interval compensation is performed in the time domain.

Figure 6 shows the packet error rate (PER) performance comparison for the
30 data rate mode of 53.3 Mbps in CM4, between conventional methods of estimating and compensating carrier frequency offset and embodiments of the invention.

Figure 7 shows an illustration of how the wrapping effects in the measured
phase when the number of OFDM symbols is large will result in

significant errors in the gradient estimation, in the first conventional method.

5 Figure 8 shows the packet error rate (PER) performance comparison for the data rate mode of 106.7 Mbps in CM4, between conventional methods of estimating and compensating carrier frequency offset and embodiments of the invention.

10 Figure 9 shows the mean squared error (MSE) of the sampling interval offset estimation observed for the different data rate modes, according to one embodiment of the invention.

15 Figure 10 shows the packet error rate (PER) performance comparison for the data rate mode of 200 Mbps in CM2, between conventional methods of estimating and compensating carrier frequency offset and embodiments of the invention.

20 Figure 11 shows the packet error rate (PER) performance comparison for the data rate mode of 480 Mbps in CM1, between conventional methods of estimating and compensating carrier frequency offset and embodiments of the invention.

25 Figure 12 shows the packet error rate (PER) performance comparison for the data rate mode of 53.3 Mbps in CM4 (with shadowing), between a conventional method of estimating and compensating carrier frequency offset and one embodiment of the invention.

30 Figure 13 shows the packet error rate (PER) performance comparison for the data rate mode of 106.7 Mbps in CM4 (with shadowing), between a conventional method of estimating and compensating carrier frequency offset and one embodiment of the invention.

Figure 14 shows the packet error rate (PER) performance comparison for the data rate mode of 200 Mbps in CM2 (with shadowing), between a conventional method of estimating and compensating carrier frequency offset and one embodiment of the invention.

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Figure 15 shows the packet error rate (PER) performance comparison for the data rate mode of 480 Mbps in CM1 (with shadowing), between a conventional method of estimating and compensating carrier frequency offset and one embodiment of the invention.

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DETAILED DESCRIPTION OF THE INVENTION

Typically, it is not possible to use identical clock crystal oscillators in the transmitter and the receiver, and that this is the root cause of why a carrier frequency offset, for example, exists between the transmitter and the receiver.

Additionally, the frequency offset between the clock crystal oscillators in the transmitter and the receiver may be scaled based on the processing involved. For example, if the signal generated from the clock crystal oscillator has a higher frequency than the oscillating frequency of the clock crystal oscillator, the frequency offset between the signals generated in the transmitter and in the receiver is higher than the frequency offset between the clock crystal oscillators in the transmitter and the receiver.

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Further, in the case where sampling is used, it can be observed that the frequency offset between the clock crystal oscillators in the transmitter and the receiver is also reflected in the sampling frequency offset between the transmitter and the receiver.

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Illustratively, according to one embodiment, a method of determining the carrier frequency offset between the transmitter and the receiver is developed by appropriately combining all the above discussed observations.

In one embodiment, the carrier frequency offset is estimated in the time domain. Next the estimated carrier frequency offset is scaled (or translated) accordingly to the estimated sampling interval offset. The estimated sampling interval offsets are then averaged across the frequency bands, since the
5 sampling interval offset for each frequency band is primarily caused by the frequency difference between the clock crystal oscillators in the transmitter and in the receiver. By so doing, a more accurate estimation of the sampling interval offset can be obtained.

10 As used herein, the term "sampling interval offset" refers to the time difference between the sampling interval used in the sampling process of a transmitter in order to generate digital data carried by a signal to be transmitted, and the sampling interval used in the sampling process of a receiver of the transmitted signal in order to recover the digital data from the transmitted signal. In this
15 context, a sampling interval offset may be considered as corresponding to a sampling frequency offset.

Following which, the respective carrier frequency offsets for each frequency band are obtained by scaling the estimated sampling interval offset
20 accordingly. The respective carrier frequency offsets for each frequency band are then used in the process of carrier frequency offset compensation for each frequency band. As a side note, the process of carrier frequency offset compensation is typically carried out in the frequency domain.

25 Next, the process of sampling interval offset compensation is carried out based on the estimated sampling interval offset. It should be noted that the process of sampling interval offset compensation may be carried out either in the frequency domain (using a frequency domain phase compensator, for example) or in the time domain (using a low complexity minimum mean
30 square error (MMSE) interpolator, for example).

According to an embodiment of the invention, a method of determining a first carrier frequency offset between a transmitter and a receiver for a first

frequency band and a second carrier frequency offset between the transmitter and the receiver for a second frequency band is provided. The method provided includes determining an estimate of the first carrier frequency offset, determining an estimate of the second carrier frequency offset, determining
5 an estimate of a first sampling interval offset between the transmitter and the receiver for the first frequency band based on the determined estimate of the first carrier frequency offset, and determining an estimate of a second sampling interval offset between the transmitter and the receiver for the second frequency band based on the determined estimate of the second
10 carrier frequency offset. The method provided further includes determining an averaged sampling interval offset based on the calculation of an average of the determined estimate of the first sampling interval offset and the determined estimate of the second sampling interval offset, and determining the first carrier frequency offset and the second carrier frequency offset based
15 on the determined averaged sampling interval offset.

Embodiments of the invention emerge from the dependent claims.

In one embodiment, the method provided includes determining an estimate of
20 the carrier frequency offset between the transmitter and the receiver for each frequency band of a multiplicity of frequency bands, and determining an estimate of the sampling interval offset between the transmitter and the receiver for each frequency band in the multiplicity of frequency bands based on the determined estimate of the carrier frequency offset for each frequency
25 band. The method provided further includes determining an averaged sampling interval offset based on the calculation of an average of the determined estimates of the sampling interval offsets for each frequency band of the multiplicity of frequency bands, and determining a carrier frequency offset for each frequency band of the multiplicity of frequency bands based on
30 the determined averaged sampling interval offset.

As used herein, the term "multiplicity" refers to "three or more". For example, a multiplicity of frequency bands refers to three or more frequency bands.

In this embodiment, the method provided may be extended to determine the carrier frequency offset for a multiplicity of frequency bands. In this case, an estimate of the carrier frequency offset between the transmitter and the receiver for each frequency band of a multiplicity of frequency bands is first determined. This means that if there are N frequency bands in the multiplicity of frequency bands, then there would be N estimates of the carrier frequency offset in total (one estimate of the carrier frequency offset for each frequency band).

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Next, the averaged sampling interval offset is then determined by averaging the N estimates of the carrier frequency offset. Finally, the respective carrier frequency offsets for each frequency band are determined based on the averaged sampling interval offset.

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In one embodiment, the first carrier frequency offset is determined by multiplying the determined averaged sampling interval offset with a first coefficient and the inverse of the sampling interval, and the second carrier frequency offset is determined by multiplying the determined averaged sampling interval offset with a second coefficient and the inverse of the sampling interval.

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In another embodiment, the estimate of the first sampling interval offset is determined by multiplying the determined estimate of the first carrier frequency offset with the sampling interval and the inverse of the first coefficient, and the estimate of the second sampling interval offset is determined by multiplying the determined estimate of the second carrier frequency offset with the sampling interval and the inverse of the second coefficient.

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In one embodiment, the ratio between the first coefficient and the second coefficient is about the same as the ratio between the carrier frequency of the first frequency band and the carrier frequency of the second frequency band.

In another embodiment, the first coefficient and the second coefficient are respectively selected from a group of numbers in the range from 0 to 255.

5 In one embodiment, the averaged sampling interval offset is calculated as an arithmetic average of the determined estimates of the sampling interval offsets for each frequency band.

According to an embodiment of the invention, a method of compensating a first carrier frequency offset between a transmitter and a receiver for a first frequency band and a second carrier frequency offset between the transmitter and the receiver for a second frequency band is provided. The method provided includes determining an estimate of the first carrier frequency offset, determining an estimate of the second carrier frequency offset, determining an estimate of a first sampling interval offset for the first frequency band
10 based on the determined estimate of the first carrier frequency offset, and determining an estimate of a second sampling interval offset for the second frequency band based on the determined estimate of the second carrier frequency offset. The method provided further includes determining an averaged sampling interval offset based on the calculation of an average of the determined estimate of the first sampling interval offset and the
20 determined estimate of the second sampling interval offset, determining the first carrier frequency offset and the second carrier frequency offset based on the determined averaged sampling interval offset, and compensating the first carrier frequency offset and the second carrier frequency offset based on the
25 determined first carrier frequency offset and the determined second carrier frequency offset.

In one embodiment, compensating the first carrier frequency offset and the second carrier frequency offset includes determining a first phase rotation
30 based on the determined first carrier frequency offset, determining a second phase rotation based on the determined second carrier frequency offset, compensating the determined first phase rotation, and compensating the determined second phase rotation. In another embodiment, compensating the

first carrier frequency offset and the second carrier frequency offset further includes determining a third coefficient iteratively, determining the residual first carrier frequency offset based on the determined third coefficient, determining the residual second carrier frequency offset based on the
5 determined third coefficient, and compensating the determined residual first carrier frequency offset and the determined residual second carrier frequency offset.

According to an embodiment of the invention, a method of compensating a
10 sampling interval offset between a transmitter and a receiver, a first carrier frequency offset between the transmitter and the receiver for a first frequency band and a second carrier frequency offset between the transmitter and the receiver for a second frequency band is provided. The method provided includes determining an estimate of the first carrier frequency offset,
15 determining an estimate of the second carrier frequency offset, determining an estimate of a first sampling interval offset for the first frequency band based on the determined estimate of the first carrier frequency offset, and determining an estimate of a second sampling interval offset for the second frequency band based on the determined estimate of the second carrier
20 frequency offset. The method provided further includes determining an averaged sampling interval offset based on the calculation of an average of the determined estimate of the first sampling interval offset and the determined estimate of the second sampling interval offset, determining the first carrier frequency offset and the second carrier frequency offset based on
25 the determined averaged sampling interval offset, compensating the first carrier frequency offset and the second carrier frequency offset based on the determined first carrier frequency offset and the determined second carrier frequency offset, and compensating the sampling interval offset based on the determined averaged sampling interval offset.

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In one embodiment, compensating the first carrier frequency offset and the second carrier frequency offset includes determining a first phase rotation based on the determined first carrier frequency offset, determining a second

phase rotation based on the determined second carrier frequency offset, compensating the determined first phase rotation, and compensating the determined second phase rotation. In another embodiment, compensating the first carrier frequency offset and the second carrier frequency offset further
5 includes determining a third coefficient iteratively, determining the residual first carrier frequency offset based on the determined third coefficient, determining the residual second carrier frequency offset based on the determined third coefficient, and compensating the determined residual first carrier frequency offset and the determined residual second carrier frequency
10 offset.

In one embodiment, compensating the sampling interval offset is carried out after the processed received signal has been further processed according to a transform. In another embodiment, the transform may be selected from a
15 group including Fast Fourier Transform (FFT), Discrete Fourier Transform (DFT) and Discrete Cosine Transform (DCT).

In one embodiment, compensating the sampling interval offset is carried out using a frequency domain compensator. In another embodiment,
20 compensating the sampling interval offset includes determining a third phase rotation based on the determined averaged sampling interval offset, and compensating the determined third phase rotation. In another embodiment, compensating the sampling interval offset further includes determining the residual sampling interval offset, and compensating the determined residual
25 first carrier frequency offset, the determined residual second carrier frequency offset and the residual sampling interval offset.

In yet another embodiment, compensating the determined residual first carrier frequency offset, the determined residual second carrier frequency offset and
30 the residual sampling interval offset includes determining a fourth phase rotation due to the residual first carrier frequency offset, the determined residual second carrier frequency offset and the residual sampling interval offset, and compensating the determined fourth phase rotation.

In one embodiment, determining the fourth phase rotation due to the residual first carrier frequency offset, the determined residual second carrier frequency offset and the residual sampling interval offset is carried out using pilot
5 symbols, preamble symbols or synchronization symbols.

In one embodiment, compensating the sampling interval offset is carried out before the processed received signal is further processed according to the transform. In another embodiment, compensating the sampling interval offset
10 is carried out using a time domain compensator. In yet another embodiment, the time domain compensator is a finite impulse response (FIR) filter.

In one embodiment, the coefficients of the FIR filter are determined based on one algorithm selected from the group including the minimum mean square
15 error (MMSE) algorithm, the linear interpolation algorithm, the polynomial-based interpolation algorithm, the Lagrange algorithm, the piece-wise polynomial interpolation algorithm, the spline interpolation algorithm, the trigonometric interpolation algorithm and the Discrete Fourier Transform (DFT) interpolation algorithm.

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According to an embodiment of the invention, a communication device is provided. The communication device includes a first determining unit for determining an estimate of a first carrier frequency offset between a
transmitter and a receiver for a first frequency band, a second determining
25 unit for determining an estimate of a second carrier frequency offset between the transmitter and the receiver for a second frequency band, a third determining unit for determining an estimate of a first sampling interval offset between the transmitter and the receiver for the first frequency band based on the determined estimate of the first carrier frequency offset, and a fourth
30 determining unit for determining an estimate of a second sampling interval offset between the transmitter and the receiver for the second frequency band based on the determined estimate of the second carrier frequency offset. The communication device further includes a fifth determining unit for determining

an averaged sampling interval offset based on the calculation of an average of the determined estimate of the first sampling interval offset and the determined estimate of the second sampling interval offset, and a sixth determining unit for determining the first carrier frequency offset and the
5 second carrier frequency offset based on the determined averaged sampling interval offset.

According to an embodiment of the invention, a communication device is provided. The communication device includes a first determining unit for
10 determining an estimate of a first carrier frequency offset between a transmitter and a receiver for a first frequency band, a second determining unit for determining an estimate of a second carrier frequency offset between the transmitter and the receiver for a second frequency band, a third determining unit for determining an estimate of a first sampling interval offset
15 between the transmitter and the receiver for the first frequency band based on the determined estimate of the first carrier frequency offset, and a fourth determining unit for determining an estimate of a second sampling interval offset between the transmitter and the receiver for the second frequency band based on the determined estimate of the second carrier frequency offset. The
20 communication device further includes a fifth determining unit for determining an averaged sampling interval offset based on the calculation of an average of the determined estimate of the first sampling interval offset and the determined estimate of the second sampling interval offset, a sixth determining unit for determining the first carrier frequency offset and the
25 second carrier frequency offset based on the determined averaged sampling interval offset, and a compensating unit for compensating the first carrier frequency offset and the second carrier frequency offset based on the determined first carrier frequency offset and the determined second carrier frequency offset.

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According to an embodiment of the invention, a communication device is provided. The communication device includes a first determining unit for determining an estimate of a first carrier frequency offset between a

transmitter and a receiver for a first frequency band, a second determining unit for determining an estimate of a second carrier frequency offset between the transmitter and the receiver for a second frequency band, a third determining unit for determining an estimate of a first sampling interval offset
5 between the transmitter and the receiver for the first frequency band based on the determined estimate of the first carrier frequency offset, and a fourth determining unit for determining an estimate of a second sampling interval offset between the transmitter and the receiver for the second frequency band based on the determined estimate of the second carrier frequency offset. The
10 communication device further includes a fifth determining unit for determining an averaged sampling interval offset based on the calculation of an average of the determined estimate of the first sampling interval offset and the determined estimate of the second sampling interval offset, a sixth determining unit for determining the first carrier frequency offset and the
15 second carrier frequency offset based on the determined averaged sampling interval offset, a first compensating unit for compensating the first carrier frequency offset and the second carrier frequency offset based on the determined first carrier frequency offset and the determined second carrier frequency offset, and a second compensating unit for compensating the
20 sampling interval offset based on the determined averaged sampling interval offset.

In one embodiment, the communication device may be, but is not limited to, a wireless communication device, a high speed wireless communication device,
25 an orthogonal frequency division multiplexing (OFDM) communication device, a multi-band (MB) OFDM communication device, a ultra-wideband (UWB) communication device, a WiMedia communication device or a Bluetooth communication device.

30 The embodiments which are described in the context of the method of determining a first carrier frequency offset between a transmitter and a receiver for a first frequency band and a second carrier frequency offset between the transmitter and the receiver for a second frequency band are

analogously valid for the method of compensating a first carrier frequency offset between a transmitter and a receiver for a first frequency band and a second carrier frequency offset between the transmitter and the receiver for a second frequency band, the method of compensating a sampling interval offset between a transmitter and a receiver, a first carrier frequency offset between the transmitter and the receiver for a first frequency band and a second carrier frequency offset between the transmitter and the receiver for a second frequency band, and the respective communication devices, and vice versa.

Fig. 1 shows a communication device 100 according to one embodiment of the invention.

The communication device 100 includes a transmitter 101 and a receiver 103.

The transmitter 101 includes a transmit data source 105, a baseband processing block (TX) 107 and a radio frequency (RF) processing block (TX) 109. The receiver 101 includes a RF processing block (RX) 113, a baseband processing block (RX) 115 and a receive data block 117.

At the transmitter 101 side, the data generated by the transmit data source 105 is first processed by the baseband processing block (TX) 107. The baseband processing block (TX) 107 may include, but is not limited to, a channel encoder, an interleaver, a data scrambler, a code spreader and a modulator, for example. The processed data is then processed by the RF processing block (TX) 109 before being transmitted over a channel 111. The RF processing block (TX) 109 may include, but is not limited to, a mixer, a frequency up-converter, a filter, an amplifier and an antenna system, for example.

The transmitted signal passes through the channel 111 before arriving at the receiver 103 side, as the received signal. In the channel 111, the transmitted signal may suffer degradation, such as additive white Gaussian noise (AWGN), fading, shadowing, reflection and refraction, for example.

At the receiver 103 side, the received signal is first processed by the RF processing block (RX) 113, and then followed by the baseband processing block (RX) 115, in order to retrieve the data transmitted for the receive data block 117. The RF processing block (RX) 113 may include, but is not limited to, an antenna system, a mixer, a frequency down-converter, a filter and an equalizer, for example. The baseband processing block (RX) 115 may include, but is not limited to, a demodulator, a code de-spreader, a data de-scrambler, an de-interleaver and a channel decoder, for example.

As a side remark, it can be seen that each block on the transmitter has a corresponding block on the receiver. For example, the RF processing block (TX) 109 on the transmitter 101 has a corresponding block on the receiver 103, namely, the RF processing block (RX) 113.

Additionally, the communication device 100 may represent an ultra-wideband (UWB) communication device (which operates based on the multi-band (MB) OFDM communication technology), for example. In the subsequent description, the embodiments of the present invention provided will be discussed using an ultra-wideband (UWB) communication device as an illustrated example.

Fig. 2 shows an illustration of the frequency bands used by the communication device 100 shown in **Fig. 1** according to one embodiment of the invention.

Fig. 2 shows 3 frequency bands, the first frequency band 201 being from 3168 MHz to 3696 MHz, the second frequency band 203 being from 3696 MHz to 4224 MHz, and the third frequency band 205 being from 4224 MHz to 4752 MHz.

As mentioned earlier, the ultra-wideband (UWB) communication device is based on the multi-band (MB) OFDM technology. In view of **Fig. 2**, the ultra-

wideband (UWB) communication device may be considered as a 3-band OFDM communication device.

Fig. 2 also shows a transmission period 207, being of 937.5 nanoseconds (ns), which consists of 3 OFDM symbol transmission periods 209 (each being of 312.5 ns). Each OFDM symbol transmission period 209 comprises a cyclic prefix 211 (being of 60.6 ns) and a guard interval 213 (being of 9.5 ns).

The arrangement of the 3 symbol transmission periods 209 in the transmission period 207 is determined according to the preamble structure used in the ultra-wideband (UWB) system. An example of the preamble structure used is shown in **Fig. 3**.

Fig. 3 shows an illustration of the preamble structure 300 used by the communication device 100 shown in **Fig. 1** according to one embodiment of the invention.

In general, the preamble structure 300 is designed to assist receiver side algorithms to perform specific functions, such as synchronization, carrier frequency offset estimation and channel estimation, for example. For OFDM based systems, the preamble structure typically consists of two portions, a time domain portion and a frequency domain portion. The time domain portion includes a packet synchronization sequence 301 and a frame synchronization sequence 303, while the frequency domain portion includes a channel estimation sequence 305.

The packet synchronization sequence 301 may be used for packet detection and acquisition, coarse carrier frequency estimation and coarse symbol timing estimation, for example. The frame synchronization sequence 303 may be used for frame synchronization and for synchronizing the relevant receiver algorithms within the preamble transmission period, for example. The channel estimation sequence 305 may be used for channel estimation, for example.

It can be seen that the packet synchronization sequence 301, the frame synchronization sequence 303 and the channel estimation sequence 305 consists of 21 OFDM symbols, 3 OFDM symbols and 6 OFDM symbols, respectively. Further, it can be seen that the preamble structure 300 requires
5 a transmission period 307 of 9.375 microseconds (μ s), which is equivalent to 10 of the transmission periods 207 shown in **Fig. 2**.

As a side note, the preamble structure shown in **Fig. 3** is for Time Frequency Code (TFC) 2, which is used to determine the "hopping" sequence shown in
10 **Fig. 2** (where the first OFDM symbol is transmitted in the third frequency band 205, the second OFDM symbol is transmitted in the second frequency band 203 and the third OFDM symbol is transmitted in the first frequency band 201).

15 **Fig. 4** shows a block diagram 400 illustrating the implementation of one embodiment of the invention, where the sampling interval compensation is performed in the frequency domain.

A signal transmitted from transmitter 401 passes through the wireless channel
20 403 before arriving at the receiver 405 (as the received signal). In order to account for the signal degradation suffered while passing through the wireless channel 403, the received signal may be considered to include additive white Gaussian noise (AWGN) 407.

25 The receiver 405 includes a local oscillator unit 409, a low pass filter (LPF) and analog-to-digital (A/D) converter unit 411, a carrier frequency offset (CFO) processing block 413, a sampling interval offset (SIO) processing block 415, a Fast Fourier Transform (FFT) unit 417, an equalizer 419, a phase compensation block 421 and a baseband processing block 423.

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Further, the carrier frequency offset (CFO) processing block 413 includes a carrier frequency offset (CFO) estimator unit 425 and a carrier frequency offset (CFO) phase compensator unit 427. Similar to the carrier frequency

offset (CFO) processing block 413, the sampling interval offset (SIO) processing block 415 includes a sampling interval offset (SIO) estimator unit 429 and a sampling interval offset (SIO) phase compensator unit 431.

- 5 Additionally, the phase compensation block 421 includes a summation and phase extractor unit 433, a residual phase averaging unit 435 and a data phase compensator unit 437. The baseband processing block 423 includes functional units such as an interleaver and a Viterbi decoder, for example.
- 10 From the point of view on how the received signal is processed in the receiver 405, first, the local oscillator unit 409 generates and provides the carrier clock signal (of frequency f_c) in order to perform frequency down-conversion of the received signal. After being processed by the low pass filter and analog-to-digital converter unit 411, parts of the preamble are then used for
- 15 synchronization and for automatic gain control (AGC), for example.

Turning now to the carrier frequency offset (CFO) estimator unit 425, for a ultra-wideband (UWB) system, 6 OFDM symbols (2 in each band) are typically used for carrier frequency offset estimation. According to one

20 embodiment of the invention, a conventional method of estimating the carrier frequency offset may be used, such as estimating an auto-correlation function based on the packet synchronization sequence in the preamble, for example.

As a side note, in order to obtain accurate carrier frequency offset estimates

25 using the method of estimating an auto-correlation function based on the packet synchronization sequence in the preamble, the symbol timing is synchronized first in one embodiment. In this context, symbol timing recovery is performed prior to carrier frequency offset estimation in one embodiment.

30 Illustratively, the method of estimating an auto-correlation function based on the packet synchronization sequence in the preamble may be carried out as follows.

Let the number of OFDM symbols used for carrier frequency offset estimation in each frequency band be N_{FOE} . Then, an estimate of the carrier frequency offset in band m (where $m = 1, 2, 3$), Δf_{cm} , is given by

$$\Delta f_{cm} = \frac{1}{2\pi T} \cdot \frac{1}{495} \arg \left\{ \sum_{i=1}^{N_{FOE}-1} \sum_{n=0}^{127} r_{i,n}^* r_{i+1,n} \right\}, \quad m = 1, 2, 3 \quad (1)$$

- 5 where $r_{i,n}$ represents the n^{th} received sample within the i^{th} OFDM symbol in band m , and T is the sample duration. As a side note, the auto-correlation function refers to the term $\sum_{i=1}^{N_{FOE}-1} \sum_{n=0}^{127} r_{i,n}^* r_{i+1,n}$ in Equation (1).

- 10 In this context, it should be noted from the value of 127 in Equation (1) that only the 128-length time domain synchronization sequence (without the pre-appended "zero samples" and guard interval) has been considered.

- 15 Further, it should also be noted that the value of 495 in Equation (1) refers to the number of samples which separates the current timing synchronization sequence to the previous timing synchronization sequence within the same band for Time Frequency Code (TFC) 1.

- 20 Additionally, it should also be noted from Equation (1) that an estimate of the carrier frequency offset should be obtained for each frequency band.

- The next step of processing is performed in the sampling interval offset (SIO) estimator unit 429. The estimated carrier frequency offset (obtained from the carrier frequency offset (CFO) estimator unit 425) is scaled (or translated) accordingly to an estimated sampling interval offset for each frequency band.
- 25 An average of the estimated sampling interval offset for each frequency band is then obtained. This is done based on the observation that the estimated sampling interval offset for each frequency band is caused by the same frequency offset between the clock crystal oscillators in the transmitter 401 and the receiver 405.

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Following which, the averaged sampling interval offset is then fed back to the carrier frequency offset (CFO) estimator unit 425. The respective carrier frequency offsets for each frequency band are then obtained by scaling the averaged sampling interval offset accordingly.

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The carrier frequency offset for each frequency band is then used to perform carrier frequency offset compensation for each frequency band, for the preamble portions used for channel estimation and for data. This processing step is performed in the carrier frequency offset (CFO) phase compensator unit 427.

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The averaged sampling interval offset (obtained from the sampling interval offset (SIO) estimator unit 429) is also used by the sampling interval offset (SIO) phase compensator unit 431, to perform sampling interval offset compensation for the preamble portions used for channel estimation and for data (in the frequency domain).

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As a side note, it should be noted that for conventional methods of compensating the sampling interval offset, an estimate of the sampling interval offset in the frequency domain is required. Typically, additional processing units or circuitry are needed for so doing; some of which may have complex circuitry.

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However, as discussed earlier, unlike the conventional methods, the estimate of the sampling interval offset in the frequency domain is obtained in this embodiment of the invention by scaling the estimated carrier frequency offset and then performing an averaging of the results of the scaling. In this context, there is no need for any additional complex processing units or circuitry. As such, the complexity of the receiver 405 may be reduced.

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Turning now to the phase compensation block 421, following the sampling interval offset compensation (performed in the sampling interval offset (SIO) phase compensator unit 431), the residual carrier frequency offset and the

residual sampling interval offset may be estimated and then compensated, using conventional methods based on the pilot signals transmitted in predetermined sub-carriers within each OFDM symbol, for example.

- 5 An example of a method for estimating and compensating the residual carrier frequency offset and the residual sampling interval offset may be the following.

The residual carrier frequency offset and the residual sampling interval offset
 10 cause a phase rotation in the received signal samples. This phase rotation increases with time. In order to be able to use a coherent detection algorithm (which generally provides better performance) in the receiver 405, this phase rotation is tracked and compensated. Since pilot signals are transmitted in predetermined sub-carriers within each OFDM symbol, these pilot signals
 15 may be used for tracking and compensating the said phase rotation.

If the transmitted signal, the received signal and the estimated channel response at pilot sub-carrier k are $x_{k,i}$, $y_{k,i}$, and $\hat{h}_k$, respectively, for the i^{th} OFDM symbol, an estimate of the phase rotation for the i^{th} OFDM symbol, $\hat{\theta}_i$,
 20 is given by

$$\hat{\theta}_i = \arg \left\{ \sum_k \hat{h}_k^* y_{k,i} / x_{k,i} \right\}, \quad k = \pm 5, \pm 15, \pm 25, \pm 35, \pm 45, \pm 55 \quad (2)$$

The estimated phase rotation may then be used to compensate for the phase rotation of the current OFDM symbol.

25

Turning now to the residual phase averaging unit 435, similar to the averaging of the estimated sampling interval offsets (performed in the sampling interval offset (SIO) estimator unit 429), the estimated residual carrier frequency offset and the estimated residual sampling interval offset may also be averaged as
 30 well. This can be done because the residual carrier frequency offset and the residual sampling interval offset are correlated from one frequency band to another, based on the earlier discussed observations.

Finally, after compensating the residual carrier frequency offset and the residual sampling interval offset in the data phase compensator unit 437 and further processing in the baseband processing block 423, the received data is
 5 obtained.

In general, the effects of the carrier frequency offset and the sampling interval offset on each sub-carrier in an ultra-wideband (UWB) system may be represented mathematically as follows.

10

Firstly, the time domain baseband received signal may be written as

$$r(t) = \sum_i \sum_{k=-\frac{N}{2}}^{\frac{N}{2}-1} a_{i,k} H_k e^{j2\pi \frac{k}{NT}(t-iMT)} + \eta(t) \quad (3)$$

where $a_{i,k}$ is the transmitted symbol at the k^{th} sub-carrier of the i^{th} OFDM symbol, H_k is the frequency-domain channel response for the k^{th} sub-carrier, T
 15 is the sampling interval at the transmitter, N is the number of inverse Fast Fourier Transform (IFFT) samples, $M \cdot T$ is the total duration of the OFDM symbol including the zero prefix duration and $\eta(t)$ is the additive white Gaussian noise (AWGN).

20 Let T' be the sampling interval at the receiver 405 such that $T' = T + \Delta T$. It should be noted that the sampling interval offset, ΔT , may be a positive number or a negative number, depending on whether the sampling clock signal at the receiver 405 has a higher frequency or a lower frequency compared to that of the transmitter 401.

25

Taking into account the sampling interval offset and the carrier frequency offset, Δf_c , the N samples in the Fast Fourier Transform (FFT) window for the i^{th} received symbol may be written as

$$\begin{aligned}
r_{i,n} &= r((iM+n)T')e^{j2\pi\Delta f_c(iM+n)T'} + \eta_{i,n} \\
&= \sum_{k=-\frac{N}{2}}^{\frac{N}{2}-1} a_{i,k} H_k \cdot e^{j2\pi\frac{nk}{N}} \cdot \underbrace{e^{j2\pi\frac{k}{N}\frac{\Delta T}{T}(iM+n)}}_A \cdot \underbrace{e^{j2\pi\Delta f_c T(iM+n)}}_B \cdot \underbrace{e^{j2\pi\Delta f_c \Delta T(iM+n)}}_C + \eta_{i,n}
\end{aligned} \tag{4}$$

where $n = 0, 1, \dots, N-1$.

It can be seen from Equation (4) that the term A corresponds to the phase distortion due to the sampling interval offset, the term B corresponds to the phase distortion due to the carrier frequency offset and the term C corresponds to the phase distortion due to the combined effect of the carrier frequency offset and the sampling interval offset.

- 10 In typical OFDM systems, the preamble is used to estimate the carrier frequency offset, Δf_c . As such, one approach for multi-band (MB) OFDM systems (including ultra-wideband (UWB) systems) is also to use the preamble to estimate the carrier frequency offset Δf_c for each frequency band. An example of such an approach is discussed earlier in relation to Equation
- 15 (1).

Using such an approach, let the respective estimates of the carrier frequency offset Δf_c obtained for each frequency band be $\tilde{\Delta f}_{c1}$, $\tilde{\Delta f}_{c2}$ and $\tilde{\Delta f}_{c3}$. As the carrier frequency for each frequency band is different, the carrier frequency offset for each frequency band is also different. However, as mentioned earlier, it is observed that the sampling interval offset, ΔT , is approximately a constant value for all frequency bands, since the sampling interval offset, ΔT , is caused by the frequency offset between the clock crystal oscillators in the transmitter 401 and the receiver 405. The quantity $\frac{\Delta T}{T}$ may be denoted as δ ,

25 which is typically measured in terms of parts per million (ppm). For example, in the proposed ultra-wideband (UWB) systems, the quantity δ is typically specified as $\delta \leq 40\text{ppm}$.

Further, the relationship between the carrier frequency offset and the sampling interval offset may be written as follows

$$\Delta f_{c1} = \frac{-\delta}{1+\delta} f_{c1}, \Delta f_{c2} = \frac{-\delta}{1+\delta} f_{c2}, \Delta f_{c3} = \frac{-\delta}{1+\delta} f_{c3} \quad (5)$$

or equivalently,

$$\Delta f_{c1} = \frac{-\Delta T}{T + \Delta T} f_{c1}, \Delta f_{c2} = \frac{-\Delta T}{T + \Delta T} f_{c2}, \Delta f_{c3} = \frac{-\Delta T}{T + \Delta T} f_{c3} \quad (6)$$

where Δf_{c1} , Δf_{c2} , Δf_{c3} are the carrier frequency offset for the first frequency band (1), the second frequency band (2) and the third frequency band (3) respectively, and f_{c1} , f_{c2} , f_{c3} are the carrier frequency for the first frequency band (1), the second frequency band (2) and the third frequency band (3), respectively.

Using the conventional approach discussed earlier in relation to Equation (1), the estimated carrier frequency offset $\tilde{\Delta f}_{c1}$, $\tilde{\Delta f}_{c2}$ and $\tilde{\Delta f}_{c3}$ may be obtained for each frequency band, for example, using either Equation (5) or Equation (6).

Since ΔT is approximately a constant value for all frequency bands, the carrier frequency offset Δf_c and the sampling interval offset ΔT may be obtained as follows. The estimated sampling interval offset for the first frequency band $\tilde{\Delta T}_1$, the estimated sampling interval offset for the second frequency band $\tilde{\Delta T}_2$ and the estimated sampling interval offset for the third frequency band $\tilde{\Delta T}_3$ may be obtained as

$$\tilde{\Delta T}_1 = \frac{-\tilde{\Delta f}_{c1}}{f_{c1} + \tilde{\Delta f}_{c1}} T, \tilde{\Delta T}_2 = \frac{-\tilde{\Delta f}_{c2}}{f_{c2} + \tilde{\Delta f}_{c2}} T, \tilde{\Delta T}_3 = \frac{-\tilde{\Delta f}_{c3}}{f_{c3} + \tilde{\Delta f}_{c3}} T \quad (7)$$

However, it should be noted that in terms of implementation, Equation (7) may not be easily implemented. Additionally, since $\tilde{\Delta f}_c \ll f_c$, and $\tilde{\Delta T} \ll T$, Equation (7) may be simplified as follows

$$\Delta\tilde{T}_1 \approx \frac{-\Delta\tilde{f}_{c1}}{f_{c1}}T, \Delta\tilde{T}_2 \approx \frac{-\Delta\tilde{f}_{c2}}{f_{c2}}T, \Delta\tilde{T}_3 \approx \frac{-\Delta\tilde{f}_{c3}}{f_{c3}}T \quad (8)$$

As a side note, simulation results which would be presented later would show that the performance loss as a result of such a simplification is actually
5 negligible.

Further, it is known that in order to reduce complexity in hardware implementation, multiplications or divisions with a large value or a non-integer value should be avoided whenever possible. In this case, the
10 coefficients $\alpha_1 \cdots \alpha_3$ may be used to replace $f_{c1} \cdots f_{c3}$ and such a simplification leads to a simple hardware design as shown below.

$$\Delta\tilde{T}_1 \approx \frac{-\Delta\tilde{f}_{c1}}{\alpha_1}T, \Delta\tilde{T}_2 \approx \frac{-\Delta\tilde{f}_{c2}}{\alpha_2}T, \Delta\tilde{T}_3 \approx \frac{-\Delta\tilde{f}_{c3}}{\alpha_3}T \quad (9)$$

In general, the coefficients $\alpha_1 \cdots \alpha_3$ may be selected to be approximately in the
15 same order as $f_{c1} \cdots f_{c3}$. In more detail, the ratio between the first coefficient α_1 , the second coefficient α_2 and the third coefficient α_3 ($\alpha_1 : \alpha_2 : \alpha_3$) may be selected to be approximately the same as the ratio between the carrier frequency of the first frequency band f_{c1} , the carrier frequency of the second frequency band f_{c2} and the carrier frequency of the third frequency band f_{c3}
20 ($f_{c1} : f_{c2} : f_{c3}$).

In one embodiment, the ratio between the first coefficient α_1 , the second coefficient α_2 and the third coefficient α_3 , ($\alpha_1 : \alpha_2 : \alpha_3$) may be selected as 13:15:17. As a side note, these numbers are selected based on the respective
25 carrier frequencies used in the frequency bands shown in **Fig. 2**.

As a side note, it should be noted that Equation (9) is not used directly. However, the simplification used to obtain Equation (9) from Equation (8) may

be applied to the averaging of the sampling interval offsets for each frequency band, as shown below.

- The averaged sampling interval offset $\Delta\hat{T}$ may be obtained by averaging the estimated sampling interval offset for all three frequency bands, namely, $\Delta\tilde{T}_1$, $\Delta\tilde{T}_2$ and $\Delta\tilde{T}_3$ as

$$\Delta\hat{T} = \sum_i^{N_B} \Delta\tilde{T}_i = \frac{T}{N_B} \sum_{i=1}^{N_B} \frac{-\Delta\tilde{f}_{ci}}{f_{ci} + \Delta\tilde{f}_{ci}} \quad (10)$$

where N_B is the number of frequency bands.

- Using the same simplification applied in Equation (9), Equation (10) may then be reduced to

$$\Delta\hat{T} = \sum_i^{N_B} \Delta\tilde{T}_i \approx -\frac{T}{N_B} \sum_{i=1}^{N_B} \frac{\Delta\tilde{f}_{ci}}{\alpha_i} \quad (11)$$

- Next, the carrier frequency offset for each frequency band may be obtained as follows

$$\Delta\hat{f}_{c1} = \frac{\Delta\hat{T}}{T + \Delta\hat{T}} f_{c1}, \Delta\hat{f}_{c2} = \frac{\Delta\hat{T}}{T + \Delta\hat{T}} f_{c2}, \Delta\hat{f}_{c3} = \frac{\Delta\hat{T}}{T + \Delta\hat{T}} f_{c3} \quad (12)$$

- It should be noted that as a result of $\Delta\hat{T}$ being averaged across the frequency bands, a more accurate estimation of the sampling interval offset is obtained. Likewise, due to the more accurate estimation of the sampling interval offset, the respective carrier frequency offset $\Delta\hat{f}_{c1}$, $\Delta\hat{f}_{c2}$ and $\Delta\hat{f}_{c3}$ for each frequency band are also more accurately estimated.

- Again, using the same simplification applied in Equation (9), Equation (12) may be reduced to

$$\Delta\hat{f}_{c1} = \frac{\Delta\hat{T}}{T} \times \alpha_1, \Delta\hat{f}_{c2} = \frac{\Delta\hat{T}}{T} \times \alpha_2, \Delta\hat{f}_{c3} = \frac{\Delta\hat{T}}{T} \times \alpha_3 \quad (13)$$

As a side note, it should be noted that an alternative simplification which may also be applied in the above discussed steps would be to use the normalized sampling interval offsets $\Delta\tilde{T}_i / T$, where $i = 1, \dots, 3$.

- 5 After compensating the carrier frequency offset in the time domain, the received signal in the time domain may be written as

$$r'_{i,n} = \sum_{k=-\frac{N}{2}}^{\frac{N}{2}-1} a_{i,k} H_k e^{j2\pi \frac{nk}{N}} \cdot \underbrace{e^{j2\pi \frac{k}{N} \frac{\Delta T}{T} (iM+n)}}_A \cdot \underbrace{e^{j2\pi f_r T (iM+n)}}_D \cdot \underbrace{e^{j2\pi f_r \Delta T (iM+n)}}_E + \eta_{i,n} \quad (14)$$

- where the term D corresponds to the phase distortion due to the residual carrier frequency offset f_r , where $f_r = \Delta f_c - \hat{\Delta f}_c$, and the term E corresponds
- 10 to the phase distortion due to the combined effect of the residual carrier frequency offset and the sampling interval offset. As mentioned earlier in relation to Equation (4), the term A corresponds to the phase distortion due to the sampling interval offset.

- 15 There are two approaches to implement the sampling interval offset compensator, either as a frequency domain compensator or as a time domain compensator. Since the block diagram 400 is also an illustration of the implementation of a frequency domain compensator for the sampling interval offset, the frequency domain compensator is discussed here. The time
- 20 domain compensator will be discussed subsequently in relation to **Fig. 5** later.

- If the frequency domain phase compensation of the sampling interval offset is used, the received time domain samples $r'_{i,n}$ are then passed through the FFT unit 417. After the FFT unit 417, the received signal at the k^{th} sub-carrier
- 25 of the i^{th} OFDM symbol may then be described as

$$\begin{aligned}
R_{i,k} &= \sum_{n=-\frac{N}{2}}^{\frac{N}{2}-1} r'_{i,n} e^{-j2\pi \frac{nk}{N}} \\
&= \sum_{n=-\frac{N}{2}}^{\frac{N}{2}-1} \sum_{m=-\frac{N}{2}}^{\frac{N}{2}-1} a_{i,m} H_m \cdot e^{j2\pi \frac{mn}{N}} \cdot e^{j2\pi \frac{m \Delta T}{N T} (iM+n)} \cdot e^{j2\pi f_r (T+\Delta T) (iM+n)} \cdot e^{-j2\pi \frac{nk}{N}} + \eta'_{i,k} \quad (15) \\
&= A_{i,k} \cdot I_{k,k} + \sum_{\substack{m=-\frac{N}{2} \\ m \neq k}}^{\frac{N}{2}-1} A_{i,m} \cdot I_{m,k} + \eta'_{i,k}
\end{aligned}$$

where

$$\begin{aligned}
I_{m,k} &= \sum_{n=-\frac{N}{2}}^{\frac{N}{2}-1} e^{j2\pi \frac{mn}{N}} e^{j2\pi \frac{m \Delta T}{N T} n} e^{j2\pi f_r (T+\Delta T) n} \\
&= \frac{\sin\left(\pi \left(m \frac{T+\Delta T}{T} - k + f_r N(T+\Delta T)\right)\right)}{N \sin\left(\frac{\pi}{N} \left(m \frac{T+\Delta T}{T} - k + f_r N(T+\Delta T)\right)\right)} e^{j\pi \frac{N-1}{N} \left(m \frac{T+\Delta T}{T} - k + f_r N(T+\Delta T)\right)} \quad (16)
\end{aligned}$$

$$A_{i,m} = a_{i,m} H_m e^{j2\pi \cdot iM \left[\frac{m \Delta T}{N T} + f_r (T+\Delta T) \right]} \quad (17)$$

5 and $\eta'_{i,k}$ is the additive white Gaussian noise (AWGN) in frequency domain.

If $a_{i,m}$ is assumed to be an independently and identically distributed (i.i.d.)

random variable, then the second term $\sum_{\substack{m=-\frac{N}{2} \\ m \neq k}}^{\frac{N}{2}-1} A_{i,m} \cdot I_{m,k}$ of Equation (15) (which

represents the inter-carrier interference (ICI)) may be simply considered as additive white Gaussian noise (AWGN).

10

Additionally, since $\Delta T \ll 1$ and $f_r N T' \approx 0$, it can also be assumed that $I_{m,m} \approx 1$.

Therefore, the combined effects due to the residual carrier frequency offset
 15 and the sampling interval offset may be considered as a phase rotation, which is dependent on the sub-carrier index k and the OFDM symbol index i . The received data in frequency domain in the presence of the sampling interval offset and the residual carrier frequency offset may then be approximated as

$$R_{i,k} \approx a_{i,k} H_k \underbrace{e^{j2\pi \frac{k}{N} \frac{\Delta T}{T} iM}}_F \cdot \underbrace{e^{j2\pi f_r (T+\Delta T) iM}}_G + V_{i,k} \quad (18)$$

where $V_{i,k}$ is the additive white Gaussian noise (AWGN), the term F corresponds to the phase distortion due to the sampling interval offset and the term G corresponds to the phase distortion due to the combined effect of the residual frequency offset and the sampling interval offset.

After compensating the sampling interval offset using the averaged sampling interval offset $\hat{\Delta T}$, the received signal in the frequency domain may be written as

$$R'_{i,k} = a_{i,k} H_k \underbrace{e^{j2\pi \frac{k}{N} \frac{\Delta T_r}{T} iM}}_U \cdot \underbrace{e^{j2\pi f_r (T+\Delta T) iM}}_V + V'_{i,k} \quad (19)$$

where ΔT_r is the residual sampling interval offset, given by $\Delta T_r = \Delta T - \hat{\Delta T}$ and the term U corresponds to the phase distortion due to the residual sampling interval offset.

As a side note, the term V is same as the term G of Equation (18), because the sampling interval offset compensation does not affect this term. This means that ΔT in term V is not compensated for, since it is already part of the phase information.

After compensating the sampling interval offset, the phase distortion in the pilot of each OFDM symbol is only due to the residual sampling interval offset and the residual carrier frequency offset. Hence, the phase distortion in the terms U and V may be compensated by using the conventional phase compensation algorithms based on the pilot symbols in each OFDM symbol.

An example of such a conventional phase compensation algorithm is described in earlier in relation to Equation (2).

It should be noted that the carrier frequency offset obtained for each frequency band is also correlated. Further, in an indoor environment, for example, where the Doppler shift is negligible, it is also reasonable to assume

that the carrier frequency offset between the transmitter 401 and the receiver 405 is mainly due to the frequency difference between the respective clock crystal oscillators of the transmitter 401 and the receiver 405. Hence, the residual carrier frequency offset and the residual sampling interval offset are correlated from one frequency band to another.

It should be noted that in conventional methods, the residual phase distortion is considered to be random and independent from one frequency band to another. As such, the phase compensation is performed on each frequency band as well.

In the embodiments of the invention, the average of the estimated carrier frequency offset and the sampling interval offset across frequency bands is used. As such, a new method to estimate and compensate the phase distortion due to the residual carrier frequency offset and the residual sampling interval offset may be used, as shown in the following.

First, the respective residual carrier frequency offset in each frequency band may be given by

$$f_{r1} = \Delta f_{c1} - \hat{\Delta f}_{c1}, \quad f_{r2} = \Delta f_{c2} - \hat{\Delta f}_{c2}, \quad f_{r3} = \Delta f_{c3} - \hat{\Delta f}_{c3} \quad (20)$$

where f_{r1} , f_{r2} , f_{r3} are the residual frequency offset for the first frequency band (1), the residual frequency offset for the second frequency band (2) and the residual frequency offset for the third frequency band (3) respectively.

Equation (20) may be rewritten as

$$f_{r1} = \left(\frac{\Delta T}{T} - \frac{\Delta \hat{T}}{T} \right) f_{c1}, \quad f_{r2} = \left(\frac{\Delta T}{T} - \frac{\Delta \hat{T}}{T} \right) f_{c2}, \quad f_{r3} = \left(\frac{\Delta T}{T} - \frac{\Delta \hat{T}}{T} \right) f_{c3} \quad (21)$$

From Equation (19), the ratio of the phase of the term $U \varphi_U$ over the phase of the term $V \varphi_V$ may be written as $\frac{\varphi_U}{\varphi_V} = Z$, where Z is a variable depending on the index of sub-carrier. Typically, Z varies from between 0 to 15%.

Since both φ_U and φ_V are caused by the residual carrier frequency offset and sampling interval offset, the absolute values for both φ_U and φ_V are relative small. As such, in the subsequent simplification, φ_U may be ignored.

Therefore, the residual phase θ for i^{th} OFDM symbol may be written as

$$5 \quad \theta_i = i \cdot \gamma \cdot f_{c_j} \quad (22)$$

where $\gamma = (2\pi M \Delta T_r (1 + \delta))$, $j = \text{mod}(i/3) + 1$, where j represents the index of the frequency bands, and $j=1,2,3$. f_{c_j} is the carrier frequency for the corresponding frequency band.

- 10 It should be noted that γ is a value which is independent from the index of frequency bands and the index of OFDM symbols. As such, a weighted average of the estimates of γ may be calculated from the preceding OFDM symbols across the frequency bands, and then used to compensate for the residual phase θ . In other words, γ may be iteratively updated in order to
- 15 obtain a more accurate estimate, since the number of OFDM symbols received has also increased.

In this context, let $\hat{\gamma}_i$ represent the estimate of γ for the i^{th} OFDM symbol derived from $\hat{\theta}_i$ (which may be estimated using the conventional method

20 discussed earlier in relation to Equation (2), for example). The weighted average $\bar{\hat{\gamma}}_i$ may be given by

$$\begin{aligned}
\bar{\hat{\gamma}}_i &= \frac{\sum_{v=1}^i v \cdot \hat{\gamma}_v}{\sum_{v=1}^i v} \\
&= \left(\frac{i \cdot \hat{\gamma}_i + \sum_{v=1}^{i-1} v \cdot \hat{\gamma}_v}{\sum_{v=1}^i v} \right) \left(\frac{\sum_{v=1}^{i-1} v}{\sum_{v=1}^{i-1} v} \right) \\
&= \left(\frac{\sum_{v=1}^{i-1} v}{\sum_{v=1}^i v} \right) \left(\frac{\sum_{v=1}^{i-1} v \cdot \hat{\gamma}_v}{\sum_{v=1}^{i-1} v} \right) + \left(\frac{1}{\sum_{v=1}^i v} \right) i \cdot \hat{\gamma}_i \\
&= \frac{1}{i+1} \bar{\hat{\gamma}}_{i-1} + \frac{2}{i(i+1)} \hat{\gamma}_i
\end{aligned} \tag{23}$$

where $\hat{\gamma}_i = \frac{\hat{\theta}_i}{i \cdot f_{c_j}}$, and $j = \text{mod}(i/3) + 1$.

As a side note, it can be seen that Equation (22) is now represented in
 5 Equation (23) as an iteratively updated estimate, with the initial value

$$\text{of } \hat{\gamma}_1 = \frac{\hat{\theta}_1}{f_{c1}}.$$

Fig. 5 shows a block diagram 500 illustrating the implementation of one
 embodiment of the invention, where the sampling interval compensation is
 10 performed in the time domain.

It can be seen that the block diagram 500 has a number of blocks and units
 which are the same as those as the block diagram 400 shown in **Fig. 4**. As
 such, the labels used for such blocks and units would have the same two
 15 rightmost digits. For example, the carrier frequency offset (CFO) processing
 block is labeled as 425 in **Fig. 4** and as 525 in **Fig. 5**.

When compared to the block diagram 400, the block diagram 500 does not
 include a phase compensation block (421) or a sampling interval offset (SIO)
 20 phase compensator unit (431). Instead, the block diagram 500 has a minimum

mean square error (MMSE) interpolator unit 539. In this context, the minimum mean square error (MMSE) interpolator unit 539 is used for compensating the averaged sampling interval offset.

- 5 Additionally, it can be seen that the arrangement of certain blocks and units is different in the block diagram 500 compared to the block diagram 400. In block diagram 500, the entire process of estimating and compensating the carrier frequency offset and the averaged sampling interval offset is performed before the Fast Fourier Transform (FFT) unit. As such, the
- 10 sampling interval compensation is considered as being performed in the time domain.

- As a side remark, it should be noted that in general, any time domain compensator may be used in place of the minimum mean square error
- 15 (MMSE) interpolator unit 539. In other words, the minimum mean square error (MMSE) interpolator unit 539 is simply used here as an illustrative example of the time domain compensator.

- In one embodiment, the time domain compensator may be a finite impulse
- 20 response (FIR) filter. In another embodiment, the coefficients of the FIR filter are determined based on one algorithm selected from the group including the minimum mean square error (MMSE) algorithm, the linear interpolation algorithm, the polynomial-based interpolation algorithm, the Lagrange algorithm, the piece-wise polynomial interpolation algorithm, the spline
- 25 interpolation algorithm, the trigonometric interpolation algorithm and the Discrete Fourier Transform (DFT) interpolation algorithm.

- In view of the above, the minimum mean square error (MMSE) interpolator unit 539 is simply a FIR filter, which employs the minimum mean square error
- 30 (MMSE) algorithm in order to determine the FIR filter coefficients. For the purpose of illustration, subsequent discussion on the block diagram 500 will be presented using the minimum mean square error (MMSE) interpolator unit 539.

In more detail, in the minimum mean square error (MMSE) interpolator unit 539, the received time domain samples $r'_{i,n}$ are passed through a digital finite impulse response (FIR) filter. A digital interpolation is then carried out based on the criterion of minimizing the mean squared error between the impulse response of an ideal filter and the (approximate) interpolated signal. This means that the digital interpolator is simply a variable N_{FIR} -tap FIR filter which has been designed to interpolate the correct sampled values from the incorrectly sampled data.

In order to limit the complexity of the variable digital interpolator, the digital interpolator may be designed to interpolate for a fixed resolution of sampling offset, i.e., the digital interpolator only works at the predetermined resolutions. For example, if the digital interpolator's predetermined resolution is 1/8 of the sampling period, T , then the digital interpolator would only be able to interpolate the sampled values at $\frac{nT}{8}, n = 0, 1, \dots, 7$.

A counter may be used to calculate the estimated accumulated timing drift due to the sampling interval offset, until the smallest resolution (i.e., $\frac{T}{8}$) is

reached. Only then the digital interpolator would be activated using the predetermined filter coefficients for the said amount of timing drift. Next, the digital interpolation will be carried out using predetermined filter coefficients, until the counter informs the digital interpolator that sufficient samples have been digitally interpolated, and that it is time to switch over to a new set of predetermined filter coefficients to compensate for a timing drift of $\frac{T}{4}$. This

process is then repeated for the next predetermined resolution according to $\frac{nT}{8}, n = 0, 1, \dots, 7$.

As such, for a N_{FIR} -tap FIR filter with a resolution of $\frac{T}{8}$ and the filter coefficients $h_{MMSE}^d(i), i = -\frac{(N_{FIR}-1)}{2}, \dots, 0, \dots, \frac{(N_{FIR}+1)}{2}$, $d = 0, \dots, 7$, where d is the index for the different coefficients for the digital interpolator, the sampling interval offset compensation process may be described as follows.

5

For an estimated $\Delta\hat{T}$, the number of samples which would result in a sampling timing drift of $\frac{T}{8}$ may be calculated as $\frac{\Delta\hat{T}}{4} \times 10^6$. As mentioned earlier, a counter may be used to keep track of the number of samples which have been received. When the counter reaches $d \times \frac{\Delta\hat{T}}{4} \times 10^6$ number of samples, a

10 control signal is sent to the FIR filter to load the next set of filter coefficients $h_{MMSE}^d(i), i = -\frac{(N_{FIR}-1)}{2}, \dots, 0, \dots, \frac{(N_{FIR}+1)}{2}$, in order to perform digital interpolation on subsequently received samples. The interpolated samples are then passed to the baseband processing block 523 for subsequent processing.

15

It should be noted that simulations have been carried out for embodiments of the invention. Each of the 3 systems used for the purpose of comparison, is similar and only employs a different method for the carrier frequency offset estimation (and compensation). For ease of reference, the 3 systems used are respectively denoted as System A, System B and System C.

20

System A uses the earlier described first conventional method [1].

25

System B uses the earlier described second conventional method [2], with some adaptations made so that it may be applied to an ultra-wideband (UWB) system (or a multi-band (MB) OFDM system). In this context, the number of OFDM symbols used for carrier frequency offset estimation is limited to only 60 (20 per frequency band) in the simulations.

System C uses the earlier described third conventional method [3], again with the appropriate modifications made so that it may be applied to a ultra-wideband (UWB) system (or a multi-band (MB) OFDM system). In the simulations, the number of preambles used in System C for carrier frequency
5 offset estimation is limited to only 30 (10 per band). This is comparable to existing ultra-wideband (UWB) systems, where 24 preambles are typically used.

10 Additionally, an ideal system, where there is no carrier frequency offset and sampling interval offset, is also included for the purpose of comparison.

The channel models (CM) used in the simulations are all taken from IEEE 802.15.3a [4]. In this context, 100 channel realizations are generated for each simulation. Simulations are then carried out for 50 data packets (each of 1
15 Kbytes in size) over the 100 channel realizations.

At the receiver side, the 10 worst performing channel realizations are discarded. The packet error rate (PER) is then calculated using the remaining 90 channel realizations. The calculated packet error rate (PER) is used for the
20 simulation results shown in Figs. 6 to 15. The different data rate modes (such as 480Mbps, 200Mbps, 106.7Mbps and 53.3 Mbps, for example) have been simulated in the likely operating channel models, CM1 to CM4 [4].

Figs. 6, 8, 10 and 11 show the simulation results for the channel models
25 without shadowing, while **Figs. 12 to 15** show the simulation results for the channel models with shadowing.

Further, for the purpose of comparison, the performance results for System A, System B, System C and the ideal system have been included in **Figs. 8, 10**
30 and **11**. Similarly, the performance results for System C and the ideal system have also been included in **Figs. 12 to 15** for the same reason. Likewise, the performance results for System A and the ideal system have been included in **Fig. 6** as well.

In view of the above, for ease of comparison, the respective performance results for System A, System B, System C and the ideal system would be labeled as *n01*, *n03*, *n05* and *n07*, where *n* corresponds to the Figure number.

5

Additionally, in the subsequent discussions on the comparison of performance results, the determination of performance loss/improvement is carried out at the packet error rate (PER) of 8×10^{-2} , unless stated otherwise.

10 **Fig. 6** shows the packet error rate (PER) performance comparison for the data rate mode of 53.3 Mbps in CM4, between conventional methods of estimating and compensating carrier frequency offset and embodiments of the invention.

15 As mentioned earlier, an averaging of the residual carrier frequency offset and the residual sampling interval offset may be carried out across the frequency bands. The performance results of the embodiment of the invention which carry out such an averaging is labeled as 611 in **Fig. 6**. Additionally, in order to demonstrate the effects of such an averaging, the performance results for
20 the embodiment where the said averaging is not carried out for the residual carrier frequency offset and the residual sampling interval offset (609) is also included in **Fig. 6**.

It can be seen from **Fig. 6** that the embodiment without carrying out the
25 averaging shows a performance loss of about 2 dB, when compared to that for the ideal system. On the other hand, the embodiment with the averaging being carried out only shows a performance loss of about 0.5 dB, when compared to that for the ideal system. As such, it can be seen that there is an about 1.5dB performance improvement which may be obtained by carrying
30 out the averaging of the residual carrier frequency offset and the residual sampling interval offset across the frequency bands.

Further, it can also be seen that the embodiments of the invention show a performance improvement over System A.

5 As a side remark, the performance results of System A (601) illustrated a fundamental disadvantage of the first conventional method, in that it is unable to handle the wrapping effects of the measured phase, and as a result, it consistently gives the wrong estimation at the tail end of the data packet.

10 In this context, it should be noted that the use of measured phase for gradient estimation in the first conventional method [1] usually provides an accurate estimate. However, the wrapping effects in the measured phase when the number of OFDM symbols is large will result in significant errors in the gradient estimation (as discussed subsequently in relation to **Fig. 7**).

15 **Fig. 7** shows an illustration of how the wrapping effects in the measured phase when the number of OFDM symbols is large will result in significant errors in the gradient estimation, in the first conventional method.

20 The wrapping effects in the measured phase (for example, when the number of OFDM symbols is large), is illustrated by the labeled lines 701, 703 and 705. When the measured phase of a sub-carrier index approaches the value of $-\pi$, the measured phase of the next sub-carrier index would have a value of about π . This is referred to as the wrapping effect.

25 As a result of the wrapping effect, the best fit line determined (which may be the weighted least squares best fit straight line, for example) is the labeled line 707. It is clear that line 707 would consistently give the wrong estimate on the gradient of the measured phase.

30 As a side note, it can also be seen from **Fig. 7** that if there were no wrapping effects, the best fit line determined would have been line 703. It is clear that the gradient estimation for the measured phase obtained based on line 703 would be accurate.

Fig. 8 shows the packet error rate (PER) performance comparison for the data rate mode of 106.7 Mbps in CM4, between conventional methods of estimating and compensating carrier frequency offset and embodiments of the invention.

It can be seen from **Fig. 8** that the embodiments of the invention (809, 811) show a performance improvement compared to that of all three conventional methods (System A (801), System B (803) and System C (805)).

10

Further, it can be seen that there is only about 1 dB performance loss in the embodiment where the averaging of the residual carrier frequency offset and the residual sampling interval offset is not carried out across the frequency bands (809), when compared to that for the ideal system (807). On the other hand, there is only about 0.2 dB performance loss in the embodiment where the averaging of the residual carrier frequency offset and the residual sampling interval offset is carried out across the frequency bands (811), when compared to that for the ideal system (807). As such, it can be seen that there is an about 0.8dB performance improvement which may be obtained by carrying out the averaging of the residual carrier frequency offset and the residual sampling interval offset across the frequency bands.

15
20

Additionally, by comparing the performance results shown in **Fig. 6** and in **Fig. 8**, it can also be seen that the performance improvement obtained by the averaging of the residual carrier frequency offset and the residual sampling interval offset across the frequency bands for the data rate of 106.7 Mbps (0.8 dB) is less than that obtained for the data rate of 53.3 Mbps (1.5dB).

25

Fig. 9 shows the mean squared error (MSE) of the sampling interval offset estimation observed for the different data rate modes, according to one embodiment of the invention.

30

It should be noted that each data rate mode has a different operating range based on the signal energy to noise ratio (E_b/N_o) parameter.

For example, for the data rate of 53.3Mbps, the operating range is from about 3dB to about 6dB (for the bit energy to noise ratio (E_b/N_o) parameter), which corresponds to the signal energy to noise ratio (E_s/N_o) parameter range from about -7.5dB to about -5dB. It can be seen from **Fig. 9** that the mean squared error (MSE) of the sampling interval offset estimation observed within the said range for the E_s/N_o parameter is in the range of from about 2×10^{-12} to about 6×10^{-12} .

For the data rate of 106.7Mbps, the operating range is from about 4dB to about 7dB (for the bit energy to noise ratio (E_b/N_o) parameter), which corresponds to the signal energy to noise ratio (E_s/N_o) parameter range from about -4.0dB to about -0.5dB. It can be seen from **Fig. 9** that the mean squared error (MSE) of the sampling interval offset estimation observed within the said range for the E_s/N_o parameter is in the range of from about 3×10^{-13} to about 10×10^{-13} .

Further, for the data rate of 200Mbps, the operating range is from about 5dB to about 8dB (for the bit energy to noise ratio (E_b/N_o) parameter), which corresponds to the signal energy to noise ratio (E_s/N_o) parameter range from about 0dB to about 2.5dB. It can be seen from **Fig. 9** that the mean squared error (MSE) of the sampling interval offset estimation observed within the said range for the E_s/N_o parameter is in the range of from about 1×10^{-13} to about 2.5×10^{-13} .

Additionally, for the data rate of 480Mbps, the operating range is from about 7dB to about 10dB (for the bit energy to noise ratio (E_b/N_o) parameter), which corresponds to the signal energy to noise ratio (E_s/N_o) parameter range from about 6dB to about 8.5dB. It can be seen from **Fig. 9** that the mean squared error (MSE) of the sampling interval offset estimation observed within the said

range for the Es/No parameter is in the range of from about 0.7×10^{-13} to about 0.8×10^{-13} .

When comparing the results for the data rate modes of 53.3Mbps and of 106.7Mbps, for example, it can be seen that the mean squared error (MSE) of the sampling interval offset estimation observed for 53.3Mbps is about 10 times greater than the one observed for 106.7Mbps. It should be noted that with larger values of the mean squared error (MSE) of the sampling interval offset estimation, the step of averaging of the residual carrier frequency offset and the residual sampling interval offset has greater effect on the performance improvement obtained.

As a side note, the performance results of the three conventional methods, (System A, System B and System C) are significantly worse off than that of the embodiments of the invention. Additionally, it should be noted that System A even failed to obtain accurate estimations of the sampling interval offset, which resulted in a packet error rate (PER) of 1.

Fig. 10 shows the packet error rate (PER) performance comparison for the data rate mode of 200 Mbps in CM2, between conventional methods of estimating and compensating carrier frequency offset and embodiments of the invention.

It can be seen from **Fig. 10** that there is only about 0.3 dB performance loss in the embodiment where the averaging of the residual carrier frequency offset and the residual sampling interval offset is not carried out across the frequency bands (1009), when compared to that for the ideal system (1007). On the other hand, there is only about 0.1 dB performance loss in the embodiment where the averaging of the residual carrier frequency offset and the residual sampling interval offset is carried out across the frequency bands (1011), when compared to that for the ideal system (1007). As such, it can be seen that there is only about 0.2dB performance improvement obtained by

carrying out the averaging of the residual carrier frequency offset and the residual sampling interval offset across the frequency bands.

However, there is a performance loss of about 6dB for System A when
5 comparing the performance results of System A (1001) against that of the
ideal system (1007). Similarly, there is a performance loss of about 4dB for
System B when comparing the performance results of System B (1003)
against that of the ideal system (1007). Additionally, there is a performance
loss of about 8dB for System C when comparing the performance results of
10 System C (1005) against that of the ideal system (1007). In view of the above,
the embodiments of the invention show better performance compared to that
of System A, System B and System C.

Further, as mentioned earlier, the performance improvement due to the
15 averaging of the residual carrier frequency offset and the residual sampling
interval offset being carried out is only 0.2dB. This performance improvement
is smaller than the one observed for the data rate mode of 53.3Mbps over that
for the data rate mode of 106.7Mbps (0.7dB). This observation may be
explained as follows, based on **Fig. 9**.

20

For the data rate mode of 200 Mbps, the mean squared error (MSE) of the
sampling interval offset estimation observed within its said operating range is
in the range of from about 3×10^{-13} to about 7×10^{-13} . This MSE range is very
small, and therefore, the effects of the averaging of the residual carrier
25 frequency offset and the residual sampling interval offset being carried out on
the performance improvement obtained is not significant.

Additionally, it can also be seen that the performance improvement of the
embodiments of the invention over the System A decreases when the data
30 rate increases. This is because when the data rate increases, the data packet
size would be decreased accordingly (since a constant data payload is
assumed), and a decrease in the data packet size would result in less severe
distortions due to the sampling interval offset.

Fig. 11 shows the packet error rate (PER) performance comparison for the data rate mode of 480 Mbps in CM1, between conventional methods of estimating and compensating carrier frequency offset and embodiments of the invention.

It can be seen from **Fig. 11** that the embodiments of the invention show better performance compared to that of System A, System B and System C.

However, it should also be noted that the performance results of System B (1103) is relatively close to those of the embodiments of the invention. This observation may be explained based on **Fig. 9** as follows.

For the data rate mode of 480 Mbps, there are only 60 OFDM symbols available for transmission. As discussed earlier in relation to **Fig. 5**, in this case, System B actually uses every available OFDM symbols for carrier frequency offset estimation. In view of the above, the case with the data rate mode of 480 Mbps may be considered as an optimum operating performance condition for System B.

Additionally, by comparing the performance results of the embodiments of the invention, it can be seen that there is only about 0.1dB performance improvement obtained by carrying out the averaging of the residual carrier frequency offset and the residual sampling interval offset across the frequency bands. This observation may be explained based on **Fig. 9** as follows.

For the data rate mode of 480 Mbps, the mean squared error (MSE) of the sampling interval offset estimation observed within its said operating range is in the range of from about 0.7×10^{-13} to about 2.5×10^{-13} . This MSE range is very small, and therefore, the effects of the averaging of the residual carrier frequency offset and the residual sampling interval offset being carried out on the performance improvement obtained is not significant.

In view of the above, it can be easily to conclude that the performance improvement of the embodiments of the invention over the three systems (employing conventional methods) would become less significant when a higher data rate mode is used. This is because as the data rate increases, the resultant decreased packet size causes less severe distortion due to the sampling interval offset.

As a side note, subsequent performance results illustrated in **Figs. 12 to 15** would show the performance comparison between a conventional method of estimating and compensating carrier frequency offset (System C) and one embodiment of the invention, over a multi-path channel with shadowing. Further, it should be noted that the averaging of the residual carrier frequency offset and the residual sampling interval offset is not carried out in the embodiment of the invention.

15

Fig. 12 shows the packet error rate (PER) performance comparison for the data rate mode of 53.3 Mbps in CM4 (with shadowing), between a conventional method of estimating and compensating carrier frequency offset and one embodiment of the invention.

20

It can be seen from **Fig. 12** that the embodiment of the invention show better performance compared to that of System C. Further, it can also be seen that the embodiment of the invention requires only about 1.2dB more (in terms of E_b/N_0) compared to the ideal system.

25

Fig. 13 shows the packet error rate (PER) performance comparison for the data rate mode of 106.7 Mbps in CM4 (with shadowing), between a conventional method of estimating and compensating carrier frequency offset and one embodiment of the invention.

30

It can be seen from **Fig. 13** that the embodiment of the invention show better performance compared to that of System C. In more detail, the embodiment of

the invention requires about 6dB less (in terms of E_b/N_0) compared to System C.

5 Additionally, it can also be seen that the embodiment of the invention requires only about 0.6dB more (in terms of E_b/N_0) compared to the ideal system. This implies that the embodiment of the invention can almost compensate fully for the sampling interval offset.

10 **Fig. 14** shows the packet error rate (PER) performance comparison for the data rate of 200 Mbps in CM2 (with shadowing), between a conventional method of estimating and compensating carrier frequency offset and one embodiment of the invention.

15 It can be seen from **Fig. 14** that the embodiment of the invention show better performance compared to that of System C. In more detail, the embodiment of the invention requires about 1.8dB less (in terms of E_b/N_0) compared to System C.

20 Further, it can also be seen that in order to achieve a PER of 8×10^{-2} , the embodiment of the invention requires only about 0.3dB more (in terms of E_b/N_0) compared to the ideal system.

25 The above discussed observations on the performance results seem to indicate that when the data rate is increased, the sampling interval offset has less effect on the performance results.

30 **Fig. 15** shows the packet error rate (PER) performance comparison for the data rate of 480 Mbps in CM1 (with shadowing), between a conventional method of estimating and compensating carrier frequency offset and one embodiment of the invention.

It can be seen from **Fig. 15** that the embodiment of the invention and System C show comparable performance results. Further, it can also be seen that the

embodiment of the invention requires only about 0.2dB more (in terms of Eb/No) compared to the ideal system.

The above discussed observations on the performance results seem to indicate that the sampling interval offset has very little effect on the performance results. Again, this observation agrees with the earlier observation (discussed in relation to **Fig. 14**) that when the data rate is increased, the sampling interval offset has less effect on the performance results.

Embodiments of the invention have the following effects.

Firstly, embodiments of the invention typically show better performance compared to the existing conventional methods. Secondly, as discussed earlier, the embodiments of the invention are easy to implement. As such, the embodiments of the invention show great promise as effective solutions for the problem of estimating and compensating the carrier frequency offset as well as the sampling interval offset.

While the invention has been particularly shown and described with reference to specific embodiments, it should be understood by those skilled in the art that various changes in form and detail may be made therein without departing from the spirit and scope of the invention as defined by the appended claims. The scope of the invention is thus indicated by the appended claims and all changes which come within the meaning and range of equivalency of the claims are therefore intended to be embraced.

In this document, the following publication is cited:

[1] SPW documentation for a timing drift compensator in WLAN library

[2] EP 1363435 A2

[3] Wen Lei, Weiming Cheng and Liming Sun, "Improved Joint Carrier and Sampling Frequency Offset Estimation Scheme for OFDM Systems", Global Telecommunications Conference 2003, vol 4, pp 2315 – 2319, December 2003.

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[4] IEEE 802.15 High Rate Alternative PHY Task Group (TG3a) for Wireless Personal Area Networks, "Multi-band OFDM Physical Layer Proposal for IEEE 802.15 Task Group 3a" IEEE P802.15-03/268r1.

CLAIMS

What is claimed is:

- 5 1. A method of determining a first carrier frequency offset between a transmitter and a receiver for a first frequency band and a second carrier frequency offset between the transmitter and the receiver for a second frequency band, the method comprising:
- 10 determining an estimate of the first carrier frequency offset;
- determining an estimate of the second carrier frequency offset;
- determining an estimate of a first sampling interval offset between the transmitter and the receiver for the first frequency band based on the determined estimate of the first carrier frequency offset;
- 15 determining an estimate of a second sampling interval offset between the transmitter and the receiver for the second frequency band based on the determined estimate of the second carrier frequency offset;
- determining an averaged sampling interval offset based on the calculation of an average of the determined estimate of the first sampling interval offset and the determined estimate of the second sampling interval
- 20 offset; and
- determining the first carrier frequency offset and the second carrier frequency offset based on the determined averaged sampling interval offset.
2. The method of claim 1, wherein
- 25 determining an estimate of the carrier frequency offset between the transmitter and the receiver for each frequency band of a multiplicity of frequency bands;
- determining an estimate of the sampling interval offset between the transmitter and the receiver for each frequency band in the multiplicity of
- 30 frequency bands based on the determined estimate of the carrier frequency offset for each frequency band;

determining an averaged sampling interval offset based on the calculation of an average of the determined estimates of the sampling interval offsets for each frequency band of the multiplicity of frequency bands; and
determining a carrier frequency offset for each frequency band of the multiplicity of frequency bands based on the determined averaged sampling interval offset.

3. The method of claim 1, wherein

the first carrier frequency offset is determined by multiplying the determined averaged sampling interval offset with a first coefficient and the inverse of the sampling interval; and

the second carrier frequency offset is determined by multiplying the determined averaged sampling interval offset with a second coefficient and the inverse of the sampling interval.

4. The method of any one of claims 1 to 3, wherein

the estimate of the first sampling interval offset is determined by multiplying the determined estimate of the first carrier frequency offset with the sampling interval and the inverse of the first coefficient; and

the estimate of the second sampling interval offset is determined by multiplying the determined estimate of the second carrier frequency offset with the sampling interval and the inverse of the second coefficient.

5. The method of any one of claims 3 or 4, wherein the ratio between the first coefficient and the second coefficient is about the same as the ratio between the carrier frequency of the first frequency band and the carrier frequency of the second frequency band.

6. The method of claim 5, wherein the first coefficient and the second coefficient are respectively selected from a group of numbers in the range from 0 to 255.

7. The method of claim 1, wherein the averaged sampling interval offset is calculated as an arithmetic average of the determined estimates of the sampling interval offsets for each frequency band.

5 8. A method of compensating a first carrier frequency offset between a transmitter and a receiver for a first frequency band and a second carrier frequency offset between the transmitter and the receiver for a second frequency band, the method comprising

determining an estimate of the first carrier frequency offset;

10 determining an estimate of the second carrier frequency offset;

determining an estimate of a first sampling interval offset for the first frequency band based on the determined estimate of the first carrier frequency offset;

15 determining an estimate of a second sampling interval offset on the second frequency band based on the determined estimate of the second carrier frequency offset;

20 determining an averaged sampling interval offset based on the calculation of an average of the determined estimate of the first sampling interval offset and the determined estimate of the second sampling interval offset;

determining the first carrier frequency offset and the second carrier frequency offset based on the determined averaged sampling interval offset; and

25 compensating the first carrier frequency offset and the second carrier frequency offset based on the determined first carrier frequency offset and the determined second carrier frequency offset.

9. The method of claim 8, wherein compensating the first carrier frequency offset and the second carrier frequency offset comprises

30 determining a first phase rotation based on the determined first carrier frequency offset;

determining a second phase rotation based on the determined second carrier frequency offset;

- compensating the determined first phase rotation;
- compensating the determined second phase rotation;
- determining a third coefficient iteratively;
- determining the residual first carrier frequency offset based on the
- 5 determined third coefficient;
- determining the residual second carrier frequency offset based on the
- determined third coefficient; and
- compensating the determined residual first carrier frequency offset and
- the determined residual second carrier frequency offset.

10

10. A method of compensating a sampling interval offset between a transmitter and a receiver, a first carrier frequency offset between the transmitter and the receiver for a first frequency band and a second carrier frequency offset between the transmitter and the receiver for a second
- 15 frequency band, the method comprising
- determining an estimate of the first carrier frequency offset;
 - determining an estimate of the second carrier frequency offset;
 - determining an estimate of a first sampling interval offset on the first
 - frequency band based on the determined estimate of the first carrier
 - 20 frequency offset;
 - determining an estimate of a second sampling interval offset on the
 - second frequency band based on the determined estimate of the second
 - carrier frequency offset;
 - determining an averaged sampling interval offset based on the
 - 25 calculation of an average of the determined estimate of the first sampling
 - interval offset and the determined estimate of the second sampling interval
 - offset;
 - determining the first carrier frequency offset and the second carrier
 - frequency offset based on the determined averaged sampling interval offset;
 - 30 compensating the first carrier frequency offset and the second carrier
 - frequency offset based on the determined first carrier frequency offset and the
 - determined second carrier frequency offset; and

compensating the sampling interval offset based on the determined averaged sampling interval offset.

11. The method of claim 10, wherein compensating the sampling interval offset is carried out after the processed received signal has been further processed according to a transform.

12. The method of claim 11, wherein the transform may be selected from a group comprising Fast Fourier Transform (FFT), Discrete Fourier Transform (DFT) and Discrete Cosine Transform (DCT).

13. The method of claim 11, wherein compensating the sampling interval offset is carried out using a frequency domain compensator.

14. The method of claim 13, wherein compensating the sampling interval offset comprises

determining a third phase rotation based on the determined averaged sampling interval offset;

compensating the determined third phase rotation;

determining the residual sampling interval offset; and

compensating the determined residual first carrier frequency offset, the determined residual second carrier frequency offset and the residual sampling interval offset.

15. The method of claim 14, wherein compensating the determined residual first carrier frequency offset, the determined residual second carrier frequency offset and the residual sampling interval offset comprises

determining a fourth phase rotation due to the residual first carrier frequency offset, the determined residual second carrier frequency offset and the residual sampling interval offset; and

compensating the determined fourth phase rotation.

16. The method of claim 15, wherein determining the fourth phase rotation due to the residual first carrier frequency offset, the determined residual second carrier frequency offset and the residual sampling interval offset is carried out using pilot symbols, preamble symbols or synchronization
5 symbols.

17. The method of claim 10, wherein compensating the sampling interval offset is carried out before the processed received signal is further processed according to the transform.
10

18. The method of claim 17, wherein compensating the averaged sampling interval offset is carried out using a time domain compensator.

19. The method of claim 18, wherein the time domain compensator is a
15 finite impulse response (FIR) filter.

20. The method of claim 19, wherein the coefficients of the FIR filter are determined based on one algorithm selected from the group comprising the minimum mean square error (MMSE) algorithm, the linear interpolation
20 algorithm, the polynomial-based interpolation algorithm, the Lagrange algorithm, the piece-wise polynomial interpolation algorithm, the spline interpolation algorithm, the trigonometric interpolation algorithm and the Discrete Fourier Transform (DFT) interpolation algorithm.

25 21. A communication device, comprising
a first determining unit for determining an estimate of a first carrier frequency offset between a transmitter and a receiver for a first frequency band;
a second determining unit for determining an estimate of a second
30 carrier frequency offset between the transmitter and the receiver for a second frequency band;

a third determining unit for determining an estimate of a first sampling interval offset between the transmitter and the receiver for the first frequency band based on the determined estimate of the first carrier frequency offset;

5 a fourth determining unit for determining an estimate of a second sampling interval offset between the transmitter and the receiver for the second frequency band based on the determined estimate of the second carrier frequency offset;

10 a fifth determining unit for determining an averaged sampling interval offset based on the calculation of an average of the determined estimate of the first sampling interval offset and the determined estimate of the second sampling interval offset; and

a sixth determining unit for determining the first carrier frequency offset and the second carrier frequency offset based on the determined averaged sampling interval offset.

15

22. A communication device, comprising

a first determining unit for determining an estimate of a first carrier frequency offset between a transmitter and a receiver for a first frequency band;

20 a second determining unit for determining an estimate of a second carrier frequency offset between the transmitter and the receiver for a second frequency band;

25 a third determining unit for determining an estimate of a first sampling interval offset between the transmitter and the receiver for the first frequency band based on the determined estimate of the first carrier frequency offset;

a fourth determining unit for determining an estimate of a second sampling interval offset between the transmitter and the receiver for the second frequency band based on the determined estimate of the second carrier frequency offset;

30 a fifth determining unit for determining an averaged sampling interval offset based on the calculation of an average of the determined estimate of the first sampling interval offset and the determined estimate of the second sampling interval offset;

a sixth determining unit for determining the first carrier frequency offset and the second carrier frequency offset based on the determined averaged sampling interval offset; and

- 5 a compensating unit for compensating the first carrier frequency offset and the second carrier frequency offset based on the determined first carrier frequency offset and the determined second carrier frequency offset.

23. The communication device of any one of claims 21 to 22,
being a multi-band (MB) orthogonal frequency division multiplexing
10 (OFDM) communication device.

24. The communication device of any one of claims 21 to 23,
being a ultra-wideband (UWB) communication device.

- 15 25. The communication device of any one of claims 21 to 24,
being a WiMedia communication device.