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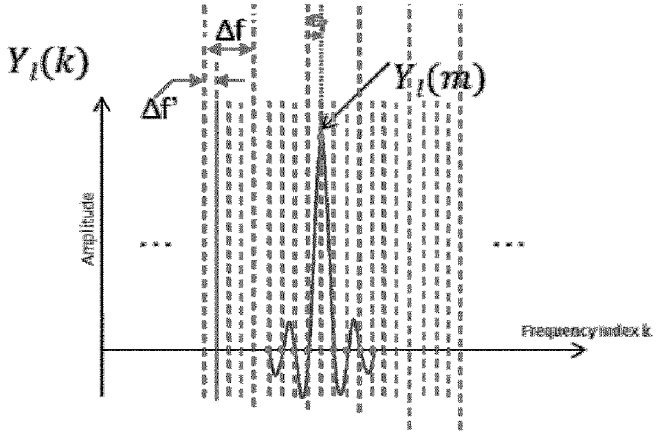


Fig. 7d

(57) Abstract: A receiver for receiving and demodulating an OFDM signal received from an emitter (EMT), comprising a receiving function module (RFM) adapted for demultiplexing said OFDM signal to generate time symbols (yl(n)) and performing a time-to-frequency conversion of said time symbols to generate received symbols ($Y_l(k)$), this OFDM signal comprising synchronization signal constituted by at least a synchronization symbol corresponding to a single subcarrier, and data signal constituted of data symbols; the receiving function module (RFM) being further adapted to receive said synchronization signal during a period substantially longer that the transmission period of said data symbols; and the receiver (RCV) further comprising a carrier frequency offset estimator (CFOE) having: - A computing circuitry (DV) for determining an estimated carrier frequency offset (ε) according to the frequency difference between the frequency (m) of said single subcarrier and the frequency (m' corresponding to a peak within said received symbols ($Y_l(k)$); - A frequency correction module (FC) for applying this estimated carrier frequency offset (ε) to said time symbols, so as to correct the carrier frequency of the received symbols.

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ESTIMATION OF THE CFO BASED ON CHANNEL IMPULSE RESPONSE FOR OFDM SYNCHRONIZATION

FIELD OF THE INVENTION

The invention relates to the field of multicarrier communications systems and more particularly to Orthogonal Frequency-Division Multiplexing (OFDM) systems, including wireless OFDM systems.

BACKGROUND OF THE INVENTION

Orthogonal Frequency-Division Multiplexing (OFDM), also referred to as "multicarrier modulation" (MCM) or "discrete multi-tone modulation" (DMTM), splits up and encodes high-speed incoming serial data, modulating it over a plurality of different carrier frequencies (called "subcarriers") within a communication channel to transmit the data from one user to another. The serial information is broken up into a plurality of sub-signals that are transmitted simultaneously over the subcarriers in parallel.

By spacing the subcarrier frequencies at intervals of the frequency of the symbols to transmit, the peak power of each modulated subcarrier lines up exactly with zero power components of the other modulated subcarriers, thereby providing orthogonality (independence and separability) of the individual subcarriers. This allows a good spectral efficiency (close to optimal) and minimal inter-channel interference (ICI), i.e. interferences between the subcarriers.

For these reasons, OFDM is used in many applications. Many digital transmission systems have adopted OFDM as the modulation technique such as digital broadcasting terrestrial TV (DVB-T), digital audio broadcasting (DAB), terrestrial integrated services digital broadcasting (ISDB-T), digital subscriber line (xDSL), WLAN systems, e.g. based on the IEEE 802.11 a/g standards, cable TV systems, etc.

However, the advantage of the OFDM can be useful only when the orthogonality is maintained. In case the orthogonality is not sufficiently warranted by any means, the performances of the OFDM system may be degraded due to inter-symbol interference (ISI) and inter-carrier interference (ICI).

This could happen as a result of synchronization issues between the clocks of the emitter and of the receiver of the OFDM system. These issues comprise:

- Symbol Timing Offset (STO) and,
- Carrier Frequency Offset (CFO).

Carrier Frequency Offset is notably caused by the mismatch of the oscillators of the emitter and of the receiver of the OFDM system, the nonlinear characteristic of the wireless channel and the Doppler shift when the emitter and/or the receiver are moving.

Even small frequency offsets can dramatically harm the signal to noise ratio (SNR) and the bit-error rate (BER). In particular, OFDM systems employing time-domain differential demodulation are very sensitive to CFO.

Therefore, accurate CFO estimation and correction algorithms should be implemented so as to avoid performance degradation.

Several solutions have been proposed so far.

Several of these solutions are based on a split of the CFO between a Fractional Carrier Frequency Offset (FFO) and an Integer Carrier Frequency Offset (IFO). Each of these two parts can be addressed separately.

However, the proposed solutions are not entirely satisfactory and efficient. These solutions have one or several of the following drawbacks:

- Some techniques decrease the spectral efficiency by using dedicated transmitted data or sample sequences to train the CFO estimator at receiver's side. It is the case of many solutions based on pilot signals as for instance described in "Frequency Synchronization Algorithms for OFDM systems suitable for Communication over Frequency Selective Fading Channels" of Ferdinand Classen and Heinrich Meyr, In Proceedings of the Vehicular Technology Conference (VTC'97).
- Some techniques are not accurate enough.
- Some techniques require complex implementation.
- Some technique implies analog treatment, leading to important silicon overhead.
- Some techniques are not fully compliant with OFDM standards (like WLAN, LTE...)

There is thus a need for a solution permitting to improve the situation by providing a better estimation of the CFO and more particularly of the Integer Carrier Frequency Offset (IFO) part..

SUMMARY OF THE INVENTION

A first aspect of the invention concerns a method for receiving and demodulating an orthogonal frequency division multiplexing signal received from an emitter by a receiver, comprising demultiplexing said orthogonal frequency division multiplexing signal to generate time symbols and performing a time-to-frequency conversion of said time symbols to generate received symbols, said orthogonal frequency division multiplexing signal comprising synchronization signal constituted by at least a synchronization symbol corresponding to a single subcarrier, and data signal constituted of data symbols; said method further comprising:

- receiving from said emitter said synchronization signal during a period substantially longer that the transmission period of said data symbols;
- determining an estimated carrier frequency offset according to the frequency difference between the frequency of said single subcarrier and the frequency corresponding to a peak within said received symbols;
- applying said estimated carrier frequency offset to said time symbols, so as to correct the carrier frequency of said received symbols.

According to embodiments of the invention, said estimated carrier frequency offset may be applied only on time symbols corresponding to said data signal.

A frequency correction signal may be determined from said estimated carrier frequency offset and applied to said time symbols. Said frequency correction signal may be a sine wave signal at a frequency determined by said estimated carrier frequency offset. Said frequency correction signal may be mixed to said time symbols.

Said estimated carrier frequency may be an estimated fractional carrier frequency offset.

The method may also comprise steps of:

- performing a cyclic convolution on said time symbols corresponding to a second synchronization signal;
- determining an estimated integer carrier frequency offset according to a measurement related to the numbers of frequency bins approximately equal to zero at the output of said time-to-frequency conversion;
- applying said estimated integer carrier frequency offset to said time symbols, so as to correct the carrier frequency of said received symbols.

Said measurement may be a difference of the number of frequency bins approximately equal to zero at the beginning and at the end of said output.

Said orthogonal frequency division multiplexing signal may be divided into packets and said synchronization signal is repeated at the beginning of said packets.

Another aspect of the invention concerns a computer program product comprising a computer readable medium, having thereon a computer program comprising program instructions, the computer program being loadable into a data-processing unit and adapted to cause execution of the method previously described, with or without any of its described options, when the computer program is run by the data-processing unit.

Another aspect of the invention concerns a receiver for receiving and demodulating an orthogonal frequency division multiplexing signal received from an emitter, comprising a receiving function module adapted for demultiplexing said orthogonal frequency division multiplexing signal to generate time symbols and performing a time-to-frequency conversion of said time symbols to generate received symbols, said orthogonal frequency division multiplexing signal comprising synchronization signal constituted by at least a synchronization symbol corresponding to a single subcarrier, and data signal constituted of data symbols; said receiving function module being further adapted to receive said synchronization signal during a period substantially longer that the transmission period of said data symbols; and said receiver further comprising a carrier frequency offset estimator having:

- A computing circuitry for determining an estimated carrier frequency offset according to the frequency difference between the frequency of

said single subcarrier and the frequency corresponding to a peak within said received symbol;

- A frequency correction module for applying said estimated carrier frequency offset to said time symbols, so as to correct the carrier frequency of said received symbols.

According to embodiments of the invention, the receiver may comprise one or several of the following features:

Said frequency correction module determines a frequency correction signal from said estimated carrier frequency offset and provides it to said receiving function module, said receiving function module being adapted to apply it to said time symbols.

Said frequency correction module generates as said frequency correction signal a sine wave signal at a frequency determined by said estimated carrier frequency offset.

The receiver further comprises:

- a cyclic convolution module for performing a cyclic convolution on time symbols corresponding to a second synchronization signal,
- a counting module for determining an estimated integer carrier frequency offset according to a measurement related to the numbers of frequency bins approximately equal to zero at the output of said time-to-frequency conversion, and ,
- a frequency correction module for applying said estimated integer carrier frequency offset to said time symbols, so as to correct the carrier frequency of said received symbols.

Said counting module is adapted to compute said measurement as a difference of the number of frequency bins approximately equal to zero at the beginning and at the end of said output.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 illustrates a simplified and high-level block diagram of an OFDM system.

FIG. 2 illustrates a possible block diagram of the carrier frequency offset estimator in accordance with an embodiment of the invention.

FIG. 3 illustrates a possible block diagram of the carrier frequency offset estimator in accordance with another embodiment of the invention.

FIGS. 4a and 4b illustrate a simplified example of transmitted OFDM spectrum.

FIG. 4 is a detailed view of the mixing circuitry according to an embodiment of the invention.

FIG. 5 is a more detailed view of a mixing circuit according to an embodiment of the invention.

FIG. 6 illustrates an OFDM signal made of several packets according to an embodiment of the invention.

FIGS. 7a, 7b, 7c, 7d illustrate a simplified example of transmitted OFDM spectrum according to embodiments of the invention.

FIGS. 8a, 8b and 8c illustrate three different outputs of the time-to-frequency conversion module during the transmission of synchronization signal according to an embodiment of the invention.

DETAILED DESCRIPTION OF EMBODIMENTS OF THE INVENTION

FIG.1 illustrates a simplified and high-level block diagram of an OFDM system comprising an emitter EMT and a receiver RCV connected by a communication channel TC. This communication channel is usually (but not necessarily) wireless and perturbed by noise.

The principle of this OFDM system consists in transmitting several symbols (or signal) in parallel by assigning to each of them a different carrier, each carrier being orthogonal to the others. The number of carriers (or subcarriers) depends on the total bandwidth and on the duration of a symbol (i.e. the size of the time window in which the receiver can capture the transmitted symbols).

The symbols to be transmitted, initially in the frequency domain, are transposed into the time domain and modulated for transmission over the communication channel TC. The receiver RCV transposes the received signals back to the frequency domain to extract the transmitted symbols.

More precisely, the symbols $X_l[k]$ to be transmitted at emitter EMT side are first appropriately encoded and then sent to a serial-to-parallel transformer SP_E. This function blocks aims in extracting from a symbol, a number N of individual values $X_l[k]$, where "k" ranges from 1 to N-1 and "l" represents the ordinal number of the OFDM symbol to be transmitted.

This number N is equal to the number of subcarriers used for the transmission over the communication channel TC. It depends on the standard. For instance according to WLAN 802.11a (on which relies the embodiment depicted on figure 5a), 52 subcarriers are used (48 data subcarriers + 4 pilot subcarriers), and 12 (6 on the "left" and 6 on the "right") subcarriers are not used (zero subcarriers).

Here and in the following descriptions, the variable k will be used for the frequency domain and the variable n for time domain.

In the figure 1, the curly brackets indicate a set of individual symbols associated with arrows. They are used to prevent having references for each arrow and helps simplifying and clarifying the figure 1.

The symbols $\{X_l[k]\}$ which are outputted by the serial-to-parallel transformer SP_E are provided to a frequency-to-time conversion module IDFT. This frequency-to-time convertor can perform an inverse discrete Fourier Transform of the symbols $\{X_l[k]\}$ to generate symbols $\{x_l[n]\}$ in the time domain. These symbols $\{x_l[n]\}$ are then multiplexed by the parallel-to-serial transformer PS_E to produce a signal transmitted over the transmitted channel TC.

$h_l(n)$ represents the time domain transfer function associated with the communication channel. This time domain transfer function $h_l(n)$ (called channel impulse response as well) may vary over time (from one OFDM symbol to another) and is therefore indexed by the number l of the transmitted symbol. The time domain transfer function $h_l(n)$ represents a multipath channel model and is therefore indexed by the number n, n represents the time delay of each of the considered paths of the multipath model.

The multiplexer PS_E modulates the orthogonal subcarriers by the symbols to be transmitted.

The transmitted OFDM symbol $x_l(n)$ signal spectrum is the sum in the frequency domain of the orthogonal subcarrier sinc functions that are superposed over each other. The individual symbols can be independently modulated by using different

types of modulations techniques, like for instance QAM (Quadrature Amplitude Modulation) or PSK (Phase-Shift Keying).

FIG. 4a and 3b illustrate a simplified example of such a transmitted OFDM spectrum at the emitter's side (FIG. 4a) and at receiver's side (FIG. 4b) according to the prior art. These explanations aim at better understanding the problem solved by the invention.

In this simplified example, only 3 subcarriers are depicted in order to keep the figure easy to read. Each subcarrier corresponds to a sinc function which peak matches with a frequency bin associated with an orthogonal modulation frequency. The frequency bins are depicted with vertical dotted lines. The sinc function is defined as $\text{sinc}(x)=\sin(\pi.x)/\ \pi.x$ (in its normalized format).

Taking the example of WLAN 802.11 a/g, the frequency bins are located at -26*312.5 kHz, -25*312.5 kHz..., 25*312.5 kHz, 26*312.5 kHz. (the 0*312.5kHz subcarrier is not used)

In the figure 4a, the symbol $X_l(m)$ corresponds to a value "a" which is at the peak of the corresponding subcarriers and thus independent of the other subcarriers.

In the figure 4b, the subcarriers are shifted by a carrier frequency offset (CFO) ε in the frequency domain. As a consequence, the peaks of the sinc functions do not match anymore the frequency bins. The received symbol $Y_l(m)$ is not equal to "a" anymore. Instead, the received signal is the addition of the values of the subcarriers, so as $Y_l(m)=b+c+d$. In other words, the received signal depends on the other subcarriers (c, d). The orthogonality of the subcarriers is violated, due to the presence of the carrier frequency offset ε; and the received and decoded symbols are in error. This is in fact mainly due to the Fractional Carrier Frequency Offset (FFO).

In conclusion, the two parts of the Carrier frequency offset (CFO) have distinct main impacts:

- The Integer Carrier Frequency Offset (IFO) ε_I shifts the received OFDM signal in the frequency domain.
- The Fractional Carrier Frequency Offset (FFO) ε_F impacts dramatically the orthogonality of the received OFDM signal and jeopardizes its decoding.

According to the invention, a CFO compensation is put in place, both for the IFO and for the FFO, so as to determine the right values of the received symbols.

The symbols $y_l(n)$ are received by the receiver RCV with, potentially such a CFO. The CFO can be positive or negative. No information can be determined by the receiver RCV about the nature of the transmission channel to help valuing the CFO. In other words, at the moment of CFO estimation, we do not have information about the transfer function of the channel. Therefore, the receiver RCV should rely on blind determination techniques to compensate the effects of the Carrier Frequency Offset.

The received symbols can be expressed with the typical following equation:

$$y_l[n] = \frac{1}{N}\sum_{k=0}^{N-1} H_l[k] X_l[k] e^{j2\pi(k+\varepsilon)(n/N)} + z_l[n]$$

Where:

- n, k represent variable over the time and frequency domains respectively.
- H_l is the channel transfer function during the l^{th} symbol.
- N is the number of subcarriers (which depends on the standard that is used).
- z_l is the time domain additive noise of the channel during the transmission of the l^{th} symbol.

$k+\varepsilon$ corresponds to the frequency shifted by the carrier frequency offset ε.

The estimation of the CFO is not a straightforward process.

Its impact on the received signal can be expressed by taking the DFT (Discrete Frequency Transform) of the previous equation. We then get:

$$Y_l[k] = \frac{\sin(\pi\varepsilon_F)}{\mathrm{N}\cdot\sin(\pi\varepsilon_F/\mathrm{N})} \cdot e^{j2\pi\varepsilon_F(N-1/N)} \cdot H_l[k] \cdot X_l[k] + L_l(k) + Z_l[k]$$

Where

$$L_l[k] = e^{j2\pi\varepsilon_F(N-1/N)} \cdot \sum_{m=0, m\neq k}^{N-1} \frac{\sin(\pi(m-k+\varepsilon_F))}{\mathrm{N}\cdot\sin(\pi(m-k+\varepsilon_F)/\mathrm{N})} \cdot H_l[m] \mathrm{X}_l[m] \cdot e^{j2\pi(m-k)(N-1/N)}$$

This $L_l(k)$ term expresses the distortion due to the inter-channel interference (ICI) from other subcarriers into the k^{th} subcarrier frequency component. As already

said, the presence of such a term implies that the orthogonality among subcarrier frequency components is not maintained any longer.

It appears from these two equations that it is in practice impossible to determine directly the FFO

The receiver RCV comprises a receiving function module RFM which generates demodulated symbols Yl[k] from the received symbols stream yl[n]. The demodulated symbols can then be passed over to other circuitry of the receiver RCV (not depicted).

The receiving function module RFM may perform different steps which are usual in OFDM systems but may be subject to variations and different implementations.

The high-level schema of the figure 1 shows a possible implementation where the receiving function module RFM comprises:

- a serial-to-parallel transformer or demultiplexer SP_R, which parallelizes the received symbol to a set of time symbols $\{y_l(n)\}$.
- A time-to-frequency conversion module DFT. This convertor can perform a discrete Fourier Transform of the time symbols $\{y_l(n)\}$ to generate a set of received frequency bins $\{Y_l(k)\}$ in the frequency domain, corresponding to determined subcarriers.
- A parallel-to-serial transformer PS_R to produce symbols $Y_l(k)$ made of these received frequency bins $\{Y_l(k)\}$. These symbols can then be transmitted to other circuitries of the receiver RCV (not depicted in the figure).

In order to perform these steps, the receiving function module RFM shares with the emitter EMT the same subcarriers frequencies, as well as the number of subcarriers N. They could have been communicated beforehand, or they may be set or tuned previously in both the emitter and receiver, for instance according to standards specifications.

The time-to-frequency conversion module DFT uses as inputs a frequency correction signal c in order to correct the effect of the CFO within the transmission channel TC. This frequency correction signal c is provided by a carrier frequency offset estimator CFOE, which will be described later.

This frequency correction signal c can be a sine wave signal at a frequency equal to an estimated frequency of the carrier frequency offset (CFO). Several embodiments are possible.

For instance, the frequency correction signal c can be mixed with the time symbol y1[0], yl[1], yl[2]… yl[N-1] before entering the time-to-frequency conversion module DFT, within a mixing circuitry MX.

Such an implementation is close to the one described in the chapter 5 of the book "MIMO-OFDM Wireles Communications with Matlab", of Yong Soo Cho, Jaekwon Kim, Won Young Yang, Chung-Gu Kang, in connection with the figure 5.16.

FIG. 5 shows the mixing circuitry MX with more details. We can see that each individual time symbol $y_l[m]$ is mixed with the frequency correction signal c in the time domain.

Other embodiments are possible. According to some embodiments, the frequency correction signal c can be provided to the time-to-frequency conversion module DFT, so as to avoid mixing signals in the time domain.

Further, the receiving function module RFM can comprise other apparatuses and circuitries to enhance the OFDM demodulation and decoding schemes, and the embodiment depicted in figure 1 may be regarded as an over simplification. Nonetheless, it is sufficient to the man skilled-in-art to situation the invention and how it interacts with the known OFDM systems and processes.

The receiver RCV receives from the emitter EMT an OFDM signal which can be composed of two parts:

- The preamble: to be used by the receiver for frame detection, time and frequency synchronization, automatic gain control, channel estimation, etc. Embodiments of the invention focus in the frequency synchronization part (synchronization signal) of the preamble.
- A data signal, which should be here understood as the part of the OFDM signal that is not the synchronization signal. It can comprise "real" data (i.e. payload, transporting higher-level datagrams), but also pilot data, CRC (cyclic redundancy check) codes, etc.

In general, the OFDM is divided in packets. Each packet is made of a plurality of OFDM symbols. The size of the packets (i.e. the number of symbols) is dependent of the standard.

FIG. 6 illustrates an OFDM signal made of P packets, P_1, P_2, $P_3 \ldots P_P$.

The synchronization signal is repeated at the beginning of the packets. In other words, the packets P_1, P_2, $P_3 \ldots P_P$ comprise synchronization signal part S_1, S_2, $S_3 \ldots S_P$ and a data part D_1, D_2, $D_3 \ldots D_P$.

According to an aspect of the invention, the synchronization data is constituted by at least a synchronization symbol corresponding to a single subcarrier. In other words, in the frequency domain before the frequency-to-time conversion module IDFT, we have:

$$X_l(k) = s_1 \text{ for } k = m$$
$$X_l(k) = 0 \text{ for } k \neq m$$

where s_1 is an amplitude value. This value can be arbitrary chosen. However an important amplitude is interesting as it allows a better discrimination between the peak and the zeros of the received single subcarrier. According to the modulation scheme, it can be equal to a complex value that has maximum amplitude on the constellation diagram.

As it will be explained later, using a single subcarrier implies that even in the presence of a fractional carrier frequency offset, no inter-channel interference (ICI) is created since there is only one channel that is used.

FIG. 7a depicts the OFDM spectrum corresponding to this synchronization symbol is constituted by a single subcarrier at a frequency m. This subcarrier corresponds to a sinc function which peak matches with a frequency bin with this modulation frequency m. The frequency bins are depicted with vertical dotted lines. The sinc function is defined as $\text{sinc}(x)=\sin(\pi.x)/\pi.x$ (in its normalized format) as it was explained with regard to figures 4a and 4b.

This synchronization signal is generated and then transmitted over the transmission channel TC during a period of time T. This period of time may be around 10 times the normal transmission duration of a data symbol. The longer the period of

time is, the better the estimation of the CFO can be. However mitigation shall be done between the needed precision of the CFO and the loss of bandwidth (or spectral efficiency) due to this additional transmission.

The value of the frequency m can be chosen in various ways. It seems however interesting to choose it in the middle of the range of available frequencies, so as to cover positive and negative values of the CFO in equivalent manner. In the context of a WLAN 802.11a/g implementation, m=32 is an interesting value.

The synchronization signal is received by the receiving function module RFM of the receiver RCV

As explained earlier, in addition to the receiving function module RFM, the receiver RCV further comprises a CFO estimator CFOE.

FIG. 2 depicts a possible embodiment of such a CFO estimator.

It comprises an estimation module EST and a frequency correction module FC.

The estimation module EST is in charge of determining an estimated carrier frequency offset $\hat{\varepsilon}$. The frequency correction module takes this estimated carrier frequency offset $\hat{\varepsilon}$ as input and output a frequency correction signal c which is provided to the mixing circuit MX or to the time-to-frequency conversion module DFT, as it was explained earlier.

The estimation module EST takes as inputs the outputs of the time-to-frequency conversion module DFT $\{Y_l(l)\}$.

In a normal situation, the received signal spectrum would resemble the one depicted on figure 7b. However, the synchronization signal is transmitted during a longer duration T and the received signal spectrum looks more like the one depicted in figure 7d. Figure 7c is a copy of the figure 7a for the purpose of better understanding by showing alignments between sent and received signal spectrums.

Figure 7b shows that a straightforward approach for determining the CFO is not possible in presence of a fractional carrier frequency offset (FFO). Due to this fractional part ε_F, the peak value of the received single subcarrier falls between two frequency indices (or bins). Therefore it can be easily detected and, a fortiori, determined.

However, as the transmitted synchronization signal is T/T_i longer than the normal transmission time T_i of an OFDM symbol, the frequency gaps between the

frequency bins is reduced by the same ratio T/T_i. This is a known mechanism underlying to the OFDM theory that in the frequency domain (after the DFT), the increase of duration by a certain factor is equivalent to the resolution of the frequency bins at the output of the DFT being multiplied by the same factor.

In the example of the figure 7d, this ratio T/T_i is equal to 4 : we can see 4 times more dashed vertical lines representing the frequency bins in the figure 7d than in the figure 7c above, and the gap $\Delta f'$ between 2 successive frequency bins is 4 times smaller than the gap Δf between 2 successive frequency bins in figure 7c.

In the case of WLAN 802.11 a/g, this gap Δf is equal to 312.5 kHz.

If this ratio is high enough, this enables the localization of the peak $Y_l(m')$ since the probability to have it matching (or approximately matching) a frequency bins is linked to the gaps between the frequency bins. In other words and as mentioned earlier, the higher the ratio T/T_i is, the more precise can be the estimation of the CFO ε_F. But increasing this ratio too much would lead to some impact in the spectral efficiency of the transmitted signal. So, a compromise should be found, which depends notably on the technology.

For instance with a ratio $T/T_i = \Delta f/\Delta f' = 4$, we get a CFO estimation accuracy of 10%. This figure can be considered as sufficient in a context of WLAN CFO synchronization.

The estimated fractional carrier frequency offset $\hat{\varepsilon}_F$ can then be determined as the frequency shift between the matching frequency bins m and m', respectively at the emitter side (figures 7a, 7c) and at the receiver side (figure d).

It can be expressed as $\hat{\varepsilon}_F = \frac{\Delta f}{\Delta f'}.(m'-m)$

The computing circuitry DV of the estimation module EST can determine an estimated carrier frequency offset according to the frequency difference between the frequency m of the single subcarrier of the synchronization symbol and the frequency m' corresponding to the peak within the received symbols $Y_l(k)$.

Of course, not only the fractional carrier frequency offset can be estimated this way but also the whole carrier frequency offset.

In the presence of an integer carrier frequency offset ε_I, the frequency shift will be larger than the gap Δf between successive initial frequency bins. Of course the carrier frequency offset is the sum of the integer and fractional parts: $\varepsilon = \varepsilon_I + \varepsilon_F$.

We can write the same with the estimations: $\hat{\varepsilon} = \hat{\varepsilon}_F + \hat{\varepsilon}_I$

According to an embodiment of the invention, the integer carrier frequency offset ε_I can be determined in a different way. In this case, the previously described computing circuitry DV only determines the fractional carrier frequency offset ε

According to this embodiment, the synchronization signal comprises symbols for which, in the frequency domain, all the subcarriers are equal, i.e. all the inputs of the frequency-to-time conversion module IDFT are equal. In other words, during the transmission of the synchronization signal, $\forall k, X_I(k) = s_2$, where s_2 is the constant value. This value can be arbitrary chosen.

According to this embodiment, this second synchronization signal can be sent after or before the previously-described synchronization signal. Each type of synchronization signal has a different characteristic and has a different aim.

As it will be later demonstrated, at the output of the frequency-to-time conversion module IDFT the time symbol vector is then given by:

$$x_I(n) \approx [\delta(n).e^{j\phi}, 0, 0, 0\ldots].$$

And the signal outputted by the parallel-to-serial transformer PS_E and transmitted over the transmission channel TC is then:

$$x_I(n) \approx \delta(n).e^{j\phi}$$

In the ideal case, the value of ϕ is zero. In this case, the convolution circuit CC at receiver side would be simpler to implement.

In practice, due to the modulation scheme that is used and due to the bit precision of the frequency-to-time conversion module IDFT, ϕ is different to zero. However, one of the advantages of the invention is not be robust enough to not be sensible to this approximation.

It aims in determining a good estimated value of the integer carrier frequency offset as perceived by the receiver RCV and in compensating for it.

FIG. 3 depicts a possible embodiment for a CFO estimator CFOE according to this embodiment.

It comprises a cyclic convolution module CC for performing a cycling convolution on the time symbols corresponding to the synchronization signal.

These time symbols $y_l(n)$ are provided to the cyclic convolution module CC by the serial-to-parallel transformer SP_R during the reception of the synchronization signal.

This cyclic convolution module CC can perform convolution between the time symbols $y_l(n)$ and the circulant matrix of the complex conjugate of the transmitted OFDM symbol $x_l(n)$.

In linear algebra, a circulant matrix is a special kind of Toeplitz matrix (or diagonal-constant matrix) where each row vector is rotated one element to the right relative to the preceding row vector. In numerical analysis, circulant matrices are important because they are diagonalized by a discrete Fourier transform, and hence linear equations that contain them may be quickly solved using a fast Fourier transform.

Such a n x n circulant matrix C may take the following form:

$$C = \begin{bmatrix} c_0 & c_{n-1} & \cdots & c_2 & c_1 \\ c_1 & c_0 & c_{n-1} & & c_2 \\ \vdots & c_1 & \ddots & & \vdots \\ c_{n-2} & & & c_0 & c_{n-1} \\ c_{n-1} & c_{n-2} & \cdots & c_1 & c_0 \end{bmatrix}$$

The transmitted OFDM symbol $x_l(n)$ can be known by the receiver RCV as it knows that synchronization signal is being transmitted and because the emitter and the receiver share some data related to this process.

The receiver RCV then knows that $x_l(n) \approx \delta(n).e^{j\phi}$

The convolution can be $y_l(n) * x_l^*(n)$, wherein « * » represents the operator for the circular convolution. $x_l^*(n)$ is the complex conjugate of $x_i(n)$.

The rational for performing such a convolution can be explained as follows:

Let's write $\tilde{y}_l(n)$ the hypothetical l^{th} received synchronization symbol in the case where the CFO ε is null. This hypothesis is made for the purpose of the demonstration.

The "real" received synchronization symbol $y_l(n)$ can then be written as:

$$y_l(n) = \tilde{y}_l(n) \cdot e^{j2\pi\varepsilon n/N}$$

According to OFDM theory, adding the cyclic prefix in the emitter and removing them in receiver can be interpreted by the possibility to express the linear convolution by a circular convolution.

Then, from the « ideal » received synchronization symbol, we can write:

$$x_l(n) * h_l(n) = \tilde{y}_l(n)$$

This result is then transmitted to the DFT module, which outputs a vector: $DFT\left\{y_l(n) * x_l^*(n)\right\}$

This expression can be rewritten according to the previous statements as:

$$DFT\left\{y_l(n) * x_l^*(n)\right\} = DFT\left\{\left[\tilde{y}_l(n) \cdot e^{j2\pi\varepsilon n/N}\right] * x_l^*(n)\right\}$$
$$= DFT\left\{\left[x_l(n) * h_l(n)\right] \cdot e^{j2\pi\varepsilon n/N} * x_l^*(n)\right\}$$

Since the synchronization signal has been chosen so that $x_l(n) \approx \delta(n).e^{j\phi}$, the result of the convolution $y_l(n) * x_l^*(n)$ is approximately δ(n).

The previous expression can then be written

$$DFT\left\{y_l(n) * x_l^*(n)\right\} = DFT\left\{h_l(n) \cdot e^{j2\pi\varepsilon n/N}\right\} = H_l(k-\varepsilon)$$

In other words, an estimation $\hat{\varepsilon}$ of the CFO can be determined by counting the number for zeros at the beginning or at the end of the expression $DFT\left\{y_l(n) * x_l^*(n)\right\}$

FIGS. 8a, 8b and 8c illustrate three different outputs of the time-to-frequency conversion module DFT during the transmission of synchronization signal, corresponding to three different situations. There are based on a WLAN 802 a/g standard and the signals, including the synchronization signal, make use of 52 subcarriers.

In the figure 8a, there is no CFO. The signal spectrum corresponds to these 52 subcarriers (48 data subcarriers and 4 pilot subcarriers). At the beginning and at the end of this spectrum, there are 12 unused subcarriers, which are set to zero according to OFDM principle.

In the figure 8b, a positive CFO has been introduced during the transmission of the synchronization signal over the transmission channel TC.

The spectrum is shifted to the left: the number of zero subcarriers at the beginning of the spectrum is reduced, while the number of zero subcarriers at the end of the spectrum is increased. The shift corresponds to the CFO ε.

In the figure 8c, a negative CFO has been introduced during the transmission of the synchronization signal over the transmission channel TC.

The spectrum is shifted to the right: the number of zero subcarriers at the beginning of the spectrum is increased, while the number of zero subcarriers at the end of the spectrum is reduced. The shift corresponds to the CFO ε.

A way to determine the estimation $\hat{\varepsilon}$ for the CFO can be to count the difference between the numbers of zero subcarrier at the beginning and at the end of the output of the DFT module. This different correspond to $2\hat{\varepsilon}$.

Accordingly, the output of the time-to-frequency conversion module DFT is provided to a counting circuitry CNT of the estimation module EST.

This counting circuitry CNT makes a measurement related to the frequency bins associated with the DFT module. More particularly, it counts the number of zero subcarriers at the beginning and the end of the provided signal $Y_l(k)$, and can then subtracts these 2 values.

In the embodiment depicted in the figure 3, this value is considered as the estimated integral carrier frequency offset $\hat{\varepsilon}_I$. This value is then provided to the frequency correction module FC.

As the zero subcarriers may not be exactly equal to zero due to noise and bit precision of the time-to-frequency and frequency-to-time modules, it could be helpful to introduce a threshold. Below this threshold, the value of the subcarrier would be considered as a zero subcarrier, whereas above this threshold, the subcarrier would be considered as transporting the symbol and will not be considered as a zero subcarrier.

More generally it can be stated that the estimated IFO is determined according to a measurement related to the numbers of frequency bins approximately equal to zero at the output of the time-to-frequency conversion.

The estimated integer carrier frequency offset $\hat{\varepsilon}_I$ can be provided by the computing circuitry DV as previously described. The estimated fractional carrier frequency offset is also provided to the frequency correction module FC.

In the embodiment depicted in figure 2, the estimated carrier frequency offset (corresponding to the integer and fractional parts so that $\hat{\varepsilon} = \hat{\varepsilon}_I + \hat{\varepsilon}_F$) is provided to the frequency correction module FC.

The frequency correction module FC takes the estimated IFO $\hat{\varepsilon}_I$, FFO $\hat{\varepsilon}_F$ or CFO $\hat{\varepsilon}$ as input so as to determine the frequency correction signal c.

In the case it receives separate signals $\hat{\varepsilon}_I$ and $\hat{\varepsilon}_F$, it can simply reconstruct an estimation of the CFO by computing $\hat{\varepsilon} = \hat{\varepsilon}_I + \hat{\varepsilon}_F$.

According to an embodiment of the frequency correction module FC, it can generate a sinusoidal wave at a frequency $F_{FC=}|\hat{\varepsilon}|$*312.5 kHz as $|\hat{\varepsilon}|$ is a normalized value with respect to the inter subcarrier frequency Δf (Δf=312.5kHz in all 802.11 OFDM WLAN standards).

- If the CFO is positive, F_{FC} down-converts the received signal by mixing down the received signal in the time domain (i.e. before the IFFT block in the receiver).
- If the CFO is negative, F_{FC} up-converts the received signal by mixing up the received signal in the time domain (i.e. before the IFFT block in the receiver).

Mixing-up and mixing-down can have different implementations in RF or baseband.

In this embodiment, a complex mixing is performed. Using a complex multiplier before the input of the S/P converter of the receiver is a well-known technique.

Functionally, the frequency correction module FC is thus performing a classical task and may be implemented in various ways accessible to the man skilled-in-the-art.

For this reason, it will not be further detailed, as the invention is independent of the actual implementation of this functional module.

As explained earlier, the frequency correction signal c is provided as input of the receiving function module RFM.

The invention has been described with reference to preferred embodiments; but other embodiments and variations are possible while being within the scope of the claimed invention.

CLAIMS

1. A method for receiving and demodulating an orthogonal frequency division multiplexing signal received from an emitter (EMT) by a receiver (RCV), comprising demultiplexing said orthogonal frequency division multiplexing signal to generate time symbols ($y_l(n)$) and performing a time-to-frequency conversion of said time symbols to generate received symbols ($Y_l(k)$), said orthogonal frequency division multiplexing signal comprising synchronization signal constituted by at least a synchronization symbol corresponding to a single subcarrier, and data signal constituted of data symbols; said method further comprising:
   - receiving from said emitter said synchronization signal during a period substantially longer that the transmission period of said data symbols;
   - determining an estimated carrier frequency offset ($\hat{\varepsilon}$) according to the frequency difference between the frequency (m) of said single subcarrier and the frequency (m') corresponding to a peak within said received symbols ($Y_l(k)$);
   - applying said estimated carrier frequency offset ($\hat{\varepsilon}$) to said time symbols, so as to correct the carrier frequency of said received symbols.

2. The method according to claim 1, wherein said estimated carrier frequency offset ($\hat{\varepsilon}$) is applied only on time symbols corresponding to said data signal.

3. The method according to any of previous claims, wherein a frequency correction signal (c) is determined from said estimated carrier frequency offset ($\hat{\varepsilon}$) and applied to said time symbols ($y_l(n)$).

4. The method according to claim 3, wherein said frequency correction signal (c) is a sine wave signal at a frequency determined by said estimated carrier frequency offset ($\hat{\varepsilon}$).

5. The method according to claim 4, wherein said frequency correction signal (c) is mixed to said time symbols ($y_l(n)$).

6. A method according to any of previous claims, wherein said estimated carrier frequency ($\hat{\varepsilon}$) is an estimated fractional carrier frequency offset ($\hat{\varepsilon}_F$).

7. A method according to claim 2, further comprising steps of:
   - performing a cyclic convolution on said time symbols corresponding to a second synchronization signal;
   - determining an estimated integer carrier frequency offset ($\hat{\varepsilon}_I$) according to a measurement related to the numbers of frequency bins approximately equal to zero at the output of said time-to-frequency conversion;
   - applying said estimated integer carrier frequency offset ($\hat{\varepsilon}_I$) to said time symbols, so as to correct the carrier frequency of said received symbols.

8. The method according to claim 7, wherein said measurement is a difference of the number of frequency bins approximately equal to zero at the beginning and at the end of said output.

9. The method according to any of the previous claims, wherein said orthogonal frequency division multiplexing signal is divided into packets and said synchronization signal is repeated at the beginning of said packets.

10. A computer program product comprising a computer readable medium, having thereon a computer program comprising program instructions, the computer program being loadable into a data-processing unit and adapted to cause execution of the method according to any of claims 1 to 8 when the computer program is run by the data-processing unit.

11. A receiver for receiving and demodulating an orthogonal frequency division multiplexing signal received from an emitter (EMT), comprising a receiving function module (RFM) adapted for demultiplexing said orthogonal frequency division multiplexing signal to generate time symbols ($y_l(n)$) and performing a

time-to-frequency conversion of said time symbols to generate received symbols ($Y_l(k)$), said orthogonal frequency division multiplexing signal comprising synchronization signal constituted by at least a synchronization symbol corresponding to a single subcarrier, and data signal constituted of data symbols; said receiving function module (RFM) being further adapted to receive said synchronization signal during a period substantially longer that the transmission period of said data symbols; and said receiver (RCV) further comprising a carrier frequency offset estimator (CFOE) having:

- A computing circuitry (DV) for determining an estimated carrier frequency offset ($\hat{\varepsilon}$) according to the frequency difference between the frequency (m) of said single subcarrier and the frequency (m') corresponding to a peak within said received symbols ($Y_l(k)$);
- A frequency correction module (FC) for applying said estimated carrier frequency offset ($\hat{\varepsilon}$) to said time symbols, so as to correct the carrier frequency of said received symbols.

12. The receiver according to claim 11, wherein said frequency correction module (FC) determines a frequency correction signal (c) from said estimated carrier frequency offset ($\hat{\varepsilon}$) and provides it to said receiving function module (RFM), said receiving function module (RFM) being adapted to apply it to said time symbols ($y_l(n)$).

13. The receiver according to claim 12, wherein said frequency correction module (FC) generates as said frequency correction signal (c) a sine wave signal at a frequency determined by said estimated carrier frequency offset ($\hat{\varepsilon}$).

14. The receiver according to claim 11 to 13, further comprising:

- a cyclic convolution module (CC) for performing a cyclic convolution on time symbols corresponding to a second synchronization signal,
- a counting module (CNT) for determining an estimated integer carrier frequency offset ($\hat{\varepsilon}$) according to a measurement related to the numbers of frequency bins approximately equal to zero at the output of said time-to-frequency conversion, and ,

- a frequency correction module (FC) for applying said estimated integer carrier frequency offset ($\hat{\varepsilon}$) to said time symbols, so as to correct the carrier frequency of said received symbols.

15. The receiver according to claim 10, wherein said counting module (CNT) is adapted to compute said measurement as a difference of the number of frequency bins approximately equal to zero at the beginning and at the end of said output.

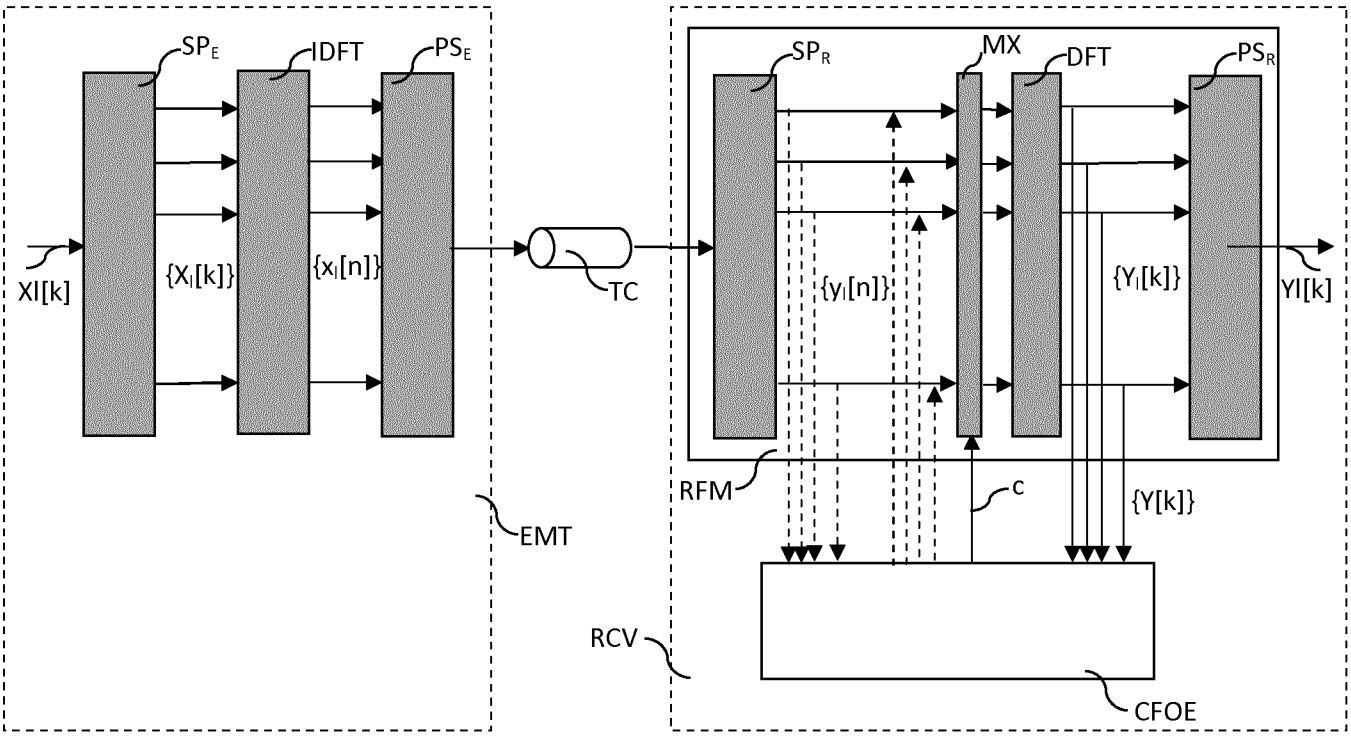

SP_E
IDFT
PS_E
XI[k]
{X_I[k]}
{x_I[n]}
TC
EMT
SP_R
MX
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PS_R
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YI[k]
RFM
c
{Y[k]}
RCV
CFOE

Fig. 1

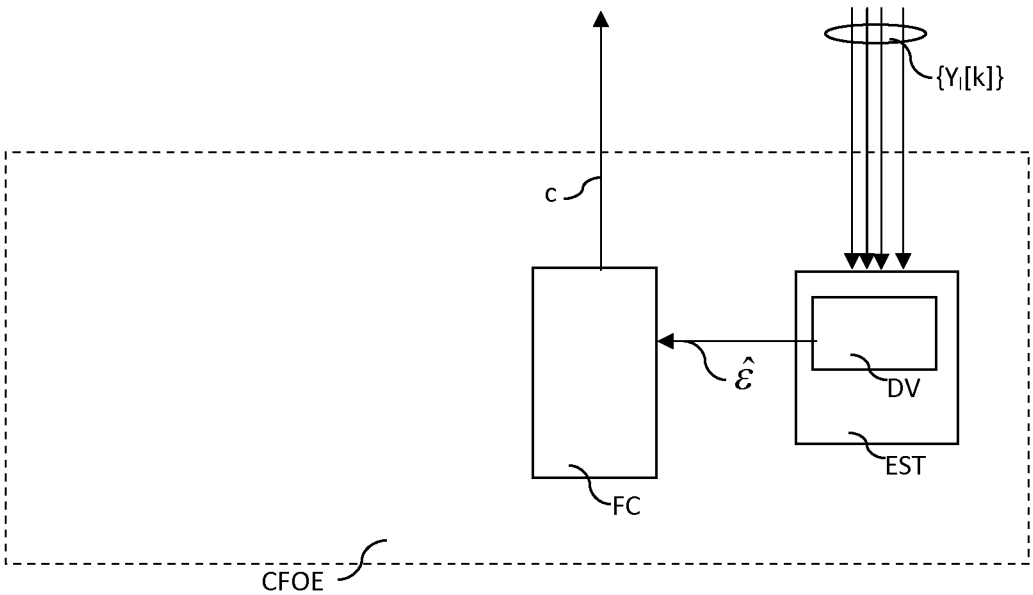

{Y_I[k]}
c
$\hat{\varepsilon}$
DV
EST
FC
CFOE

Fig. 2

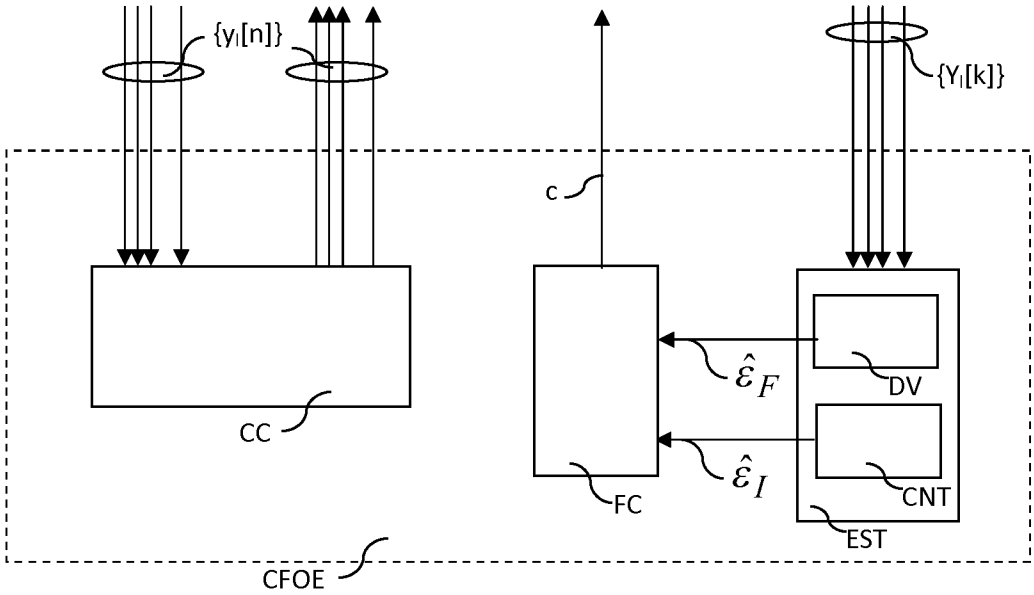


Fig. 3

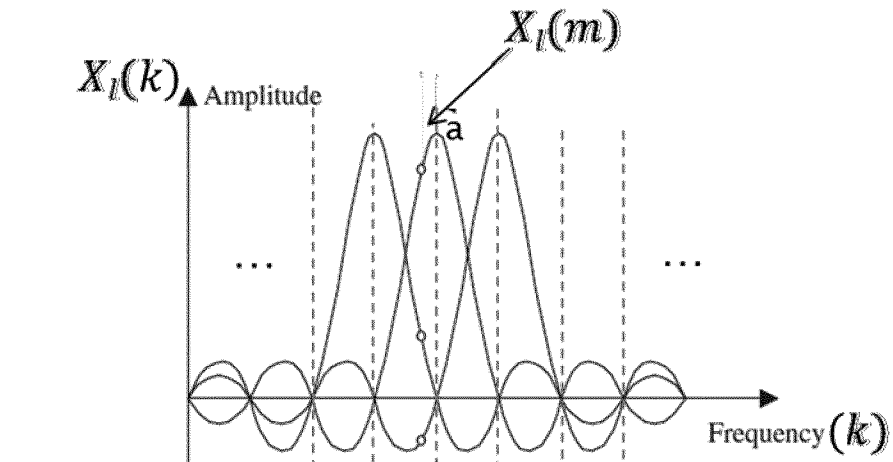


Fig. 4a

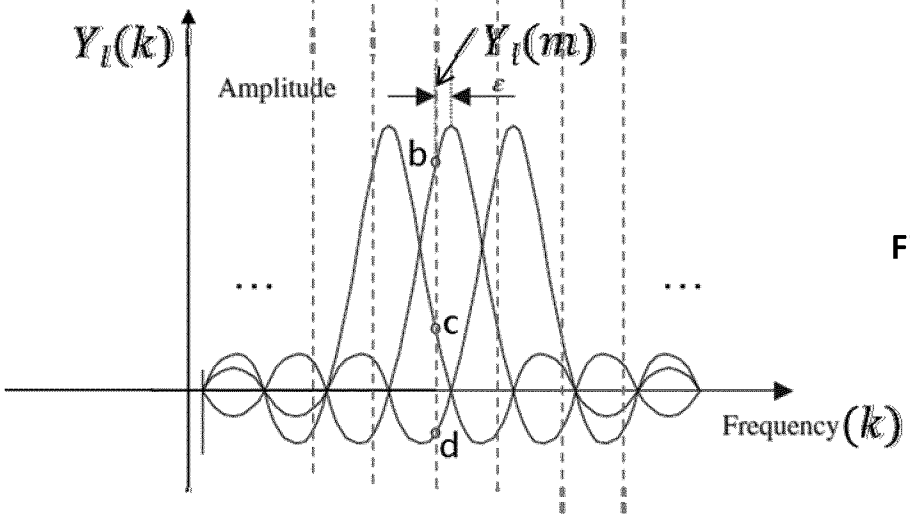


Fig. 4b

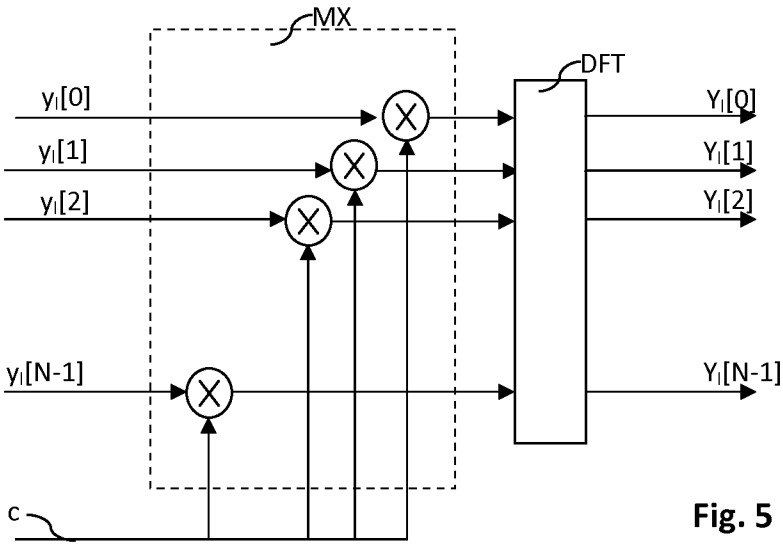


Fig. 5

Fig. 7a

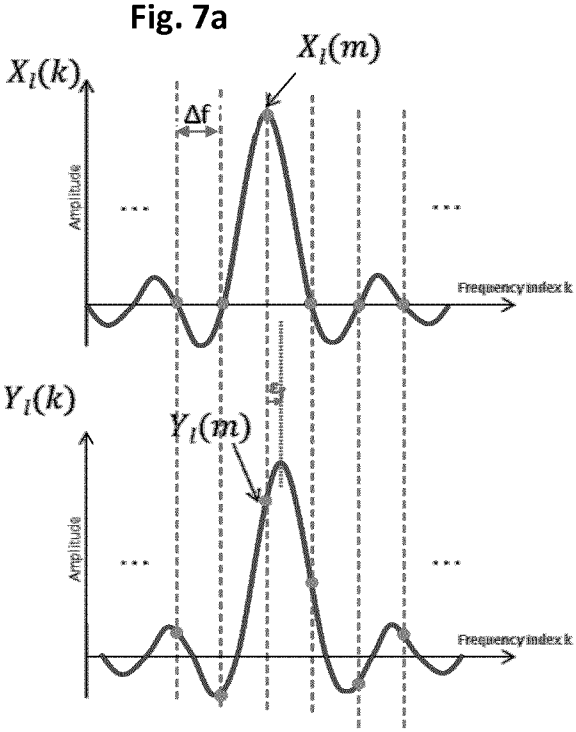


Fig. 7b

Fig. 7c

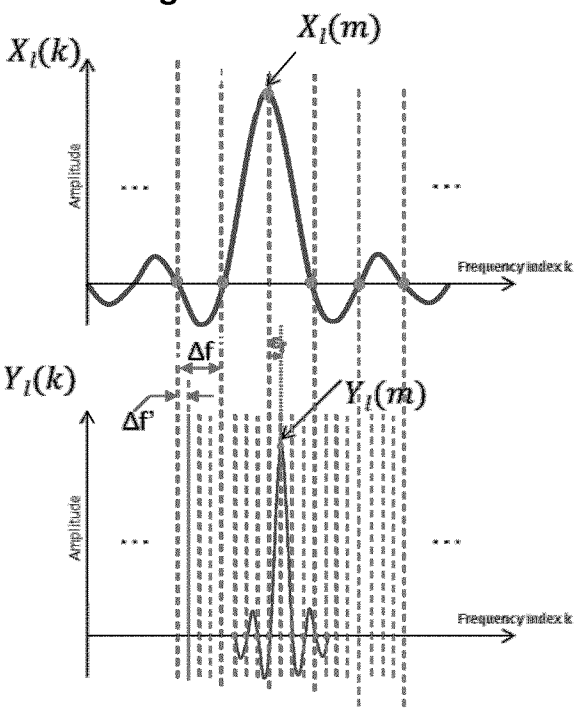


Fig. 7d

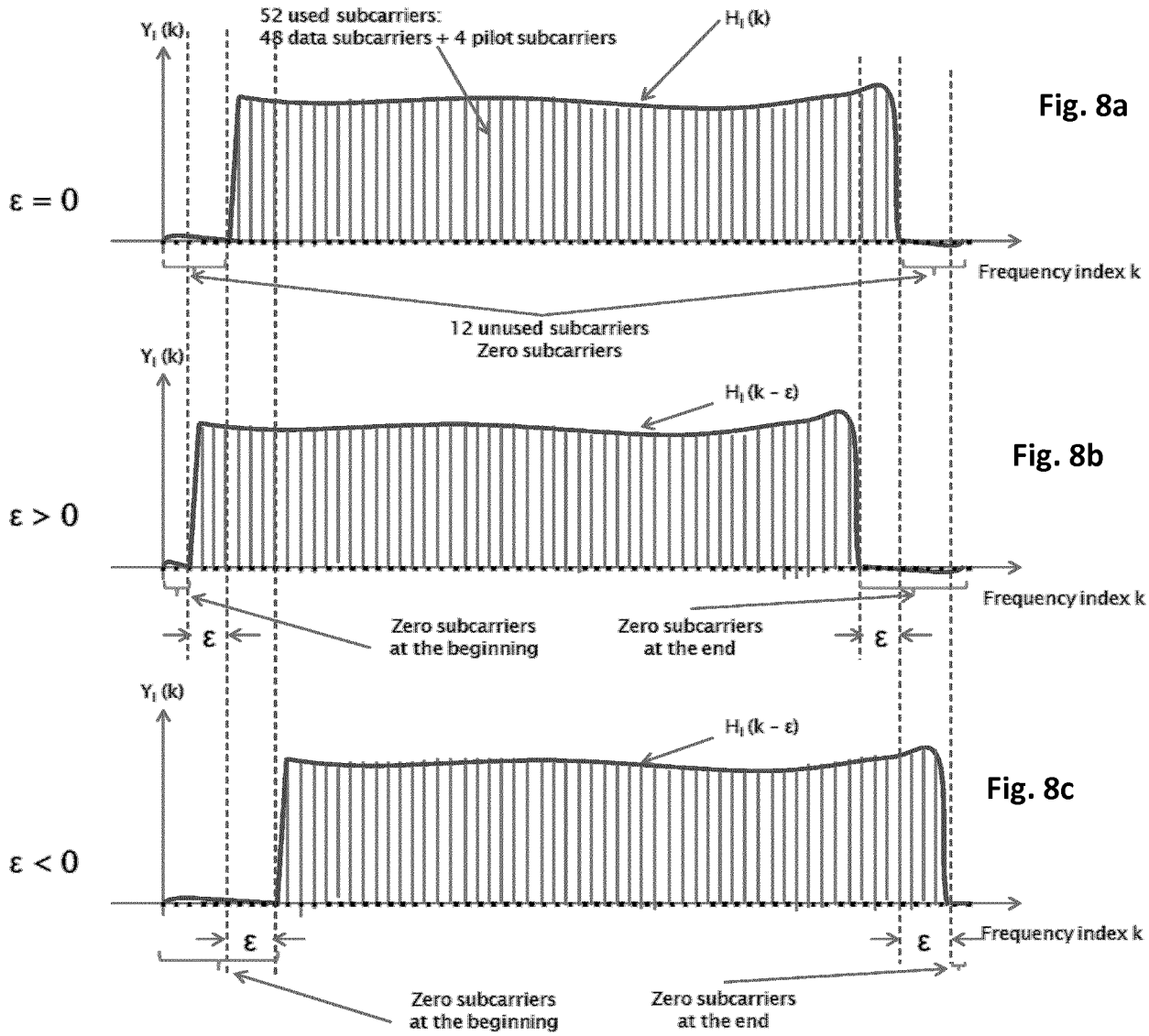


Fig. 8a

Fig. 8b

Fig. 8c

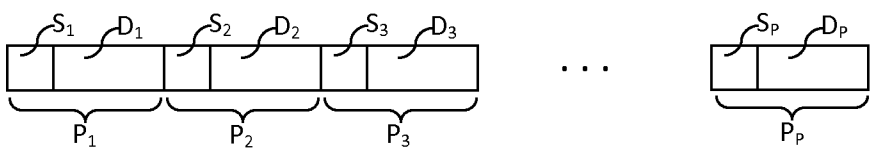


Fig. 6

INTERNATIONAL SEARCH REPORT

International application No
PCT/EP2013/075001

A. CLASSIFICATION OF SUBJECT MATTER
INV. H04L27/26
ADD.

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
H04L

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

EPO-Internal, WPI Data

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	US 2004/120410 A1 (PRIOTTI PAOLO [JP]) 24 June 2004 (2004-06-24) paragraph [[0016]] - paragraph [[0027]] paragraph [[0044]] - paragraph [[0045]] paragraph [[0049]] - paragraph [[0050]] paragraph [[0056]] - paragraph [[0057]] -----	1-15

☐ Further documents are listed in the continuation of Box C.

☒ See patent family annex.

* Special categories of cited documents :

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier application or patent but published on or after the international filing date

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"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
27 January 2014	04/02/2014

Name and mailing address of the ISA/	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Fax: (+31-70) 340-3016	Douglas, Ian

1

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No
PCT/EP2013/075001

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
US 2004120410 A1	24-06-2004	AU 2003297345 A1	22-07-2004
		CN 1748397 A	15-03-2006
		EP 1573997 A1	14-09-2005
		JP 4162248 B2	08-10-2008
		JP 2006512032 A	06-04-2006
		KR 20050089840 A	08-09-2005
		RU 2303856 C2	27-07-2007
		UA 82209 C2	25-03-2008
		US 2004120410 A1	24-06-2004
		WO 2004059936 A1	15-07-2004