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(54) Title: METHOD OF TRANSMITTING A SIGNAL COMPRISING A SEQUENCE OF ORIGINAL DATA SYMBOLS, METHOD OF RECOVERING THE SIGNAL, TRANSMITTER, RECEIVER AND SIGNAL

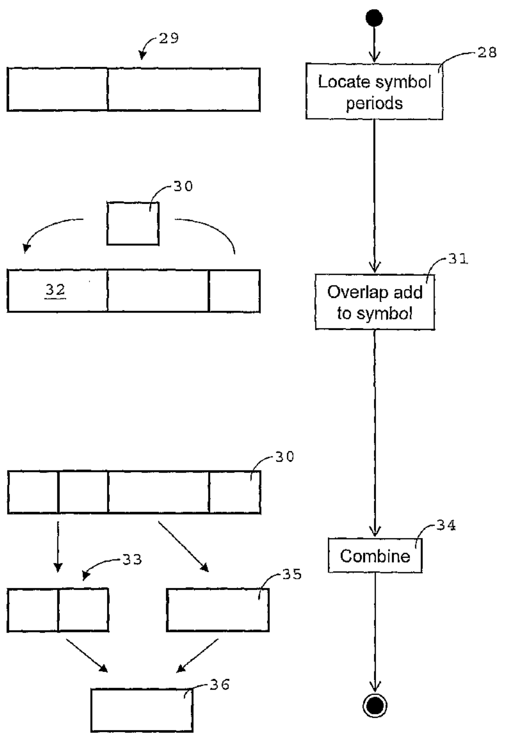

Fig. 3

(57) Abstract: A method of transmitting a number of parallel sequences of original data symbols includes modulating the parallel sequences on to respective orthogonal sub-carriers by applying a discrete inverse transform to each original data symbol to obtain a corresponding number of parallel symbol sequences, each symbol (14, 16) having a length corresponding to a number of samples in an original data symbol. The method further includes generating one of a corresponding number of parallel signals from each symbol sequence, each of the parallel signals being partitioned into symbol periods (ΔT_1-AT_4) of a generally equal length corresponding to at least the length of one symbol (14, 16). At least one symbol period [ΔT_2, ΔT_4) consisting of at least part of a padding sequence (15,17) is included adjacent a symbol period [ΔT_1, ΔT_3) including one of the symbols (14, 16) in at least one of the parallel signals.

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METHOD OF TRANSMITTING A SIGNAL COMPRISING A SEQUENCE OF ORIGINAL DATA SYMBOLS, METHOD OF RECOVERING THE SIGNAL, TRANSMITTER, RECEIVER AND SIGNAL

The invention relates to a method of transmitting a number of parallel sequences of original data symbols,

modulating the parallel sequences on to respective orthogonal sub-carriers by applying a discrete inverse transform to each original data symbol to obtain a corresponding number of parallel symbol sequences, each symbol having a length corresponding to a number of samples in an original data symbol, and

generating one of a corresponding number of parallel signals from each symbol sequence, each of the parallel signals being partitioned into symbol periods of a generally equal length corresponding to at least the length of one symbol.

The invention also relates to a transmitter for transmitting a number of parallel sequences of original data symbols, including a system for modulating the parallel sequences on to respective orthogonal sub-carriers by applying a discrete inverse transform to each original data symbol to obtain a corresponding number of parallel symbol sequences, each symbol having a length corresponding to a number of samples in an original data symbol, which system is arranged to generate one of a corresponding number of parallel signals from each symbol sequence, such that each of the parallel signals are partitioned into symbol periods of a generally equal length corresponding to at least the length of one symbol.

The invention also relates to a method of recovering a signal comprising a sequence of original data symbols, including:

receiving a composite signal, the composite signal being a composite of a number of parallel signals, each partitioned into symbol periods of a generally equal length, each of the parallel signals being obtainable by modulating a plurality of parallel data sequences onto orthogonal sub-carriers to obtain a corresponding number of parallel symbol sequences and by inserting data samples between the symbols,

locating sections of the parallel signals corresponding to the symbol periods,

obtaining a block of successive data samples spanning at least two successive symbol periods in one of the parallel signals and commencing with a symbol,

element-by-element addition of a number of data samples at a first end of the obtained block to a corresponding number of data samples at an opposite, second end,

combining one or more symbol-length blocks of data with a result of the element-by element addition and

application of a discrete transform to a result of the combination.

The invention also relates to a receiver for recovering a signal comprising a sequence of original data symbols, including:

an input for receiving a composite signal, the composite signal being a composite of a number of parallel signals, each partitioned into symbol periods of a generally equal length, each of the parallel signals being obtainable by modulating a plurality of parallel data sequences onto orthogonal sub-carriers to obtain a corresponding number of parallel symbol sequences and by inserting data samples between the symbols,

a data processing system for locating sections of the parallel signals corresponding to the symbol periods, wherein the data processing system is configured to:

obtain a block of successive data samples spanning at least two successive symbol periods in one of the parallel signals and commencing with a symbol,

perform element-by-element addition of a number of data samples at a first end of the obtained block to a corresponding number of data samples at an opposite, second end,

combine one or more symbol-length blocks of data with a result of the element-by element addition and

apply a discrete transform to a result of the combination.

The invention also relates to a signal composed of a number of parallel signals,

each partitioned into symbol periods of a generally equal length, each of the parallel signals being obtainable by modulating a plurality of parallel data sequences onto orthogonal sub-carriers to obtain a corresponding number of parallel symbol sequences and by inserting data samples between the symbols,

wherein the signal includes data for locating the symbol periods.

The invention also relates to a computer programme.

WO 2005/114858 *discloses a transmitter and receiver for* ultra-wideband OFDM signals employing a low-complexity CDMA layer for bandwidth expansion. The proposed signal waveform is OFDM symbols that have been upsampled by repetition. The repetition is done in the time-domain in units of whole OFDM signals. A receiver architecture designed to receive the bandwidth-expanded OFDM signal in the presence of multi-path delay in the radio frequency channel includes a conventional down-conversion receiver followed by a pair of Analogue to Digital converters and a complex sample former. The complex samples are first applied to a preamble detection block, followed in succession by a synchronisation block and a channel estimation block. Polarity inversion, which reverses that done in the transmitter, is represented by a digital multiplier inserted directly before a block labelled "Store and additively combine N OFDM symbols". Bandwidth/rate reduction in the receiver is performed by the "Store and additively combine N OFDM symbols" block. This operation is a simple additive operation. An "overlap and add" block is responsible for creating the required cyclic properties for a subsequent Fast Fourier Transform (FFT) operation.

A problem of the known method is that it requires a relatively complex receiver to avoid inter-symbol-interference, and thus inter-carrier interference. This is because the samples of the zero energy-suffix following an OFDM symbol must be large in number to avoid inter-symbol interference, and the OFDM symbol must conventionally be comprised of more than that number of samples in order to avoid excessive deterioration of the transmission efficiency.

It is an object of the invention to provide methods, a transmitter, receiver, signal and computer programme of the types mentioned above that provide the potential for increasing the signal-to-interference ratio with sufficient multi-path energy capture, and which are suitable for implementation in a relatively simple receiver.

This object is achieved by the method of transmitting a signal comprising a sequence of original data symbols, which is characterised by including at least one symbol period consisting of at least part of a padding sequence adjacent a symbol period including one of the symbols in at least one of the parallel signals.

By including at least one symbol period consisting of at least part of a padding sequence adjacent a symbol period including one of the symbols, a larger number of padding data samples can be inserted between symbols without increasing the symbol period. Because a padding sequence or padding sequence part of the length of a symbol period is added, the potential for use of diversity combination to increase the multi-path signal energy capture is provided. Although there is a decrease in efficiency, this is compensated for by the potential for an increase in multi-path signal energy capture, indirectly improving the efficiency. Moreover, a relatively long padding sequence can be concatenated with a symbol based on an original data symbol. Indeed the padding sequence is longer than the number of data samples in a symbol. For a given channel length, the symbol length can therefore be quite short. The implication is that the number of points of the discrete transform used in a receiver to obtain an original data symbol can be low. Thus, a relatively simple receiver can be used. Where the potential for diversity combination between the symbol and a symbol formed from the part of the signal corresponding to the symbol period consisting of padding (which, at the receiver, comprises echoes of the symbol formed from the original data symbol) is used, shorter registers can be employed. The relatively large amount of padding compared to the length of a symbol is effective in avoiding inter-symbol interference. Where inter-symbol interference is absent at the receiver, the orthogonality of the parallel signals is maintained, so that inter-carrier interference is also avoided. An added effect is that, because the symbol period consisting of at least part of a padding sequence is included adjacent a symbol period including one of the symbols in at least one of the parallel signals, there is time spreading within one band. This symbol-spreading method therefore requires no switching between bands - although switching, at a still relatively low rate, could be carried out additionally - in the receiver. The receiver can be simpler as a consequence of this.

An embodiment of the method includes transmitting the parallel signals to a receiver through a channel, wherein the length(s) of the padding sequence(s) in the at least one symbol period and of any padding sequence part included in the symbol period including one of the symbols is greater in total than a channel excess delay of the channel.

An effect is that, after receipt of the symbol at a receiver, all echoes have died out by the time the next symbol is received. Inter-symbol interference is thus avoided.

An embodiment includes transmitting the parallel signals to a receiver arranged to apply an element-by-element addition of a block of samples retrieved from an end of a padding sequence of that one of the at least one symbol periods furthest removed from the symbol to a block of samples of the symbol at an opposite end of the symbol.

An effect is that all the multi-path energy is captured in an efficient manner, because a relatively short discrete transform operation is used to obtain the continuous transform of a relatively long sequence. This sequence includes the full convolution of the symbol with the channel.

In an embodiment, the original data symbols are obtained by applying a multi-level signalling scheme to a bit sequence, wherein the number of levels is at least sixteen.

An effect is to raise the bandwidth efficiency, because each original symbol is based on a larger number of bits. It is only possible to do this with an acceptable bit error rate because of the relatively high signal to interference ratio provided by the method. Thus, there is a synergistic effect in that the efficiency-lowering effect of symbol spreading is compensated for by the use of a higher order signalling scheme.

According to another aspect, the transmitter according to the invention is characterised in that the transmitter is arranged to insert at least one symbol period consisting of a padding sequence adjacent a symbol period including one of the symbols in at least one of the parallel signals.

In an embodiment, the transmitter is arranged to carry out a method according to the invention.

According to another aspect, the method of recovering a signal comprising a sequence of original data symbols according to the invention is characterised in that the symbol-length blocks of data are obtained by partitioning the data between the symbol and the number of data samples at the first end in the block of successive data samples into one or more symbol-length blocks of data.

An effect is that a relatively large amount of the multi-path energy is captured. Delayed versions of the data symbol are summed before the transform is applied to obtain the original data symbol.

An embodiment of the method includes recovering an original bit sequence by applying to the original data symbols a multi-level signalling scheme, wherein the number of levels is at least sixteen.

An effect is to increase the bandwidth efficiency whilst achieving a good bit error rate.

According to another aspect, the receiver according to the invention is characterised in that the data processing system is arranged to obtain the symbol-length blocks of data by partitioning the data between the symbol and the number of data samples at the first end in the block of successive data samples into one or more symbol-length blocks of data.

In an embodiment, the receiver is arranged to carry out a method according to the invention.

According to another aspect, the signal according to the invention is characterised in that at least one of the parallel signals includes at least one symbol period consisting of a padding sequence adjacent a symbol period including one of the symbols in at least one of the parallel signals.

According to another aspect, the computer programme according to the invention is capable, when incorporated in a machine-readable medium, of causing a system having information processing capabilities to perform a method according to the invention.

The invention will be explained in further detail with reference to the accompanying drawings in which:

Fig. 1 is a diagram of a transmission system;

Figs. 2A and 2B are schematic diagrams illustrating the use of zero padding using symbol spreading according to two different schemes;

Fig. 3 is a flow chart illustrating the recovery of an original symbol at a receiver from the signal illustrated in Fig. 2B;

Fig. 4 is a diagram comparing the bit-error rate achieved using an embodiment of the signal illustrated in Fig. 2B with that achieved using conventional methods;

Fig. 5 is a diagram showing the ratio between the signal power of a conventional method and that obtained using an embodiment of the method according to Fig. 3 and the signal illustrated in Fig. 2B for two models of a transmission channel;

Fig. 6 is a diagram showing the reduction in Inter-Symbol Interference (ISI) obtained using an embodiment of the method according to Fig. 3 and the signal illustrated in Fig. 2B for the same two models of a transmission channel;

Fig. 7 is a diagram showing the reduction in Inter-Carrier Interference (ICI) obtained using an embodiment of the method according to Fig. 3 and the signal illustrated in Fig. 2B for the same two models of a transmission channel; and

Fig. 8 is a diagram plotting the Bit-Error Rate against the Signal-to-Noise Ratio for the same two channel models, both for the conventional method and for the embodiment of the method according to Fig. 3 and the signal illustrated in Fig. 2B.

Referring to Fig. 1, a transmitter receives a bit sequence at an input 1. The bit sequence is converted into a composite signal to be transmitted to a receiver and recovered therein. It is observed that Fig. 1 illustrates the transmitter and the receiver in terms of functional units, rather than units corresponding to discrete devices.

The bit sequence is converted into a sequence of original data symbols by a modulator 2 using a signalling scheme. In one embodiment, the scheme is a binary scheme such as Binary Phase Shift Keying (BPSK). In alternative embodiments, it is a multi-level signalling scheme using four (two bits per symbol), sixteen (four bits per symbol), sixty-four or even 256 levels (six bits per symbol), such as MPSK or QAM (Quadrature Amplitude Modulation). The higher the number of levels, the greater is the bandwidth efficiency that is achieved using the system. This description will proceed using the example of M-ary QAM (MQAM) symbols as original data symbols.

The sequence of original data symbols is converted into a number of parallel sequences of original data symbols by a serial to parallel converter 3.

An OFDM modulator 4 transforms the original data symbols of each of the parallel sequences of original data symbols into parallel sequences of OFDM (Orthogonal Frequency Division Multiplexing) symbols, thus modulating them onto orthogonal sub-carriers. The transformer transforms the original data symbols from the frequency domain to the time domain by applying an N-point inverse Fast Fourier Transform. In an alternative embodiment, a different N-point inverse transform such as the inverse Discrete Cosine Transform is used. To avoid complexity at particularly the receiver, N is generally chosen to have a low value, for example 128 or lower, e.g. 64 or 32.

It will be assumed herein that the number of parallel sequences of MQAM and OFDM symbols is equal to the length of the transform applied by the OFDM modulator 4, although that need not be the case. Fewer than all N sub-carriers may be used to transmit OFDM symbols.

Take a bit sequence B_i, $i = 0,...qNN_fI$ at the input 1, where q is the number of bits per MQAM symbol, N as defined above and N_f the number of OFDM symbols per frame. The modulator 2 produces $Q = N{\cdot}N_f$ original data symbols. The serial-to-parallel converter 3 parses these into groups of N to obtain a frame of N_f groups. If $X_k[b]$, $k = 0,1,...N\text{-}1$, $b = 0,1,...,N_f\text{-}1$ represents the bth group in the frame, then the output of the OFDM modulator 4 is given by:

$$x_n[b] = F^{-1}X_k[b]. \quad (1)$$

F^{-1} is the $N \times N$ Inverse Fast Fourier Transform (IFFT) matrix, with:

$$F^{-1}(n,k) = \exp(j2\pi nk / N) \quad (2)$$

Because an N-point IFFT is used and the sub-carriers are spaced $2\pi/N$ apart, the sub-carriers are orthogonal. Provided they remain orthogonal, each of the parallel OFDM symbol sequences can be de-modulated independently to recover the original symbol sequence at the receiver. If this orthogonality is not maintained, Inter-Carrier Interference (ICI) will occur. The manner in which the orthogonality is maintained is explained below.

A padding inserter 5 inserts zero padding into the sequence of OFDM symbols. A number of zero data samples are added to the OFDM symbols $x_n[b]$ to obtain N parallel signals partitioned into symbol periods of length p. The notion of length is used throughout this text to mean the number of data samples. The length p of a symbol period is equal to at least the OFDM symbol length N.

It is observed that the transmitter implements a type of symbol spreading using time diversity, in that multiple symbol periods are allocated to each OFDM symbol in the N parallel signals that emerge from the padding inserter 5. A conventional form of symbol spreading is illustrated in Fig. 2A. In Fig. 2A, a first instance 6 of a first OFDM symbol is followed by a ZP sequence 7 of length $G = p\text{-}N$. This is followed by a second instance 8 of the first OFDM symbol (i.e. a copy), followed by a ZP sequence 9 of length $G = p\text{-}N$, to occupy a second symbol period ΔT_2. A third symbol period ΔT_3 is occupied by a first instance 10 of a second

OFDM symbol and ZP sequence 11. The second OFDM symbol is repeated again in a fourth symbol period ΔT_4 containing a second instance 12 of the second OFDM symbol and a further ZP sequence 13. Thus, there are two symbol periods for each OFDM symbol to be transmitted. The different instances of an OFDM symbol are transmitted on different frequency bands.

The padding inserter 5 according to Fig. 1 implements a different type of symbol spreading (Fig. 2B) in which, assuming a symbol period of length p, a first symbol period ΔT_1 includes a first OFDM symbol 14, and a second symbol period ΔT_2 adjacent the first symbol period ΔT_1 consists of a zero-padding sequence. In fact, the remainder of the first symbol period ΔT_1 also consists of a zero-padding sequence, so that the first symbol 14 is followed by a zero-padding sequence 15 of length $p \cdot (t-1) + G$, $t = 2$. As in the scheme of Fig. 2A, a second OFDM symbol is included in the third symbol period ΔT_3, but again, the adjacent fourth symbol period ΔT_4 is occupied by a zero-padding sequence. Thus, the second OFDM symbol 16 is also followed by a zero-padding sequence 17 of length $p(t-1) + G$. Unlike in the conventional scheme of Fig. 2A, only one sub-band is used for each OFDM symbol.

Using the scheme of Fig. 2A, padded OFDM symbols $x_n^p[b]$ can be represented as follows:

$$x_n^p[b] = \begin{bmatrix} x_n[b] \\ 0_{G\times 1} \end{bmatrix} \tag{3}$$

By contrast, padded OFDM symbols $x_n^p[b]$ in the scheme of Fig. 2B can be represented as:

$$x_n^p[b] = \begin{bmatrix} x_n[b] \\ 0_{w\times 1} \end{bmatrix}, \tag{4}$$

$w = p(t-1) + G.$

As is well-known, a transmission channel 18 between the transmitter and receiver can be characterised by a tapped delay channel impulse h_l = $[h_0, h_1, \ldots, h_{L-1}]$, with L the channel excess delay. To implement a ZP-OFDM system that is capable of completely mitigating multi-path fading, the ZP sequence length should be at least L-1 discrete samples. For a given transmission efficiency $e = qN/2p$, this is achievable with a smaller value of N using the scheme of Fig. 2B than using the scheme of Fig. 2A. Compared to a scheme that does not use symbol spreading, the efficiency can be improved by using a higher number q of bits per original symbol, made possible by the reduced Inter-Symbol Interference (ISI), and thus ICI, afforded by the longer ZP sequence length.

The padding inserter 5 is followed by a parallel-to-serial converter 19 that produces a composite signal comprised of the N parallel signals. Conversion to an analogue signal for transmission involves the use of an RF circuit 20, which includes a carrier oscillator 21 and phase shift 22 to generate a modulated signal. In an embodiment, a frequency f_c of the signal generated by the carrier oscillator 21 is varied.

At the receiver side, a corresponding RF circuit 23 includes a carrier oscillator 24 and phase shift 25 to retrieve the IQ components of the RF signal. A serial-to-parallel converter 26 enables N parallel signals to be recovered from the composite signal transmitted to the receiver.

Symbols $y_n^p[b]$ of which the N parallel signals output by the serial-to-parallel converter 26 are comprised are a convolution of the zero-padded OFDM symbols and the channel impulse response for the carriers on which the OFDM symbols are transmitted.

Conventionally, in a symbol spreading scheme according to Fig. 2A, overlap-add-processing is applied to obtain blocks $y_n[b]$ of N data samples corresponding in length to the length of an OFDM symbol. That is to say that the symbol periods are located, that the first N data samples are retrieved, and that the last G data samples of each symbol period are added element-by-element to the first G data samples of the retrieved block of N data samples. An N-point discrete transform is applied to recover the original data symbols (i.e. BPSK or QAM data symbols). The output of this transform, for the case of an N-point Fast Fourier Transform, is:

$$Y_k[b] = F\sum_{j=0}^{b} H_c^j F^{-1} X_k[b-j] + Z_k[b], \tag{5}$$

where Z_k represents a noise vector, H_c is the channel matrix, and F is the $N \times N$ Fast Fourier Transfer Matrix, for which $F(n,k) = \frac{1}{2\pi}\exp(-j2\pi nk/N)$.

In a generalised case of t-times symbol spreading (Fig. 2A is the specific case in which $t=2$), a diversity combiner is used to de-spread the symbols, as follows (in the case of equal gain combination):

$$Y_k^D[u] = \frac{1}{t}\sum_{b=tu}^{t(u+1)-1} Y_k[b], \tag{6}$$

for u = $0,1,\ldots,N\text{-}1$. It can be shown that, for ISI to be zero, it is required that $h_l^{t\text{-}1}$ = 0 for $l \geq G+1$, where $h_l^{t\text{-}1}$ is the channel impulse response of the t^{th} sub-band, and that the same condition applies for ICI to be zero.

In contrast to the conventional scheme, an OLA and diversity combination unit 27 implements a method as illustrated in Fig. 3 for the case in which t = 2. In a first step 28, the symbol periods are located in one of the N parallel signals received from the serial-to-parallel converter 26. The start of the symbol periods can be determined using a synchronisation scheme, usually implemented just after conversion from analogue to digital signals and prior to processing in the serial-to-parallel converter 26. A block 29 of successive data samples spanning two symbol periods is obtained. A first end block 30 at the end of the two symbol periods is added element-by-element (step 31) to a corresponding number of data samples at the start of a larger block 32 corresponding in length to the length of an OFDM symbol. The size of the first end block 30 is equal to $2 \cdot G$ in this example. More generally, the size of the first end block 30 is equal to the remainder of the block 29 spanning successive symbol periods divided by the symbol length N.

To a result 33 of the overlap-add operation is added (step 34) element-by-element a symbol-length block 35 of data samples that separates the first end block 30 from the larger block 32. The result of the addition is a symbol-length block 36 that forms the input to an FFT unit 37 (Fig. 1).

A received padded OFDM symbol, such as the block 29 of data samples spanning two symbol periods, is given by:

$$y_k^p[b] = \sum_{j=0}^{b} H_j F^{-1} X_k[b-j], \qquad (7)$$

where H_j is the matrix for which $H_j[m,n] = h[pj+m-n], m = 0,1,\ldots pt-1, n = 0,1,\ldots,p-G-1$.

The received symbol after the steps 31,34 of performing the overlap-add operation and the diversity combination is given by:

$$y_k[b] = \sum_{j=0}^{b} H_0^j F^{-1} X_k[b-j], \qquad (8)$$

where:

$$H_0^j = \sum_{v=0}^{m-1} H_{jv}, m = \left\lceil {}^{pt}\!/_{N} \right\rceil, \qquad (9)$$

for t-times symbol spreading.

For $0 \leq v \leq (m\text{-}2)$, the matrix H_{jv} is given by $H_{jv}[k,l] = h[p \cdot t \cdot j + N \cdot v + k - l]$. For $v = m\text{-}1$, the matrix H_{jv} is given by:

$$H_{j(m-1)} = \begin{bmatrix} H_e \\ 0_{w \times N} \end{bmatrix}, \qquad (10)$$

in which $H_e[k,l] = h[p \cdot t \cdot j + N \cdot v + k - l]$, $k = 1,\ldots,N$, $l = 1,\ldots,pt\text{-}Nv$.

The output of the FFT unit 37 is a sequence of original data symbols given by the following equation:

$$Y_k^D[b] = F \sum_{j=0}^{b} H_0^j F^{-1} X_k[b-j] + Z_k[b]. \qquad (11)$$

By separating this equation into an ISI-free component and an ISI component, it can be shown that there is no ISI if $L \leq G+1$. Similarly, it can be shown that ICI is absent if $L \leq (pt\text{-}N+1)$.

The output of the FFT unit 37 is provided to a parallel-to-serial converter 38. A demodulator 39 demodulates the original data symbols recovered by the FFT unit 37 in accordance with the signalling scheme being applied, in order to provide a bit sequence on an output 40 of the receiver.

Fig. 4 compares the average Bit-Error Rate against the signal-to-noise-plus-interference ratio for a choice of parameters of $N = 128$, $G = 32$ and $p = 160$ between a scheme without symbol spreading, a scheme with two-times symbol spreading in which each OFDM symbol is transmitted once on a first frequency band and once on a second frequency band, and a scheme in accordance with Fig. 3. The simulation used a model, CM4, of the channel as defined for evaluating Ultra Wideband communications, and is based on MQAM as the signalling scheme.

Fig. 4 demonstrates that the bit error rate is lower when the channel is poor, even though the comparison is between schemes using the same bit rate.

Figs. 5-8 show the result of a similar simulation, comparing the performance of a two-times symbol spreading scheme according to Fig. 2A to a scheme according to Figs. 2B and 3. For this comparison, BPSK was used as the signalling method by means of which a bit sequence was transformed into a number of parallel symbol sequences. Channel model 1 is a line-of-sight channel with a transmitter-receiver distance of up to four metres. The value of N was 128, and the value of G was $N/4 = 32$.

Fig. 5 shows the gain in desired signal as a ratio between the scheme set out herein and the conventional two-times symbol spreading scheme, for each sub-carrier. Fig. 6 is a plot of the ratio between ICI powers of the two schemes, and Fig. 7 is a similar plot for the ratio of ISI powers of the two schemes. Finally, Fig. 8 is a diagram of the Bit-Error Rate for the conventional (P_c) and the proposed (P_p) scheme outlined herein against the Signal-to-Noise ratio per bit. It can be seen that there is an increase in power in the desired signal and suppression of ICI and ISI for all sub-carriers, whilst the bit error probability is lower for the method outlined herein as compared to a conventional two-times symbol spreading scheme.

The invention is not limited to the embodiments described above, which may be varied within the scope of the accompanying claims. The illustrated transmitter and receiver have been somewhat simplified. A practical transmission system will include functional unit for implementing a type of equalisation, for example.

CLAIMS

1. Method of transmitting a number of parallel sequences of original data symbols,
modulating the parallel sequences on to respective orthogonal sub-carriers by applying a discrete inverse transform to each original data symbol to obtain a corresponding number of parallel symbol sequences, each symbol (14,16) having a length corresponding to a number of samples in an original data symbol, and
generating one of a corresponding number of parallel signals from each symbol sequence, each of the parallel signals being partitioned into symbol periods (ΔT_1-ΔT_4) of a generally equal length corresponding to at least the length of one symbol (14,16), **characterised by**
including at least one symbol period ($\Delta T_2, \Delta T_4$) consisting of at least part of a padding sequence (15,17) adjacent a symbol period ($\Delta T_1, \Delta T_3$) including one of the symbols (14,16) in at least one of the parallel signals.

2. Method according to claim 1, including transmitting the parallel signals to a receiver through a channel (18), wherein the length(s) of the padding sequence(s) in the at least one symbol period ($\Delta T_2, \Delta T_4$) and of any padding sequence part included in the symbol period including one of the symbols (14,16) is greater in total than a channel excess delay of the channel (18).

3. Method according to claim 1 or 2, including transmitting the parallel signals to a receiver arranged to apply an element-by-element addition of a block of samples 30 retrieved from an end of a padding sequence of that one of the at least one symbol periods furthest removed from the symbol to a block (32) of samples of the symbol (14,16) at an opposite end of the symbol.

4. Method according to any one of claims 1-3, wherein the original data symbols are obtained by applying a multi-level signalling scheme to a bit sequence, wherein the number of levels is at least sixteen.

5. Transmitter for transmitting a number of parallel sequences of original data symbols, including a system (4) for modulating the parallel sequences on to respective orthogonal sub-carriers by applying a discrete inverse transform to each original data symbol to obtain a corresponding number of parallel symbol sequences, each symbol (14,16) having a length corresponding to a number of samples in an original data symbol, which system is arranged to generate one of a corresponding number of parallel signals from each symbol sequence, such that each of the parallel signals are partitioned into symbol periods (ΔT_1-ΔT_4) of a generally equal length corresponding to at least the length of one symbol, **characterised in that** the transmitter is arranged to insert at least one symbol period (ΔT_2, ΔT_4) consisting of at least part of a padding sequence (15,17) adjacent a symbol period (ΔT_1, ΔT_3) including one of the symbols (14,16) in at least one of the parallel signals.

6. Transmitter according to claim 5, arranged to carry out a method according to any one of claims 1-4.

7. Method of recovering a signal comprising a sequence of original data symbols,
including:

receiving a composite signal, the composite signal being a composite of a number of parallel signals, each partitioned into symbol periods (ΔT_1-ΔT_4) of a generally equal length, each of the parallel signals being obtainable by modulating a plurality of parallel data sequences onto orthogonal sub-carriers to obtain a corresponding number of parallel symbol sequences and by inserting data samples between the symbols (14,16),

locating sections of the parallel signals corresponding to the symbol periods,

obtaining a block (29) of successive data samples spanning at least two successive symbol periods in one of the parallel signals and commencing with a symbol,

element-by-element addition of a number (30) of data samples at a first end of the obtained block to a corresponding number (32) of data samples at an opposite, second end,

combining one or more symbol-length blocks (35) of data with a result (33) of the element-by element addition and

application of a discrete transform to a result (36) of the combination,

characterised in that

the symbol-length blocks (35) of data are obtained by partitioning the data between the symbol and the number (30) of data samples at the first end in the block (29) of successive data samples into one or more symbol-length blocks of data.

8. Method according to claim 7, including recovering an original bit sequence by applying to the original data symbols a multi-level signalling scheme, wherein the number of levels is at least sixteen.

9. Receiver for recovering a signal comprising a sequence of original data symbols,
including:

an input for receiving a composite signal, the composite signal being a composite of a number of parallel signals, each partitioned into symbol periods (ΔT_1-ΔT_4) of a generally equal length, each of the parallel signals being obtainable by modulating a plurality of parallel data sequences onto orthogonal sub-carriers to obtain a corresponding number of parallel symbol sequences and by inserting data samples between the symbols (14,16),

a data processing system for locating sections of the parallel signals corresponding to the symbol periods, wherein the data processing system is configured to:

obtain a block (29) of successive data samples spanning at least two successive symbol periods in one of the parallel signals and commencing with a symbol,

perform element-by-element addition of a number (30) of data samples at a first end of the obtained block to a corresponding number (32) of data samples at an opposite, second end,

combine one or more symbol-length blocks(35) of data with a result (33) of the element-by element addition and

apply a discrete transform to a result (36) of the combination,

characterised in that

the data processing system is arranged to obtain the symbol-length blocks (35) of data by partitioning the data between the symbol and the number (30) of data samples at the first end in the block of successive data samples into one or more symbol-length blocks (35) of data.

10. Receiver according to claim 9, arranged to carry out a method according to claim 9.

11. Signal composed of a number of parallel signals,

each partitioned into symbol periods (ΔT_1-ΔT_4) of a generally equal length, each of the parallel signals being obtainable by modulating a plurality of parallel data sequences onto orthogonal sub-carriers to obtain a corresponding number of parallel symbol sequences and by inserting data samples between the symbols (15,17), wherein the signal includes data for locating the symbol periods (ΔT_1-ΔT_4),

characterised in that at least one of the parallel signals includes at least one symbol period (ΔT_2, ΔT_4) consisting of at least part of a padding sequence (15,17) adjacent a symbol (ΔT_1, ΔT_3) period including one of the symbols (14,16) in at least one of the parallel signals.

12. Computer programme including a set of instructions capable, when incorporated in a machine-readable medium, of causing a system having information processing capabilities to perform a method according to any one of claims 1-4 or 7-8.

13. Method of transmitting a number of parallel sequences of original data symbols, substantially as described herein with reference to Figs. 1, 2B and 3 of the drawings.

14. Transmitter substantially as described herein with reference to Figs. 1, 2B and 3 of the drawings.

15. Method of recovering a signal comprising a sequence of original data symbols, substantially as described herein with reference to Figs. 1, 2B and 3 of the drawings.

16. Receiver, substantially as described herein with reference to Figs. 1, 2B and 3 of the drawings.

17. Signal, substantially as described herein with reference to Figs. 2B and 3 of the drawings.

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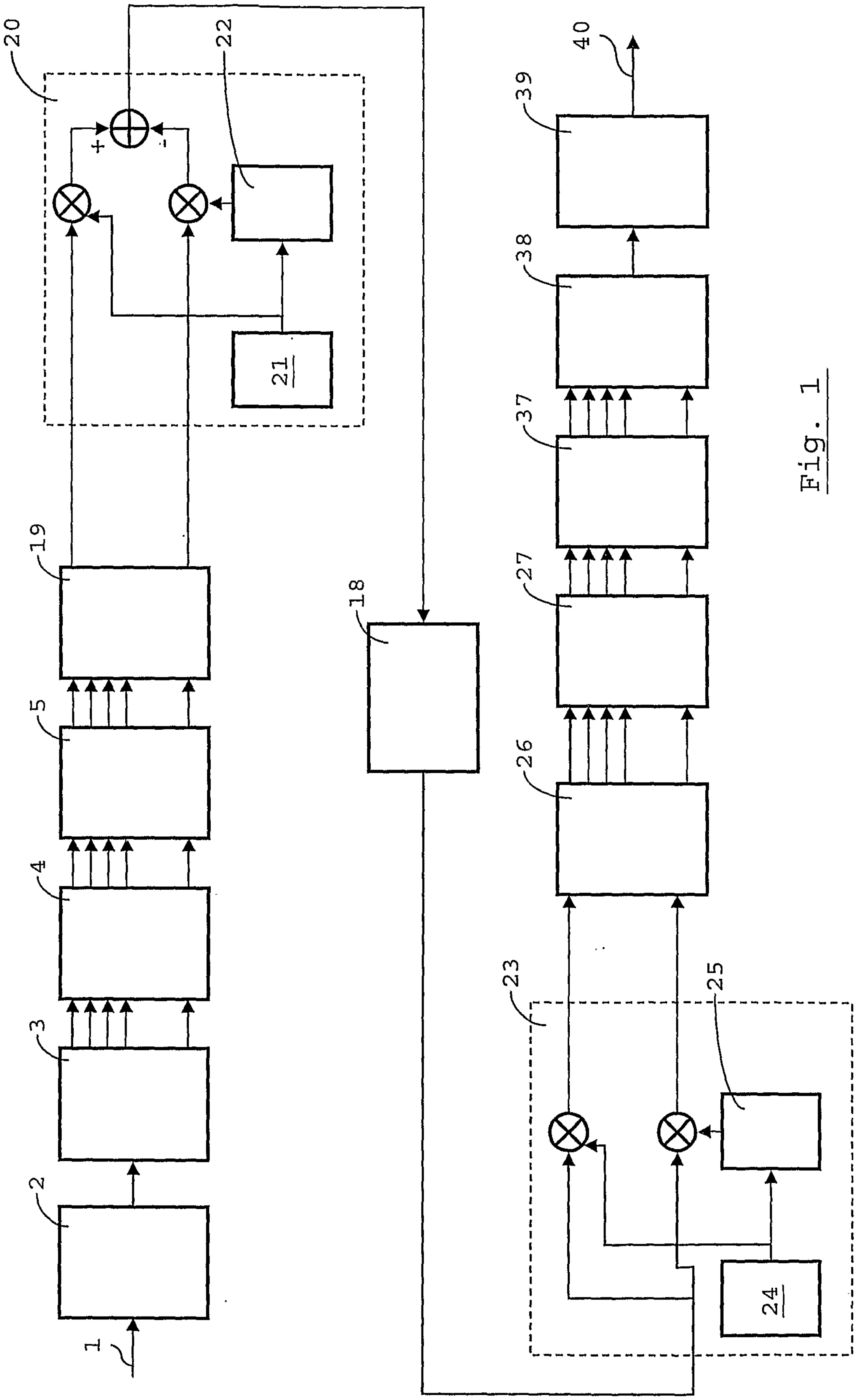


Fig. 1

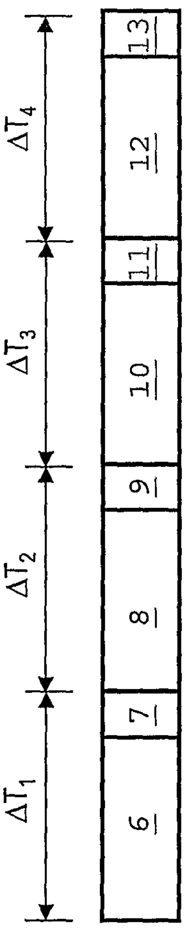

ΔT_1
ΔT_2
ΔT_3
ΔT_4
6
7
8
9
10
11
12
13

Fig. 2A

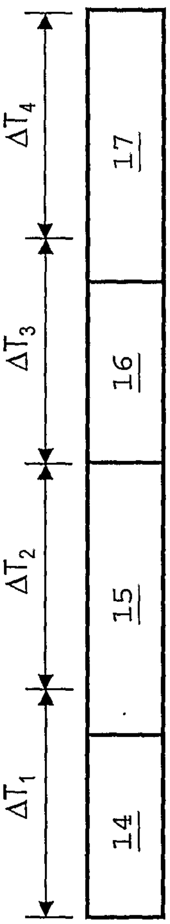

ΔT_1
ΔT_2
ΔT_3
ΔT_4
14
15
16
17

Fig. 2B

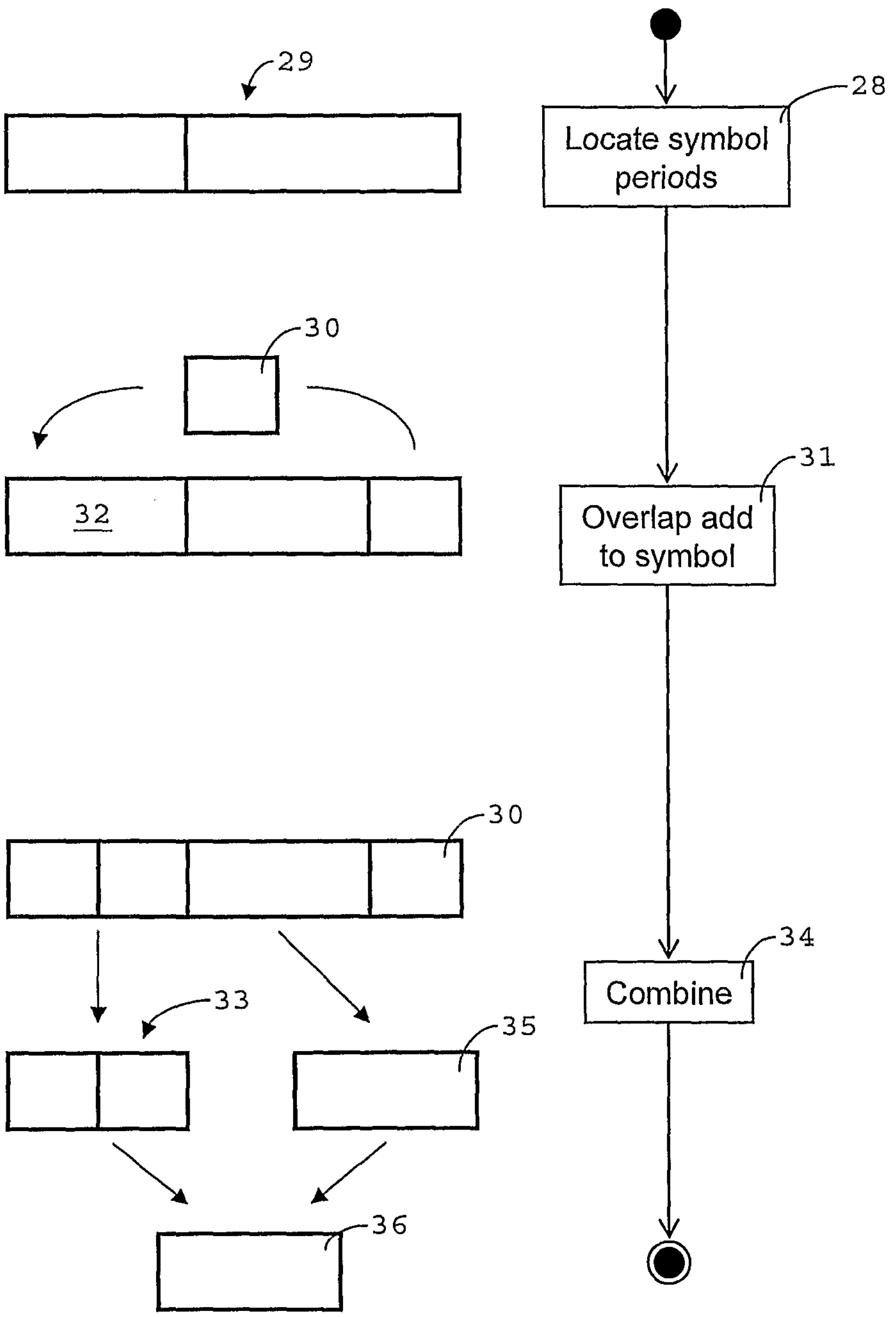

29
28
Locate symbol periods
30
32
31
Overlap add to symbol
30
34
Combine
33
35
36

Fig. 3

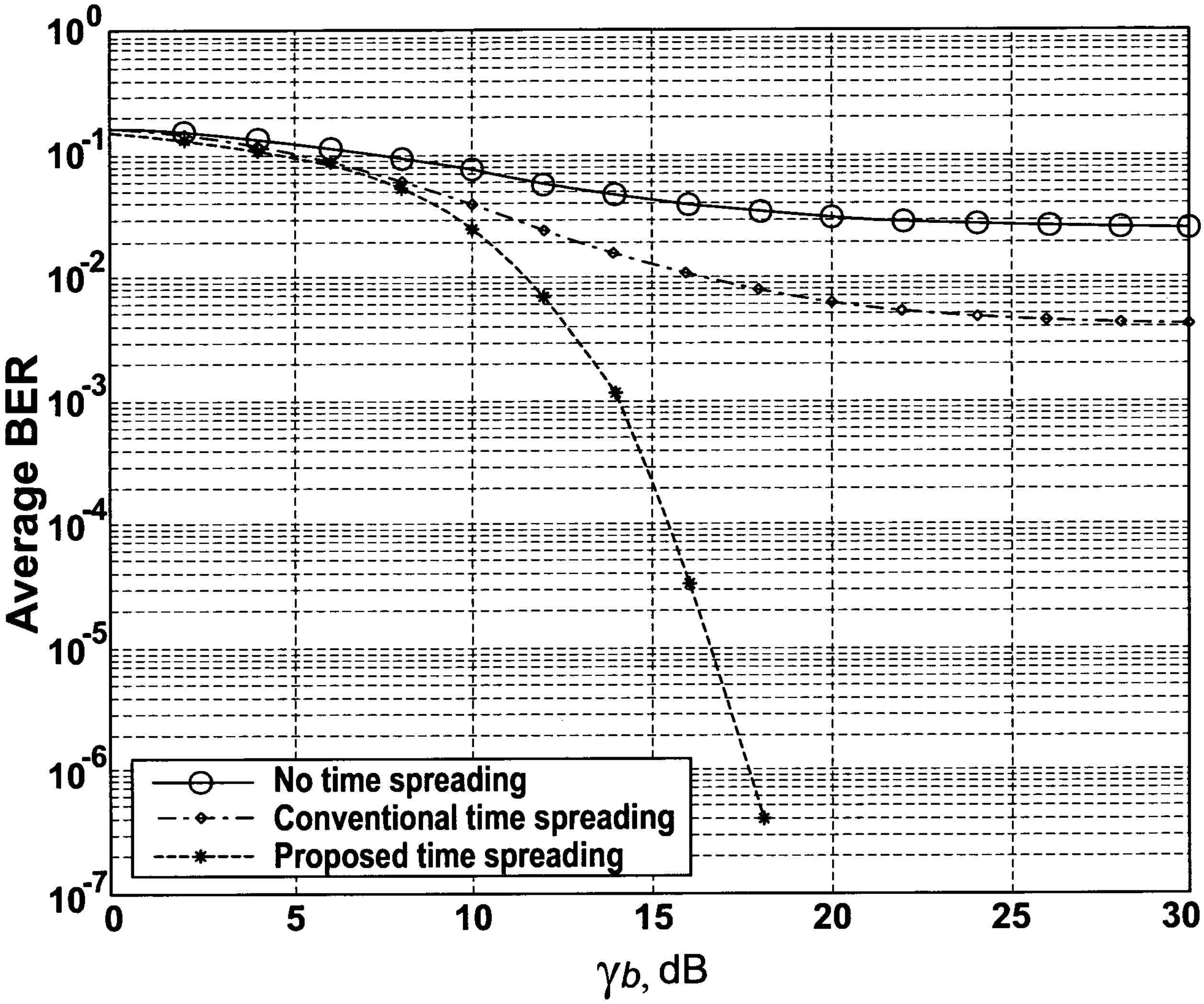

10^0
10^-1
10^-2
10^-3
10^-4
10^-5
10^-6
10^-7
Average BER
0
5
10
15
20
25
30
γb, dB
No time spreading
Conventional time spreading
Proposed time spreading

Fig. 4

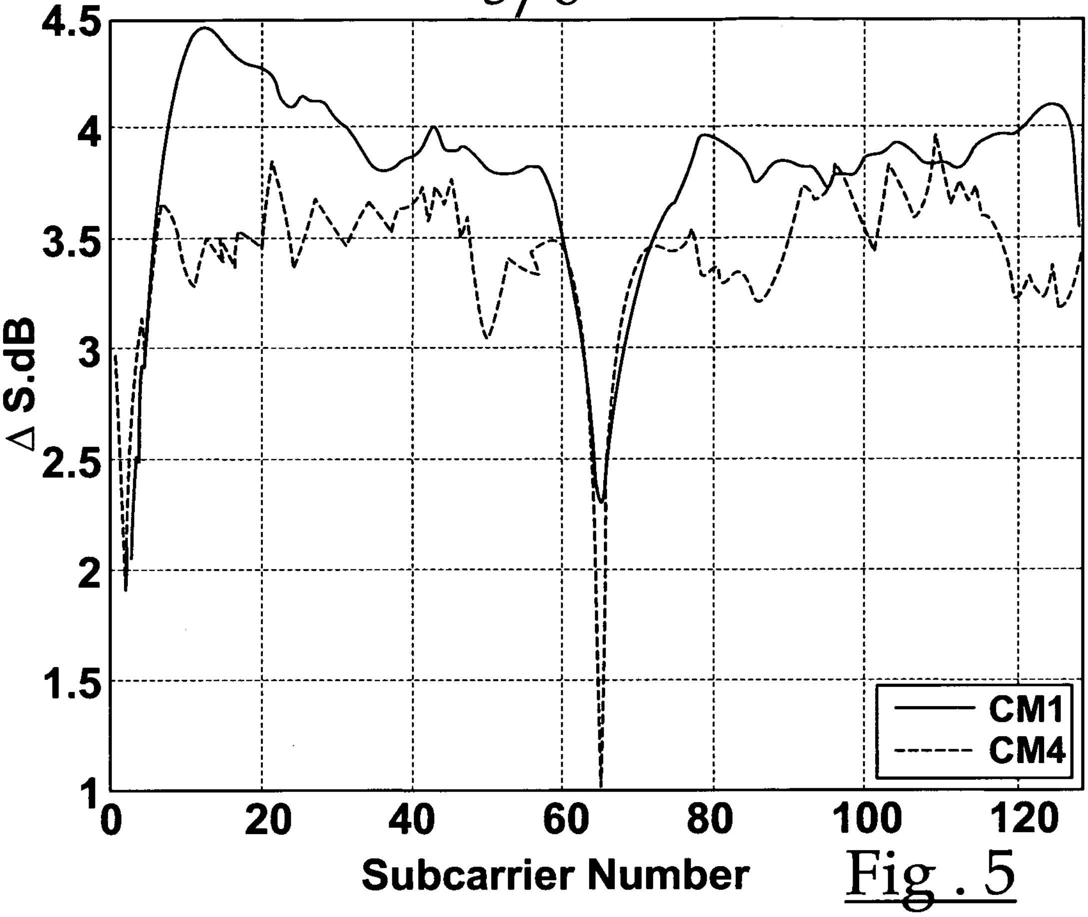

4.5
4
3.5
3
2.5
2
1.5
1
Δ S.dB
0
20
40
60
80
100
120
Subcarrier Number
CM1
CM4

Fig . 5

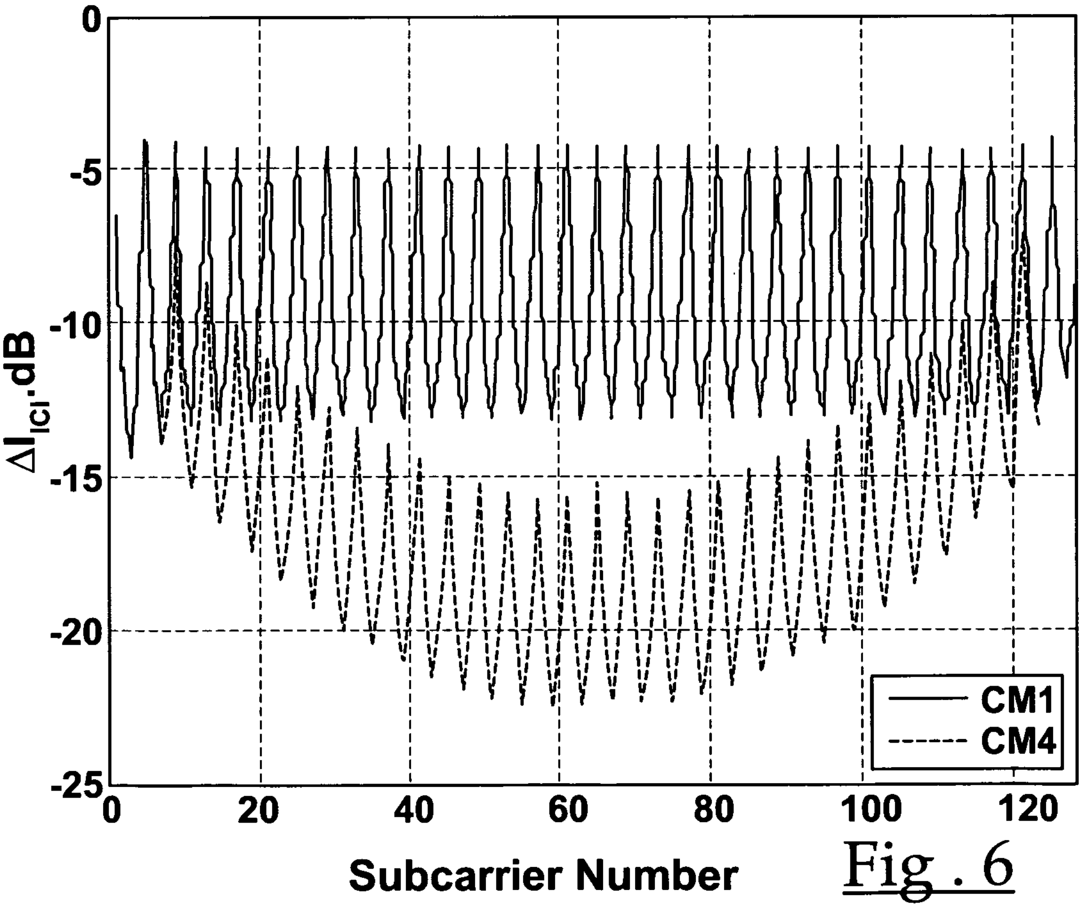
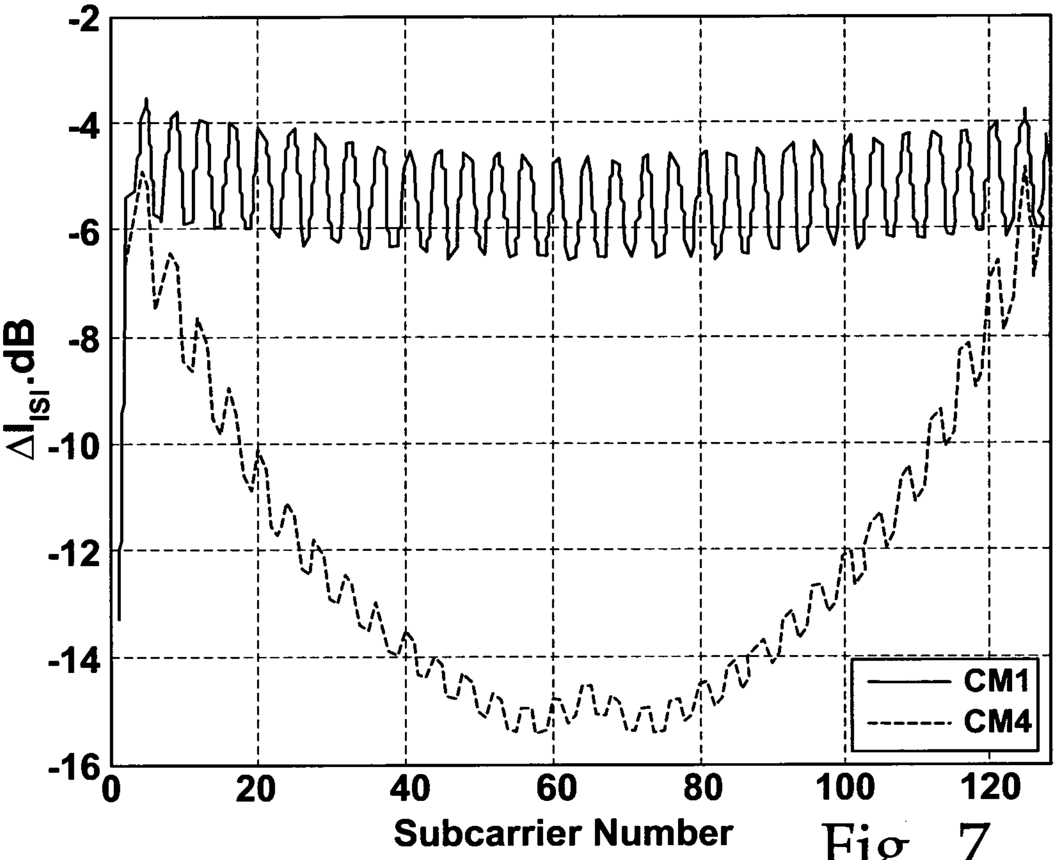
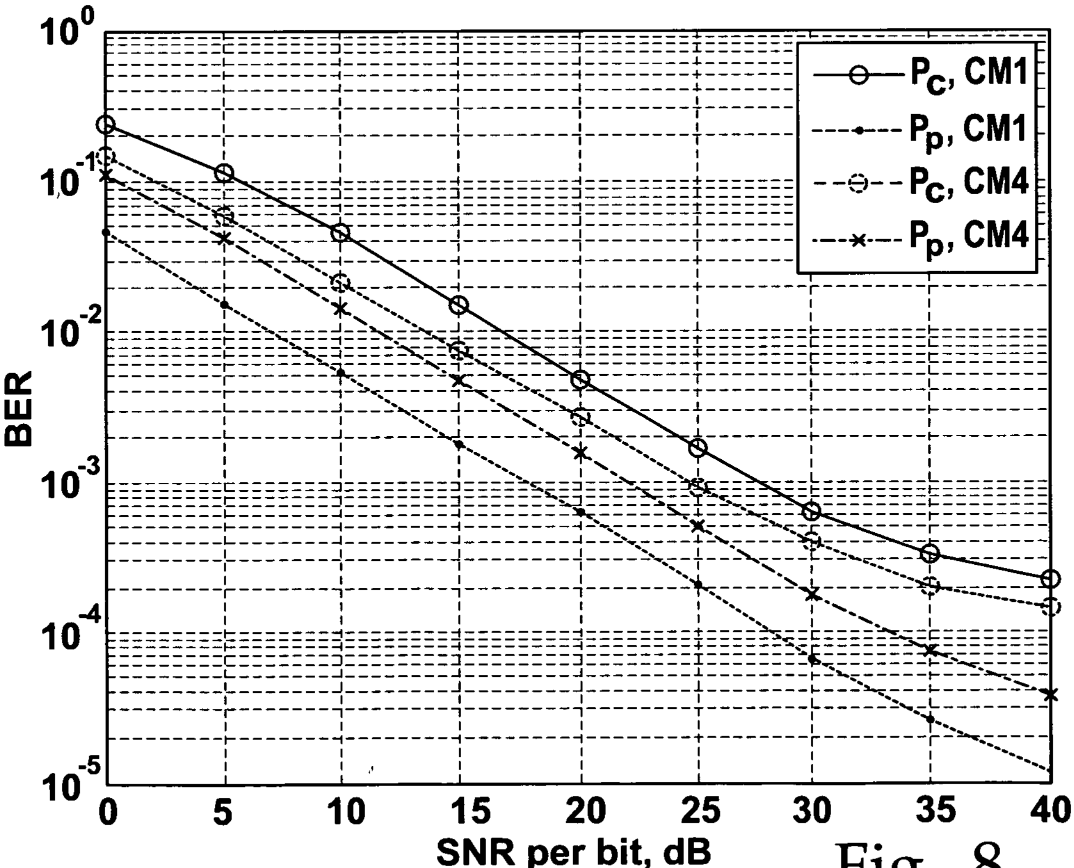

0
-5
-10
-15
-20
-25
ΔI_{ICI}.dB
0
20
40
60
80
100
120
Subcarrier Number
CM1
CM4

Fig . 6



-2
-4
-6
-8
-10
-12
-14
-16
ΔI_{ISI}.dB
0
20
40
60
80
100
120
Subcarrier Number
CM1
CM4

Fig . 7



10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
BER
0
5
10
15
20
25
30
35
40
SNR per bit, dB
P_c, CM1
P_p, CM1
P_c, CM4
P_p, CM4

Fig . 8