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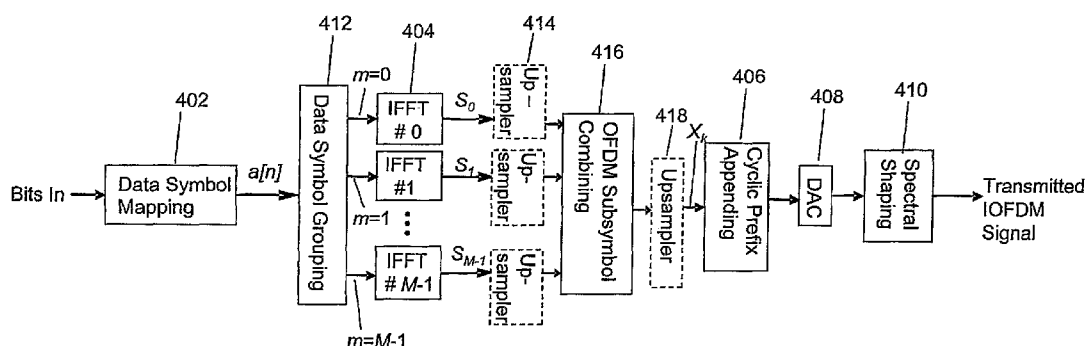
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(54) Title: ORTHOGONAL FREQUENCY DIVISION MULTIPLEXING USING SUBSYMBOL PROCESSING

400

(57) Abstract: In one embodiment, a transmitter converts digital input data into combined-OFDM signals and a receiver recovers data from the transmitted combined-OFDM signals. For transmission, digital data is mapped into data symbols using a commonly known modulation technique, such as QAM or DQPSK. The data symbols are subsequently divided into two or more groups according to a specified grouping pattern. Each group of data symbols is then converted into a separate OFDM subsymbol using IFFT processing. The OFDM subsymbols are then combined according to a specified combining pattern to create a combined-OFDM symbol. Combined-OFDM symbols are then prepared for transmission by affixing cyclic prefixes, converting the symbols to analog format, and performing spectral shaping of the analog signal. Upsampling may be employed to increase the signal bandwidth. In alternative embodiments, OFDM subsymbols may be combined using interleaving to create an interleaved-OFDM symbol.

ORTHOGONAL FREQUENCY DIVISION MULTIPLEXING USING SUBSYMBOL PROCESSING

CROSS-REFERENCE TO RELATED APPLICATIONS

[0001]   This application claims the benefit of the filing date of U.S. provisional application no. 60/813,667, filed on 06/14/06 as attorney docket no. Huang 1-1, the teachings of which are incorporated herein by reference.

BACKGROUND OF THE INVENTION

[0002]   Field of the Invention

[0003]   The present invention relates to signal processing, and more specifically to orthogonal frequency division multiplexing techniques used in signal transmission and reception.

[0004]   Description of the Related Art

[0005]   Orthogonal frequency division multiplexing (OFDM) is a signal processing technology well known in the field of communications. In general, OFDM operates by dividing a frequency spectrum into smaller subbands (a.k.a. subcarriers) and modulating these subcarriers with data symbols.

[0006]   FIG. 1 shows a simplified block diagram of one implementation of a prior-art OFDM transmitter 100. Transmitter 100 receives digital input data and converts the data into analog OFDM signals for transmission. Conversion of the data occurs through sequential steps of data symbol mapping 102, inverse fast Fourier transform (IFFT) processing 104, cyclic prefix appending 106, digital-to-analog conversion (DAC) 108, and spectral shaping 110.

[0007]   Data symbol mapping block 102 receives binary bits of data, which are divided into groups of finite length. One or more data symbols $a[n]$ are created for each group of bits, using any one of a number of modulation techniques commonly known in the art, such as differential quadrature phase-shift-keying (DQPSK) or quadrature amplitude modulation (QAM). The length of each group and thus the number of input data bits per data symbol is determined by the modulation technique employed.

[0008]   IFFT 104 subsequently applies each set of N data symbols $a[n]$ to a set of N subcarriers, which are numbered from 0 to N-1, where one data symbol $a[n]$ is paired with each subcarrier. The subcarriers employed by OFDM are arranged orthogonally to one another, so that each subcarrier can be distinguished without intersymbol interference. Each set k of N data symbol $a[n]$ and subcarrier pairs is then converted by IFFT 104 from frequency-domain representations into a time-domain OFDM symbol S_k, consisting of N samples $S_k[i]$, where i equals 0 to N-1. The discrete model for each OFDM symbol S_k may be expressed by Equation (1) as follows:

$$S_k[i] = S_k\left(i\frac{T}{N}\right) = \sum_{n=0}^{N-1} a[n]e^{j\frac{2\pi}{N}ni} w[i] = \sum_{n=0}^{N-1} a[n]c[i,n] \qquad (1)$$

where $\dfrac{T}{N}$ is the sample period, $w[i]$ is a discrete window function, and $c[i,n] = e^{j\frac{2\pi}{N}ni}\,w[i]$ denotes the finite length complex exponential sequence of the subcarriers.

[0009]   The OFDM symbols S_k are then prepared for transmission. First, a cyclic prefix is inserted at the beginning of each OFDM symbol S_k by cyclic prefix appending 106. This prefix enables the receiver to cope with signal echoes that result from multipath reflections. Next, the OFDM symbols and prefixes are converted from digital format to analog format using digital-to-analog converter (DAC) 108. Finally, the analog output from DAC 108 undergoes spectral shaping by spectral shaping block 110 to produce an OFDM signal for transmission.

[0010]   As an example of the production of a prior-art OFDM signal, assume that IFFT 104 receives 384 data symbols $a[n]$, where $n = 0,...,383$, and employs N=128 subcarriers. Since one data symbol $a[n]$ in each set of N data symbols $a[n]$ is assigned to each subcarrier, the number of OFDM symbols S_k generated is equal to 3 (384 data symbols $a[n]$ divided by 128 subcarriers). The grouping of data symbols $a[n]$ in the frequency domain is shown in Table I. As shown in Table I, in a prior-art OFDM system, data symbols $a[0]$ to $a[127]$ are assigned to OFDM symbol S_0, data symbols $a[128]$ to $a[255]$ are assigned to OFDM symbol S_1, and data symbols $a[256]$ to $a[383]$ are assigned to OFDM symbol S_2.

TABLE I. GROUPING OF DATA SYMBOLS $a[n]$ IN THE FREQUENCY DOMAIN OF A PRIOR-ART OFDM SIGNAL						
Subcarrier Index	0	1	2	3	...	127
OFDM Symbol 0 (S_0)	$a[0]$	$a[1]$	$a[2]$	$a[3]$	...	$a[127]$
OFDM Symbol 1 (S_1)	$a[128]$	$a[129]$	$a[130]$	$a[131]$	...	$a[255]$
OFDM Symbol 2 (S_2)	$a[256]$	$a[257]$	$A[258]$	$a[259]$	...	$a[383]$

[0011]   Table II shows the grouping of samples $S_k[i]$, where $k = 0, 1, 2$ and $i = 0,...,127$, in the time domain after conversion by IFFT 104. In a prior-art OFDM system, the samples $S_k[i]$ of each OFDM symbol S_k remain grouped together, and the OFDM symbols S_k are transmitted in succession. In other words, samples $S_0[0]$ to $S_0[127]$ of OFDM symbol S_0 are transmitted before samples $S_1[0]$ to $S_1[127]$ of OFDM symbol S_1, which are transmitted before samples $S_2[0]$ to $S_2[127]$ of OFDM symbol S_2.

TABLE II. GROUPING OF SAMPLES $S_k[i]$ IN THE TIME DOMAIN OF A PRIOR-ART OFDM SIGNAL																	
	OFDM Symbol S_0						OFDM Symbol S_1						OFDM Symbol S_2				
Sample Index	0	1	2	3	...	127	128	129	130	131	...	255	256	257	258	259	...	383
Trans-mitted Data	$S_0[0]$	$S_0[1]$	$S_0[2]$	$S_0[3]$	...	$S_0[127]$	$S_1[0]$	$S_1[1]$	$S_1[2]$	$S_1[3]$	...	$S_1[127]$	$S_2[0]$	$S_2[1]$	$S_2[2]$	$S_2[3]$	...	$S_2[127]$

[0012]   FIG. 2 shows a frequency-domain representation of prior-art OFDM symbol S_0 described in the example above. Each subcarrier, represented by a single waveform, is assigned one data symbol $a[n]$. Additionally, note that the subcarriers are spaced apart so that the peak of each subcarrier corresponds to a zero level of every other subcarrier. This is representative of the orthogonal nature of the set of subcarriers.

[0013]   FIG. 3 shows a simplified block diagram of one implementation of a prior-art OFDM receiver 300, which reverses the operations performed by OFDM transmitter 100. Receiver 300 receives analog OFDM signals and extracts the original digital data. Extraction occurs through sequential steps of matched filtering 302, analog-to-digital conversion (ADC) 304, cyclic prefix removal 306, fast Fourier transform (FFT) processing 308, and data symbol demapping 310.

[0014]   First, the received OFDM signal is down-converted into a baseband analog signal at the receiver's RF front end. The baseband analog signal is filtered by matched filtering block 302 and converted to digital format by ADC 304. Next, synchronization and channel estimation may be performed (not shown). Then, cyclic prefix removal block 306 removes the cyclic prefixes from the time-domain OFDM symbols S_k.

[0015]   FFT 308 receives digital OFDM symbols S_k and extracts the N subcarriers from each to obtain data symbols $a[n]$, according to Equation (2) as follows:

$$a[n] = \sum_{i=0}^{N-1} S_k[i] e^{-j\frac{2\pi}{N}ni} w[n] \tag{2}$$

Finally, data symbols $a[n]$ are demapped into the original binary bits using data symbol demapping block 310 which demodulates the data symbols in accordance with the modulation technique employed by data symbol mapping 102 of FIG. 1.

SUMMARY OF THE INVENTION

[0016]   In one embodiment, the present invention is a method for modulating a set of data symbols into a combined modulated symbol. The method comprises: (1) dividing the set of data symbols into M groups of data symbols where M is greater than 1, (2) transforming each group of data symbols into a time-domain subsymbol, and (3) combining the M time-domain subsymbols to form the combined

modulated symbol. The transformation of each group of data symbols is based on a set of subcarriers, of which only a subset of the subcarriers is modulated by the group of data symbols. Furthermore, each data symbol in each group modulates a different subcarrier in a corresponding subset of the subcarriers, and no two subsets of subcarriers have a subcarrier in common.

5   [0017]   In another embodiment, the present invention is an apparatus comprising a transmitter adapted to modulate a set of data symbols into a combined modulated symbol. The transmitter comprises: (1) a data symbol grouper adapted to divide the set of data symbols into M groups of data symbols, where M is greater than 1, (2) one or more transforms adapted to transform each group of data symbols into a time-domain subsymbol, and (3) a subsymbol combiner adapted to combine the M time-

10   domain subsymbols to form the combined modulated symbol. The transformation of each group of data symbols is based on a set of subcarriers, of which only a subset of the subcarriers is modulated by the group of data symbols. Furthermore, each data symbol in each group modulates a different subcarrier in a corresponding subset of the subcarriers, and no two subsets of subcarriers have a subcarrier in common.

15   [0018]   In a further embodiment, the present invention is a method for demodulating a combined modulated symbol into a set of demodulated data symbols. The method comprises: (1) separating the combined modulated symbol into M time-domain subsymbols, where M is greater than 1, (2) transforming each time-domain subsymbol into a group of demodulated data symbols, and (3) de-grouping the M groups of demodulated data symbols to generate the set of demodulated data symbols.

20   The transformation of each time-domain subsymbol is based on a set of subcarriers, of which only a subset of the subcarriers is modulated by the group of demodulated data symbols. Furthermore, each demodulated data symbol in each group modulates a different subcarrier in a corresponding subset of the subcarriers, and no two subsets of subcarriers have a subcarrier in common.

       [0019]   In yet a further embodiment, the present invention is an apparatus comprising a receiver for

25   demodulating a combined modulated symbol into a set of demodulated data symbols. The receiver comprises: (1) a subsymbol separator adapted to separate the combined modulated symbol into M time-domain subsymbols, where M is greater than 1, (2) one or more transforms adapted to transform each time-domain subsymbol into a group of demodulated data symbols, and (3) a data symbol de-grouper adapted to de-group the M groups of demodulated data symbols to generate the set of

30   demodulated data symbols. The transformation of each time-domain subsymbol is based on a set of subcarriers, of which only a subset of the subcarriers is modulated by the group of demodulated data symbols. Furthermore, each demodulated data symbol in each group modulates a different subcarrier in a corresponding subset of the subcarriers, and no two subsets of subcarriers have a subcarrier in common.

BRIEF DESCRIPTION OF THE DRAWINGS

[0020] Other aspects, features, and advantages of the present invention will become more fully apparent from the following detailed description, the appended claims, and the accompanying drawings in which like reference numerals identify similar or identical elements.

[0021] FIG. 1 shows a simplified block diagram of one possible implementation of a prior-art OFDM transmitter;

[0022] FIG. 2 graphically illustrates a frequency-domain representation of an exemplary prior-art OFDM signal;

[0023] FIG. 3 shows a simplified block diagram of one possible implementation of a prior-art OFDM receiver;

[0024] FIG. 4 shows a simplified block diagram of a combined-OFDM transmitter according to one embodiment of the present invention;

[0025] FIG. 5 graphically illustrates one implementation of a grouping pattern of frequency-domain data symbols according to one embodiment of the present invention;

[0026] FIG. 6 graphically illustrates one implementation of an interleaving pattern of time-domain samples according to one embodiment of the present invention;

[0027] FIG. 7 shows a simplified block diagram of a combined-OFDM receiver according to one embodiment of the present invention; and

[0028] FIG. 8 graphically illustrates the imaging that occurs in the frequency domain of an upsampled combined-OFDM signal according to one embodiment of the present invention.

DETAILED DESCRIPTION

[0029] Certain embodiments of the present invention relate to combined-OFDM methods and apparatuses for practicing these methods. In one such embodiment, data symbols $a[n]$ are divided into groups, where each group is converted into an OFDM subsymbol using an inverse fast Fourier transform. Then, multiple OFDM subsymbols are combined to produce a combined-OFDM symbol.

[0030] FIG. 4 shows a simplified block diagram of a combined-OFDM transmitter 400 according to one embodiment of the present invention. Transmitter 400 receives digital input data and converts the data into analog combined-OFDM signals for transmission. Conversion of the data occurs through sequential steps of data symbol mapping 402, data symbol grouping 412, inverse fast Fourier transform (IFFT) processing 404, OFDM subsymbol combining 416, cyclic prefix appending 406, digital-to-analog conversion (DAC) 408, and spectral shaping 410.

[0031] In prior-art transmitter 100 of FIG. 1, IFFT 104 receives a set of N data symbols $a[n]$ from data symbol mapping block 102 and assigns the N data symbols $a[n]$ to N subcarriers. The N data symbol $a[n]$ and subcarrier pairs are then converted from frequency-domain representations into a time-domain OFDM symbol S_k. According to the embodiment of FIG. 4, transmitter 400 has data

symbol mapping block **402**, which performs operations analogous to those of data symbol mapping block **102** of prior-art transmitter **100**. Additionally, transmitter **400** has M instances of IFFT **404**, $M >$ 1, each instance utilizing N subcarriers. A set of N data symbols $a[n]$ is divided into M groups by data symbol grouping **412**. Each group m, numbered consecutively from 0 to M-1, is then transmitted to a separate instance of IFFT **404**. Division of data symbols $a[n]$ amongst the M groups is performed according to a grouping pattern. This pattern is described further in the example below.

[0032]   Each instance of IFFT **404** receives one group m of $\frac{N}{M}$ data symbols $a[n]$ and assigns the

$\frac{N}{M}$ data symbols to the N subcarriers. Since the number $\frac{N}{M}$ of data symbols $a[n]$ in each group m is

smaller than the number N of subcarriers per IFFT **404**, not every subcarrier is assigned a data symbol

$a[n]$ for modulation. Thus, the number N_m of modulated subcarriers per IFFT **404** is equal to $\frac{N}{M}$.

Each IFFT **404** then converts the N subcarriers (i.e. the N_m modulated subcarriers and $(N - N_m)$ unmodulated subcarriers) from frequency-domain representations into a time-domain OFDM subsymbol S_m. As such, M instances of IFFT **404** produce M time-domain OFDM subsymbols S_m, each subsymbol S_m consisting of N samples. The discrete model for each OFDM subsymbol S_m may be expressed by Equation (3) as follows:

$$S_m[i] = \sum_{n=0}^{N_m-1} a_m[n] c_m[i,n] \tag{3}$$

where $i = 0,..., N-1$, $a_m[n]$ are the data symbols in OFDM subsymbol m, and the finite length complex

exponential sequence for each group of modulated subcarriers N_m is $c_m[i,n] = e^{j\frac{2\pi}{N}(m+Mn)i} w[i]$. Note

that this grouping sequence varies depending on the grouping pattern used.

[0033]   Next, OFDM subsymbol combining **416** receives M OFDM subsymbols, each containing N samples, from the M instances of IFFT **404**. According to this embodiment, the $(N \times M)$ total samples are combined using an interleaving pattern, to create one type of combined-OFDM symbol, herein referred to as an interleaved-OFDM (IOFDM) symbol. This interleaving pattern is discussed further in the example below. The resulting IOFDM symbol is expressed in Equation (4) below:

$$X_k(q) = \sum_{m=0}^{M-1}\sum_{i=0}^{N-1} S_m[i]\delta[q - m - iM] \tag{4}$$

where $\delta[.]$ denotes a unit impulse sequence. This unit impulse sequence varies depending on the OFDM subsymbol combining (e.g., interleaving) pattern used.

[0034]   The IOFDM symbols X_k are then prepared for transmission. Similar to prior-art transmitter **100** of **FIG. 1**, transmitter **400** performs cyclic prefix appending **406**, digital-to-analog conversion (DAC) **408**, and spectral shaping **410**.

[0035]   As an example of an IOFDM signal according to this embodiment, assume that data symbol grouping block 412 receives 128 data symbols $a[n]$, $n = 0,\ldots, 127$, and each instance of IFFT 404 employs $N=128$ subcarriers. Also, assume that the number M of groups is chosen to be 4. The 128 data symbols $a[n]$ may be divided into M groups by data symbol grouping block 412 as shown in

5   Table III.

TABLE III. GROUPING OF DATA SYMBOLS $a[n]$ IN THE FREQUENCY DOMAIN OF AN IOFDM SIGNAL ACCORDING TO ONE EMBODIMENT							
Subcarrier Index	0	1	2	3	4	...	127
OFDM Subsymbol 0 (S_0)	$a[0]$				$a[4]$	...	
OFDM Subsymbol 1 (S_1)		$a[1]$				...	
OFDM Subsymbol 2 (S_2)			$a[2]$			...	
OFDM Subsymbol 3 (S_3)				$a[3]$		...	$a[127]$

According to this grouping pattern, the first data symbol $a[0]$ is assigned to subcarrier 0 in OFDM subsymbol S_0, the second data symbol $a[1]$ is assigned to subcarrier 1 in the second OFDM subsymbol S_1, the third data symbol $a[2]$ is assigned to subcarrier 2 in the third OFDM subsymbol S_2, and the fourth data symbol $a[3]$ is assigned to subcarrier 3 in the fourth OFDM subsymbol S_3. This grouping

10   pattern is continued beginning with the fifth data symbol $a[4]$ being assigned to subcarrier 4 in the first OFDM subsymbol S_0 and concluding with the last data symbol $a[127]$ being assigned to subcarrier 127 in the fourth OFDM subsymbol S_3.

[0036]   FIG. 5 further demonstrates the data symbol grouping pattern described in the example above. This frequency-domain representation shows each modulated subcarrier N_m, represented by a

15   single waveform. FIGS. 5 (a), (b), (c), and (d) show the first modulated subcarriers of OFDM subsymbols S_0, S_1, S_2, and S_3, respectively. FIG. 5 (e) shows the frequency-domain representation of the corresponding IOFDM symbol. Note that $P(f)$ is the frequency response of spectral shaping block 410.

[0037]   After conversion from frequency-domain representations into time-domain OFDM

20   subsymbols S_m by the 4 instances of IFFT 404, samples $S_m[i]$ may be interleaved as shown in Table IV to produce an IOFDM symbol X_k.

TABLE IV. GROUPING OF SAMPLES $S_m[i]$ IN THE TIME DOMAIN ACCORDING TO ONE EMBODIMENT																
IOFDM Symbol $X_k(q)$, $q = 0,...,511$																
Sample Index q	0	1	2	3	4	5	6	7	8	9	10	11	...	508	509	510	511
Trans-mitted Data	$S_0[0]$	$S_1[0]$	$S_2[0]$	$S_3[0]$	$S_0[1]$	$S_1[1]$	$S_2[1]$	$S_3[1]$	$S_0[2]$	$S_1[2]$	$S_2[2]$	$S_3[2]$	...	$S_0[127]$	$S_1[127]$	$S_2[127]$	$S_3[127]$

Note that one sample $S_m[i]$ is created for each subcarrier, even if the subcarrier is not assigned a data symbol $a[n]$. In this interleaving pattern, sample $S_0[0]$, is followed by samples $S_1[0]$, $S_2[0]$, and $S_3[0]$. Following $S_3[0]$, the pattern continues beginning with $S_0[1]$ and followed by $S_1[1]$, $S_2[1]$, and $S_3[1]$. This interleaving pattern is repeated for all samples $S_m[i]$.

[0038]   FIG. 6 further demonstrates the interleaving pattern described in the example above. FIGS. 6 (a), (b), (c) and (d) represent OFDM subsymbols S_0, S_1, S_2, and S_3, respectively. FIG. 6 (e) represents the interleaved OFDM symbol X_k.

[0039]   According to the exemplary IOFDM symbol given above, 512 samples $X_k[q]$, where $q = 0,...,511$, are transmitted for each set of 128 data symbols $a[n]$. This is in contrast to the example provided for prior-art OFDM transmitter 100 in the background section, where each set of 128 data symbols is transmitted using 128 OFDM samples. Thus, the IOFDM symbol duration of this example is 4 times longer than the OFDM symbol duration of the corresponding prior-art example. On the other hand, an IOFDM symbol X_k is more robust against noise effects during transmission than the corresponding prior-art OFDM symbol S_k. In addition, the sample period (T/N) of the IOFDM symbol X_k is the same as the sample period of the prior-art OFDM symbol S_k. Thus, the bandwidth of the IOFDM symbol X_k is the same as that of the OFDM symbol S_k.

[0040]   FIG. 7 shows a simplified block diagram of one implementation of a combined-OFDM receiver 700, which reverses the operations performed by combined-OFDM transmitter 400. Receiver 700 receives analog combined-OFDM signals and extracts the original digital data. Extraction occurs through sequential steps of matched filtering 702, analog-to-digital conversion (ADC) 704, cyclic prefix removal 706, OFDM subsymbol separating 714, fast Fourier transform (FFT) processing 708, data symbol de-grouping and equalization 718, and data symbol de-mapping 710.

[0041]   First, receiver 700 down-converts the received signal into a baseband analog signal at the receiver's RF front end. Then, similar to prior-art receiver 300 of FIG. 3, receiver 700 performs matched filtering 702, analog-to-digital conversion ADC 704, and cyclic prefix removal 706. Additionally, synchronization and channel estimation may be performed (not shown).

[0042]   OFDM subsymbol separating block 714 separates (e.g., deinterleaves) the digital IOFDM symbols X_k to recover the M OFDM subsymbols S_m. The M OFDM subsymbols S_m are subsequently transmitted to the M instances of FFT 708. Each instance of FFT 708 extracts N subcarriers from the

corresponding OFDM subsymbol S_m to obtain the corresponding group m of data symbols $a[n]$. The M groups of data symbols $a[n]$ are then equalized and de-grouped by data symbol de-grouping and equalization block **718**. Finally, data symbols $a[n]$ are de-mapped into the original binary bits using conventional data symbol de-mapping block **710**.

[0043]   Various embodiments of the present invention may be envisioned in which alternative grouping patterns are employed. In the IOFDM example above, data symbols $a[n]$ were grouped using an interleaving pattern. Another grouping pattern using interleaving may be employed for the above IOFDM example in which the first two data symbols ($a[0]$ and $a[1]$) are assigned to subcarriers 0 and 1 in OFDM subsymbol S_0, the third and fourth data symbols ($a[2]$ and $a[3]$) are assigned to subcarriers 2 and 3 in OFDM subsymbol S_1, the fifth and sixth data symbols ($a[4]$ and $a[5]$) are assigned to subcarriers 4 and 5 in OFDM subsymbol S_2, and the seventh and eighth data symbols ($a[6]$ and $a[7]$) are assigned to subcarriers 6 and 7 in OFDM subsymbol S_3. This process is then continued beginning with the ninth and tenth data symbols $a[8]$ and $a[9]$ being assigned to subcarriers 8 and 9 in OFDM subsymbol S_0 and concluding with data symbols $a[126]$ and $a[127]$ being assigned to subcarriers 126 and 127 in OFDM subsymbol S_3. A vast number of alternative grouping patterns may be envisioned within the scope of this invention.

[0044]   Various embodiments of the present invention may also be envisioned in which alternative combining patterns using interleaving are employed. In one such alternative to the IOFDM example above, OFDM subsymbol combining block **416** may assign two consecutive samples $S_m[i]$ to IOFDM symbol $X(k)$ at a time. In other words, OFDM subsymbol combining block **416** may assign $S_0[0]$ and $S_0[1]$, followed by $S_1[0]$ and $S_1[1]$, followed by $S_2[0]$ and $S_2[1]$, followed by $S_3[0]$ and $S_3[1]$ to IOFDM symbol $X(k)$. This process is then repeated beginning with $S_0[2]$ and ending with $S_3[127]$. A vast number of alternative combining patterns using interleaving may be envisioned within the scope of this invention.

[0045]   Furthermore, the above mentioned examples demonstrate one type of combined-OFDM symbol, referred to as an IOFDM symbol. In another type of combined-OFDM symbol, subsymbols S_k can be appended to each other without interleaving, such that, samples $S_0[0]$ to $S_0[127]$ of subsymbol S_0 are followed by samples $S_1[0]$ to $S_1[127]$ of subsymbol S_1, which are followed by samples $S_2[0]$ to $S_2[127]$ of subsymbol S_2, which are followed by samples $S_3[0]$ to $S_3[127]$ of subsymbol S_3. The order in which subsymbols S_k are appended may also vary.

[0046]   Further embodiments of the present invention may be envisioned in which the combined-OFDM symbol duration is the same as the corresponding prior-art OFDM symbol duration. In such embodiments, OFDM subsymbols S_m or combined-OFDM symbols X_k are upsampled by upsamplers **414** or **418**, respectively, to increase the data rate. For instance, in the IOFDM example above, the 128 samples $S_m[i]$ may be upsampled by 4 (i.e., upsampled by M), so that the total number of modulated samples transmitted per IOFDM symbol increases from 128 to 512. As a result of upsampling,

imaging in DAC **408** produces a larger signal bandwidth. The resulting upsampled IOFDM signal may
be represented by Equation (5) as follows:

$$x(t) = \sum_q x[q]\delta(t - qT_C) * p(t) = \sum_{m=0}^{M-1}\sum_{i=0}^{N-1} s_m[i]p(t - mT_C - iMT_C) \tag{5}$$

where *p(t)* is the impulse response of the spectral shaping filter, and $T_C = \dfrac{T}{MN}$ is the new sample

5   period. **FIG. 8** graphically demonstrates this imaging in the frequency domain. Note that the
modulated subcarriers are repeated at higher frequencies. This phenomenon increases the overall signal
bandwidth. Additionally, in order to accommodate upsampling, receiver **700** has downsamplers **712** or
716, which downsample either the combined-OFDM symbols X_k or the OFDM subsymbols S_m of the
received signal, respectively.

10   **[0047]**   The present invention has been described using a number of data symbols *a[n]* that is
equal to the number *N* of subcarriers; however, the present invention is not so limited. The number of
data symbols *a[n]* may be fewer than the number *N* of subcarriers. Therefore, the number N_m of

subcarriers modulated with data symbols *a[n]* per IFFT **404** could be less than $\dfrac{N}{M}$. The excess

unmodulated subcarriers could then be used for other purposes such as implementation as guard
15   channels or pilot channels.

[0048]   Additional embodiments of the present invention may be envisioned in which the number
M of groups varies. In the above-mentioned IOFDM example, the number *M* of groups (i.e., 4) was
chosen based on the number *N* (i.e., 128) of subcarriers such that the number N_m of modulated

subcarriers per group (i.e., $\dfrac{N}{M}$) is an integer (i.e., 32). While it is preferred that the number of data

20   symbols per group N_m be an integer, it is not necessary. For example, the number *M* of groups could
be 3, in which case each group would not necessarily have the same number of data symbols *a[n]*.
Additionally, by increasing the number *M* of groups, and employing upsampling, the width of the
overall frequency spectrum is increased. Selecting a number *M* of groups that is equal to the number *N*
of subcarriers allows for the greatest possible spectrum spreading. Alternatively, as the number *M* of
25   groups is decreased, the frequency spectrum width is decreased. Selecting the number *M* of groups
such that *M*=1, results in the production of a prior-art OFDM signal. Combined OFDM, therefore,
provides a means to construct a variable spreading ratio system according to different applications
and/or channel conditions. This spectrum spreading ability allows combined OFDM to be suitable for
use in ultra-wideband (UWB) applications. Additionally, due to the wider spectrum of the combined-
30   OFDM signal, lower power operation can be achieved, thereby easing issues of interference
compliance.

[0049]   In yet other embodiments, the number of IFFT blocks in transmitter **400** and FFT blocks in receiver **700** may vary. For instance, in the above-mentioned IOFDM example, transmitter **400** might have only one shared IFFT block that receives the M groups of data symbols $a[n]$ in succession and converts the M groups in succession into M subsymbols S_m in a time-multiplexed manner. .

[0050]   Other elements of OFDM are supported by this invention. For example, this invention may be implemented using coded OFDM (COFDM). Additionally, piconet channelization methods such as code division multiple access (CDMA) and frequency division multiple access (FDMA) can be used in conjunction with combined OFDM so that multi-piconet performance can be improved.

[0051]   The present invention has been described as a transmitter and a receiver; however, the present invention may also be implemented as a transceiver. Furthermore, receivers, transmitters, and transceivers may be implemented in a wide variety of applications, including any suitable consumer product or other suitable apparatus. Such apparatuses include devices such as cellular phones and cellular phone base stations.   .

[0052]   The present invention may be implemented as (analog, digital, or a hybrid of both analog and digital) circuit-based processes, including possible implementation as a single integrated circuit (such as an ASIC or an FPGA), a multi-chip module, a single card, or a multi-card circuit pack. As would be apparent to one skilled in the art, various functions of circuit elements may also be implemented as processing blocks in a software program. Such software may be employed in, for example, a digital signal processor, micro-controller, or general-purpose computer.

[0053]   The present invention can be embodied in the form of methods and apparatuses for practicing those methods. The present invention can also be embodied in the form of program code embodied in tangible media, such as magnetic recording media, optical recording media, solid state memory, floppy diskettes, CD-ROMs, hard drives, or any other machine-readable storage medium, wherein, when the program code is loaded into and executed by a machine, such as a computer, the machine becomes an apparatus for practicing the invention. The present invention can also be embodied in the form of program code, for example, whether stored in a storage medium, loaded into and/or executed by a machine, or transmitted over some transmission medium or carrier, such as over electrical wiring or cabling, through fiber optics, or via electromagnetic radiation, wherein, when the program code is loaded into and executed by a machine, such as a computer, the machine becomes an apparatus for practicing the invention. When implemented on a general-purpose processor, the program code segments combine with the processor to provide a unique device that operates analogously to specific circuits.

[0054]   The present invention can also be embodied in the form of a bitstream or other sequence of signal values electrically or optically transmitted through a medium, stored magnetic-field variations in a magnetic recording medium, etc., generated using a method and/or an apparatus of the present invention.

[0055] Unless explicitly stated otherwise, each numerical value and range should be interpreted as being approximate as if the word "about" or "approximately" preceded the value of the value or range.

[0056] It will be further understood that various changes in the details, materials, and arrangements of the parts which have been described and illustrated in order to explain the nature of this invention may be made by those skilled in the art without departing from the scope of the invention as expressed in the following claims. For example, various equalization techniques commonly known in the art may be employed in receiver **700**. As another example, methods other than cyclic prefix appending might be employed, including use of a zero pad.

[0057] The use of figure numbers and/or figure reference labels in the claims is intended to identify one or more possible embodiments of the claimed subject matter in order to facilitate the interpretation of the claims. Such use is not to be construed as necessarily limiting the scope of those claims to the embodiments shown in the corresponding figures.

[0058] It should be understood that the steps of the exemplary methods set forth herein are not necessarily required to be performed in the order described, and the order of the steps of such methods should be understood to be merely exemplary. Likewise, additional steps may be included in such methods, and certain steps may be omitted or combined, in methods consistent with various embodiments of the present invention.

[0059] Although the elements in the following method claims, if any, are recited in a particular sequence with corresponding labeling, unless the claim recitations otherwise imply a particular sequence for implementing some or all of those elements, those elements are not necessarily intended to be limited to being implemented in that particular sequence.

[0060] Reference herein to "one embodiment" or "an embodiment" means that a particular feature, structure, or characteristic described in connection with the embodiment can be included in at least one embodiment of the invention. The appearances of the phrase "in one embodiment" in various places in the specification are not necessarily all referring to the same embodiment, nor are separate or alternative embodiments necessarily mutually exclusive of other embodiments. The same applies to the term "implementation."

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CLAIMS

We claim:

1.   A method for modulating a set of data symbols into a combined modulated symbol, the method comprising:

5   (a)   dividing the set of data symbols into M groups of data symbols, $M>1$;

              (b)   transforming each group of data symbols into a time-domain subsymbol to produce M time-domain subsymbols, wherein:

                      the transformation of each group of data symbols is based on a set of subcarriers, of which only a subset of the subcarriers is modulated by the group of data symbols;

10   each data symbol in each group modulates a different subcarrier in a corresponding subset of the subcarriers; and

                      no two subsets of subcarriers have a subcarrier in common; and

              (c)   combining the M time-domain subsymbols to form the combined modulated symbol.

15 2.   The invention of claim 1, wherein the total number of subcarriers in the M subsets of subcarriers is equal to the number of subcarriers in the set of subcarriers.

3.   The invention of claim 1, wherein step (b) comprises, for each subset of modulated subcarriers, transforming both the subset of modulated subcarriers and one or more unmodulated subcarriers to

20   form the corresponding time-domain subsymbol.

4.   The invention of claim 3, wherein for each group of data symbols, the sum of (1) the number of the modulated subcarriers and (2) the number of the one or more unmodulated subcarriers is equal to the total number of subcarriers in the set.

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5.   The invention of claim 1, wherein:

        each time-domain subsymbol is represented by a plurality of time-domain samples; and

        step (c) comprises interleaving the time-domain samples of the M subsymbols to form a sequence of interleaved time-domain samples for the combined modulated symbol.

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6.   The invention of claim 1, wherein step (c) comprises generating an upsampled combined modulated symbol by upsampling either (i) the M time-domain subsymbols prior to the combining or (ii) the combined modulated symbol after the combining.

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7.   The invention of claim 1, wherein:

        the transformation is an inverse fast Fourier transformation (IFFT);

        each time-domain subsymbol is an OFDM subsymbol; and

        the combined modulated symbol is a combined OFDM symbol.

8.   The combined modulated symbol generated by the method of claim 1.

9.   Apparatus comprising a transmitter for modulating a set of data symbols into a combined modulated symbol, the transmitter comprising:

        a data symbol grouper adapted to divide the set of data symbols into M groups of data symbols, $M>1$;

        one or more transforms adapted to transform each group of data symbols into a time-domain subsymbol, wherein:

                the transformation of each group of data symbols is based on a set of subcarriers, of which only a subset of the subcarriers is modulated by the group of data symbols;

                each data symbol in each group modulates a different subcarrier in a corresponding subset of the subcarriers; and

                no two subsets of subcarriers have a subcarrier in common; and

        a subsymbol combiner adapted to combine the M time-domain subsymbols to form the combined modulated symbol.

10.   The invention of claim 9, the one or more transforms comprise two or more transforms, each transform adapted to transform one or more groups of data symbols into one or more time-domain subsymbols.

11.   The invention of claim 9, the one or more transforms comprise a shared transform adapted to transform two or more groups of data symbols into two or more time-domain subsymbols in a time-multiplexed manner.

12.   The invention of claim 9, wherein:

        each time-domain subsymbol is represented by a plurality of time-domain samples; and

        the subsymbol combiner is adapted to interleave the time-domain samples of the M subsymbols to form a sequence of interleaved time-domain samples for the combined modulated symbol.

13.   The invention of claim 9, wherein:

the one or more transforms are adapted to implement one or more IFFTs;

each time-domain subsymbol is an OFDM subsymbol; and

the combined modulated symbol is a combined OFDM symbol.

14.   The invention of claim 9, further comprising one or more upsamplers adapted to generate an upsampled combined modulated symbol by upsampling either (i) the M time-domain subsymbols prior to the combining or (ii) the combined modulated symbol after the combining.

15.   A method for demodulating a combined modulated symbol into a set of demodulated data symbols, the method comprising:

(a)   separating the combined modulated symbol into M time-domain subsymbols, $M>1$;

(b)   transforming each time-domain subsymbol into a group of demodulated data symbols, wherein:

the transformation of each time-domain subsymbol is based on a set of subcarriers, of which only a subset of the subcarriers is modulated by the group of demodulated data symbols;

each demodulated data symbol in each group modulates a different subcarrier in a corresponding subset of the subcarriers; and

no two subsets of subcarriers have a subcarrier in common; and

(c)   de-grouping the M groups of demodulated data symbols to generate the set of demodulated data symbols.

16.   The invention of claim 15, wherein:

the combined modulated symbol comprises a sequence of interleaved time-domain samples; and

step (a) comprises de-interleaving the interleaved time-domain samples to obtain the M time-domain subsymbols.

17.   The invention of claim 15, wherein the total number of subcarriers in the M subsets of subcarriers is equal to the number of subcarriers in the set of subcarriers.

18.   The invention of claim 15, wherein step (b) comprises, for each subset of modulated subcarriers, transforming both the subset of modulated subcarriers and one or more unmodulated subcarriers to form the corresponding group of demodulated data symbols.

19.   The invention of claim 18, wherein for each group of demodulated data symbols, the sum of (1) the number of the modulated subcarriers and (2) the number of the one or more unmodulated

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subcarriers is equal to the total number of subcarriers in the set.

20.   The invention of claim 15, wherein step (a) comprises generating downsampled time-domain subsymbols by downsampling either (i) the combined modulated symbol prior to the separating or (ii)

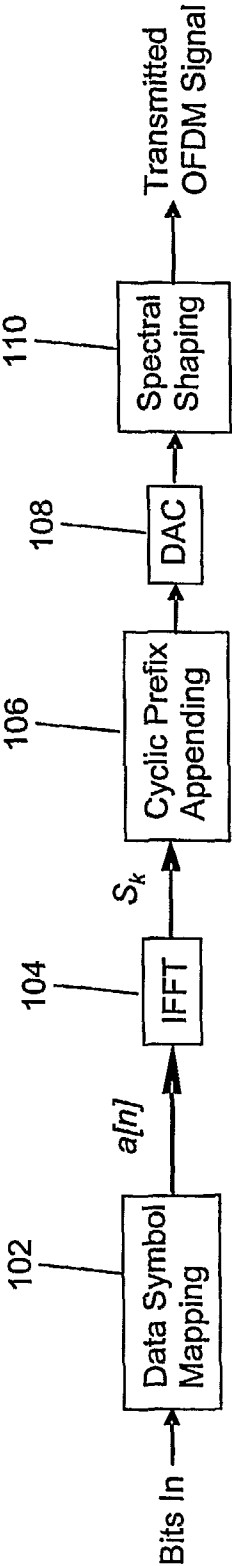5   the M time-domain subsymbols after the separating.

21.   The invention of claim 15, wherein:

the transformation is a fast Fourier transformation (FFT);

each time-domain subsymbol is an OFDM subsymbol; and

10   the combined modulated symbol is a combined OFDM symbol.

22.   Apparatus comprising a receiver for demodulating a combined modulated symbol into a set of demodulated data symbols, the receiver comprising:

a subsymbol separator adapted to separate the combined modulated symbol into M time-

15   domain subsymbols, $M>1$;

one or more transforms adapted to transform each time-domain subsymbol into a group of demodulated data symbols, wherein:

the transformation of each time-domain subsymbol is based on a set of subcarriers, of which only a subset of the subcarriers is modulated by the group of demodulated data symbols;

20   each demodulated data symbol in each group modulates a different subcarrier in a corresponding subset of the subcarriers; and

no two subsets of subcarriers have a subcarrier in common; and

a data symbol de-grouper adapted to de-group the M groups of demodulated data symbols to generate the set of demodulated data symbols.

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23.   The invention of claim 22, wherein:

the combined modulated symbol comprises a sequence of interleaved time-domain samples; and

the subsymbol separator is adapted to de-interleave the interleaved time-domain samples to

30   obtain the M time-domain subsymbols.

24.   The invention of claim 22, the one or more transforms comprise two or more transforms, each transform adapted to transform one or more time-domain subsymbols into one or more groups of demodulated data symbols.

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25.   The invention of claim 22, the one or more transforms comprise a shared transform adapted to

transform two or more time-domain subsymbols into two or more groups of demodulated data symbols in a time-multiplexed manner.

26.   The invention of claim 22, wherein:

the one or more transforms are adapted to implement one or more FFTs;

each time-domain subsymbol is an OFDM subsymbol; and

the combined modulated symbol is a combined OFDM symbol.

27.   The invention of claim 22, further comprising one or more downsamplers adapted to generate downsampled time-domain subsymbols by downsampling either (i) the combined modulated symbol prior to the separating or (ii) the M time-domain subsymbols after the separating.
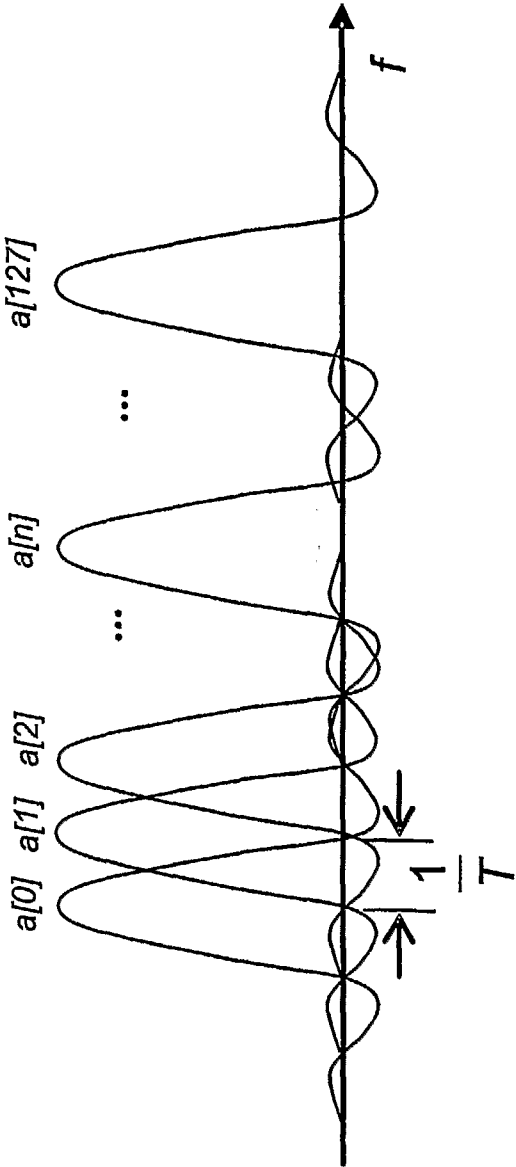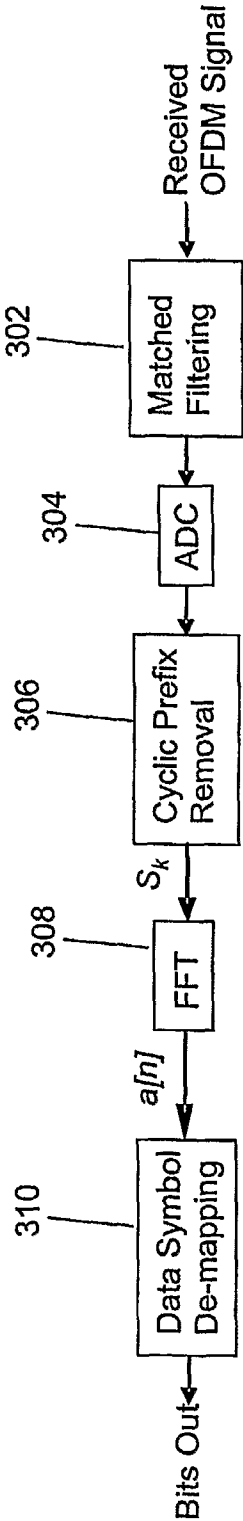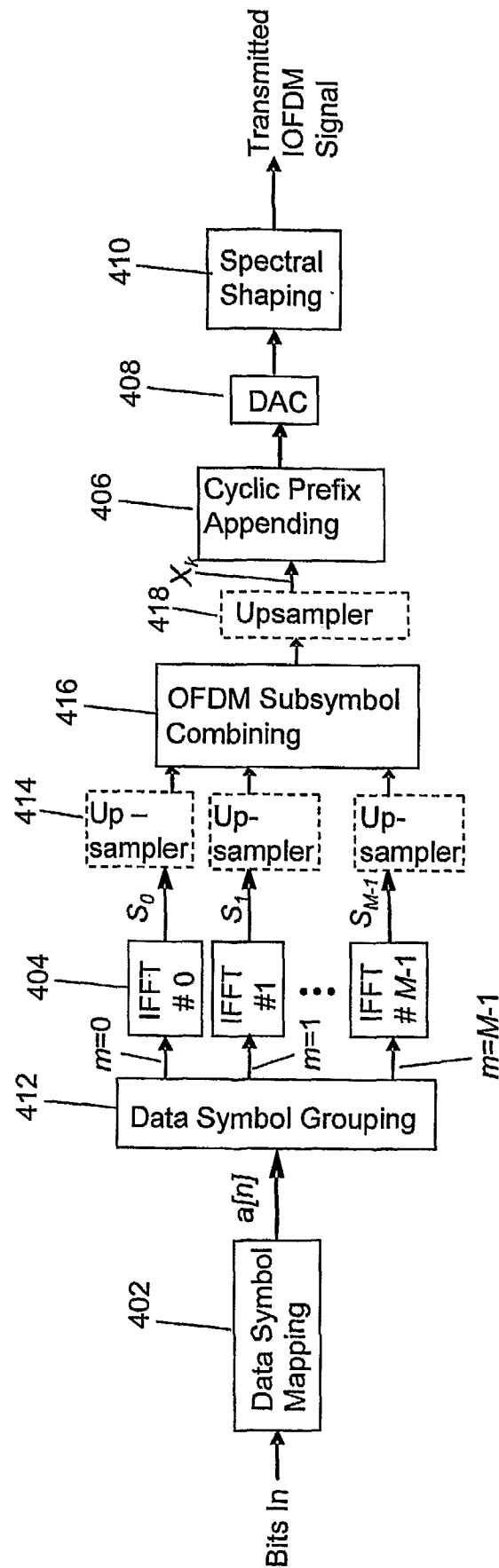
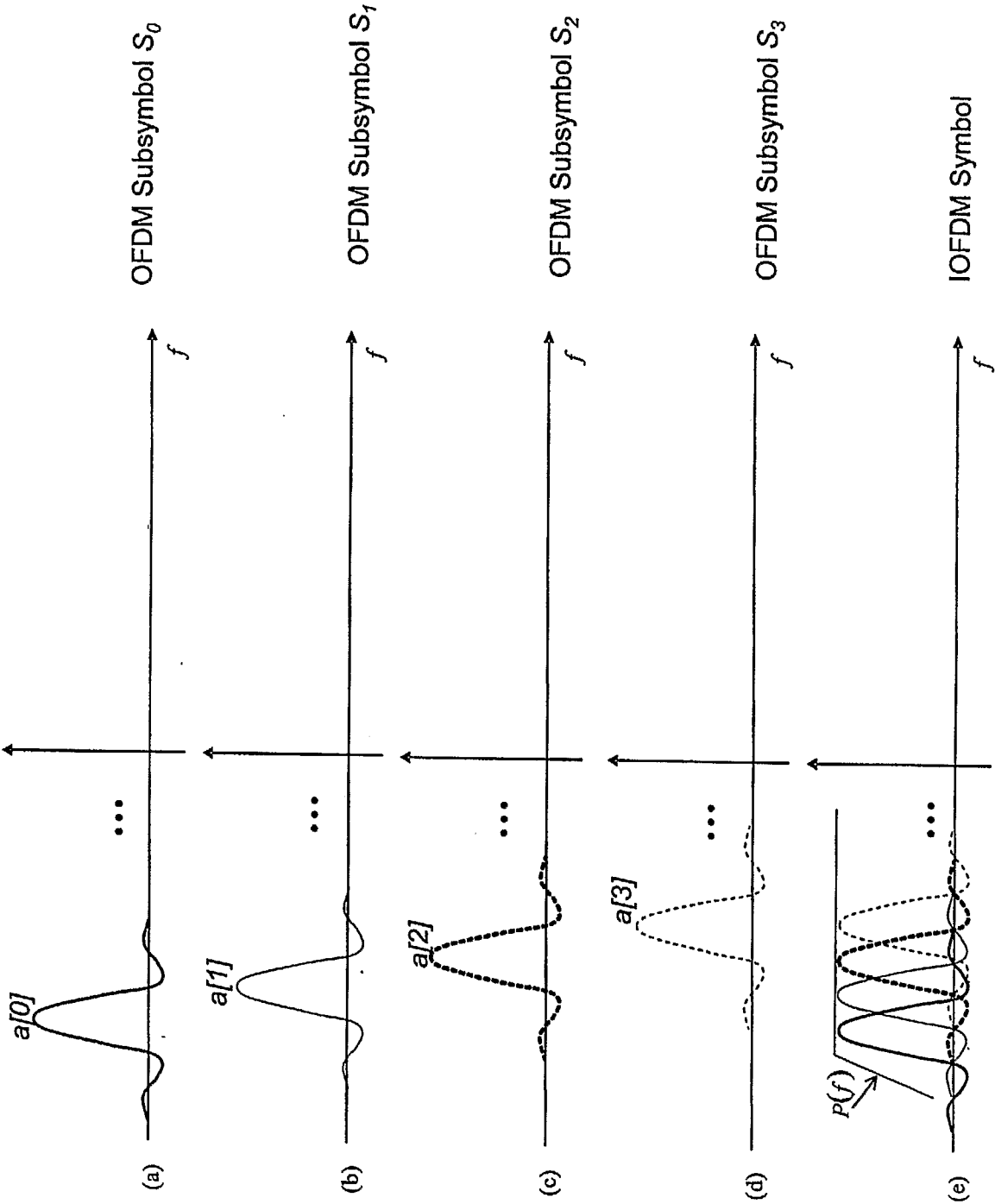FIG. 1 (Prior Art)

FIG. 2 (Prior Art)
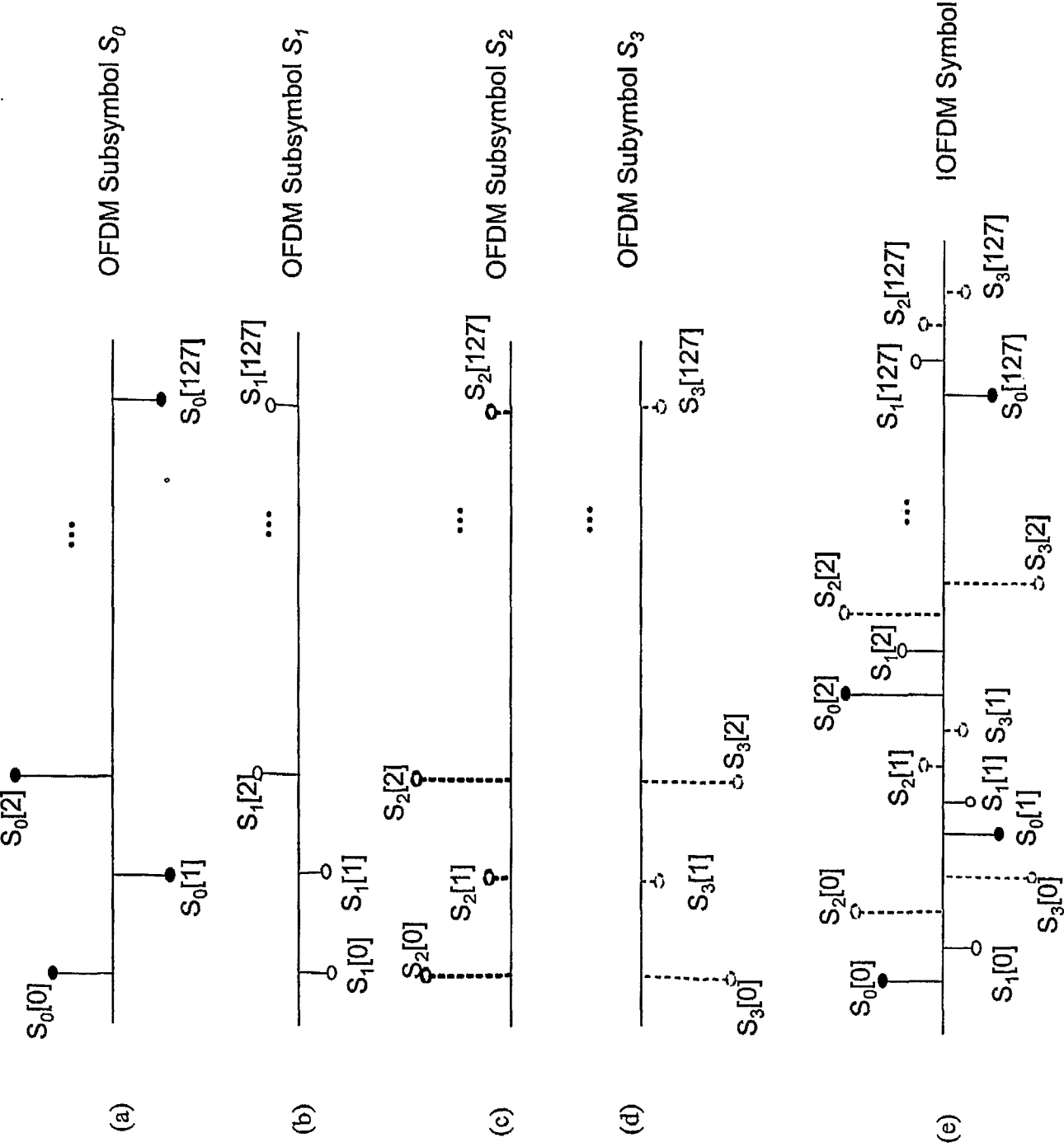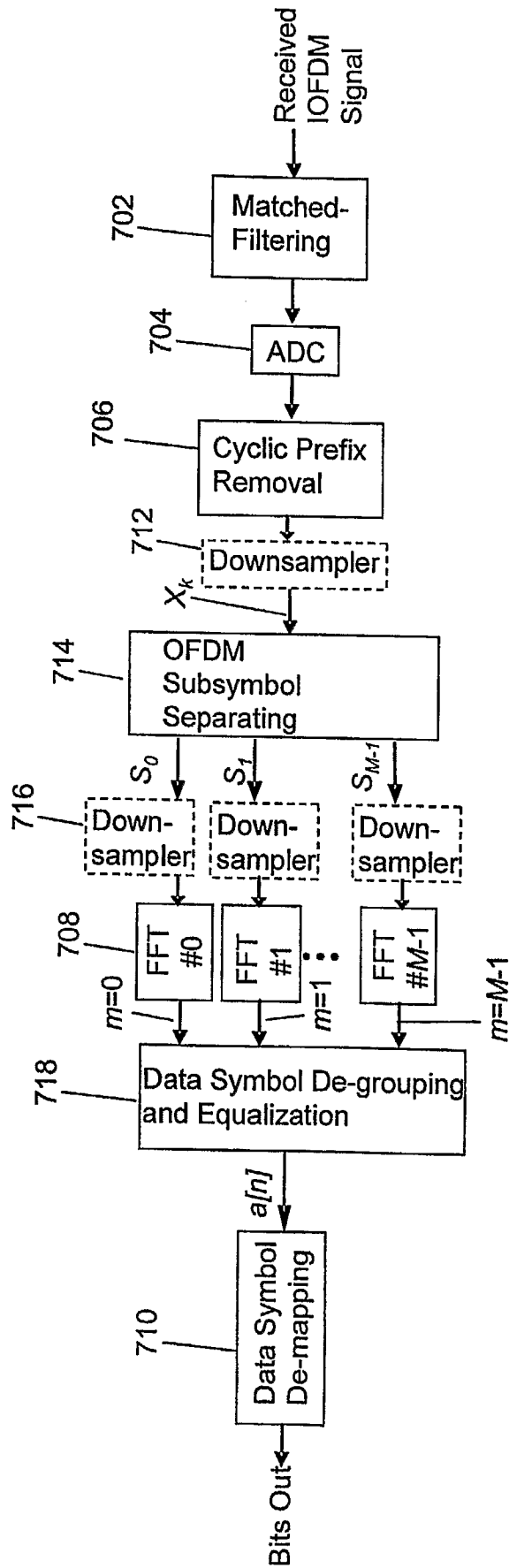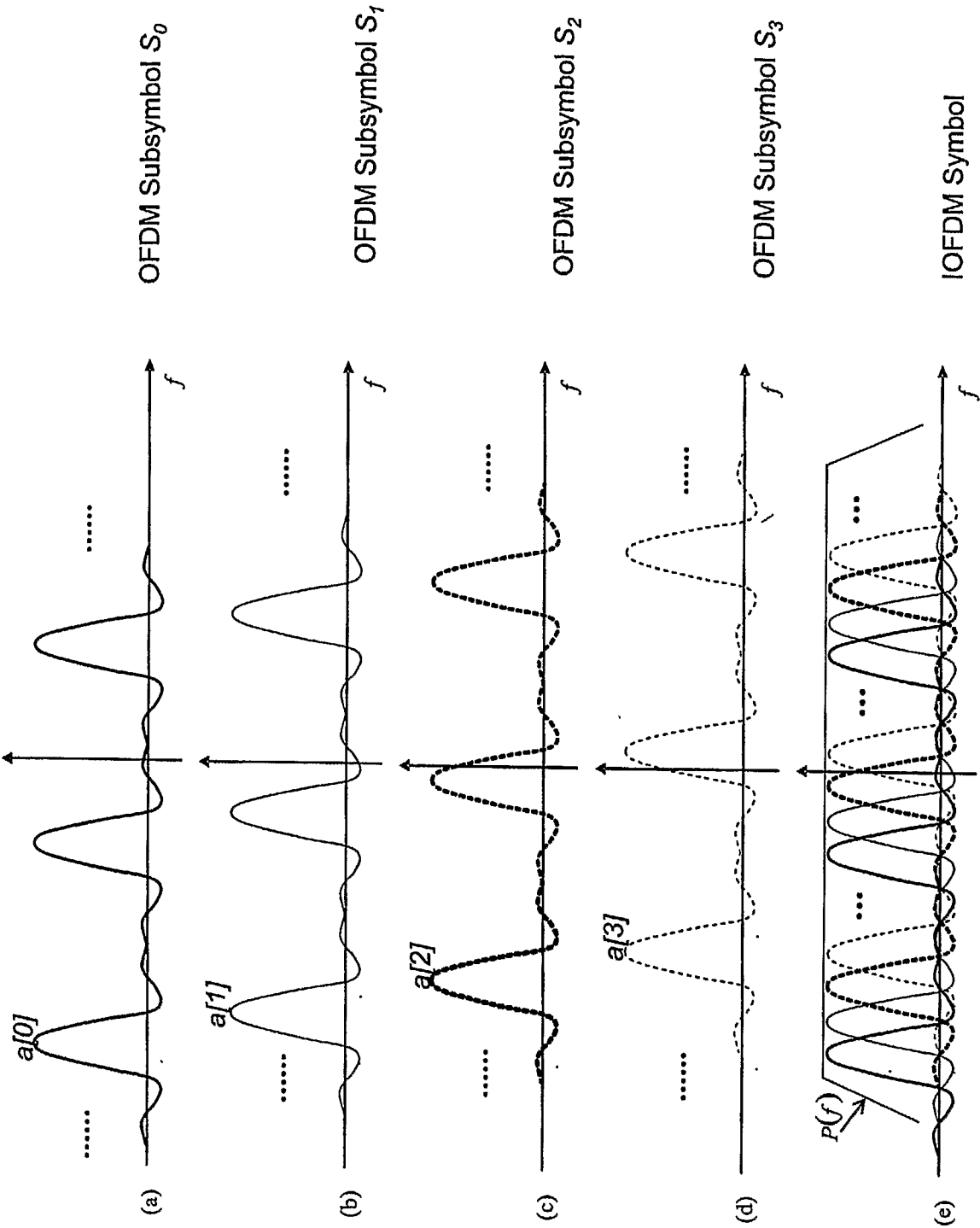
FIG. 3 (Prior Art)

FIG. 4

FIG. 5

FIG. 6

FIG. 7

OFDM Subsymbol S_0

OFDM Subsymbol S_1

OFDM Subsymbol S_2

OFDM Subsymbol S_3

IOFDM Symbol

$a[0]$

$a[1]$

$a[2]$

$a[3]$

$P(f)$

(a)

(b)

(c)

(d)

(e)

FIG. 8

INTERNATIONAL SEARCH REPORT

A. CLASSIFICATION OF SUBJECT MATTER
INV. H04L27/26

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 H04B

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 practical, search terms used)

EPO-Internal

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	MULLER S H ET AL: "A novel peak power reduction scheme for OFDM" PERSONAL, INDOOR AND MOBILE RADIO COMMUNICATIONS, 1997. WAVES OF THE YEAR 2000. PIMRC '97., THE 8TH IEEE INTERNATIONAL SYMPOSIUM ON HELSINKI, FINLAND 1-4 SEPT. 1997, NEW YORK, NY, USA,IEEE, US, vol. 3, 1 September 1997 (1997-09-01), pages 1090-1094, XP010247616 ISBN: 0-7803-3871-5 paragraph [0004]; figure 1	1-27
X	EP 1 357 718 A (SAMSUNG ELECTRONICS CO LTD [KR]) 29 October 2003 (2003-10-29) paragraphs [0011] - [0024]; figure 1	1-27

☐ 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 document but published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"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
16 April 2007	23/04/2007

Name and mailing address of the ISA/ European Patent Office, P.B. 5818 Patentlaan 2 NL – 2280 HV Rijswijk Tel. (+31–70) 340-2040, Tx. 31 651 epo nl, Fax: (+31–70) 340-3016	Authorized officer Fouasnon, Olivier

Patent document cited in search report		Publication date	Patent family member(s)		Publication date
EP 1357718	A	29-10-2003	AU	2003223129 A1	10-11-2003
			CA	2452277 A1	06-11-2003
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			US	2003202460 A1	30-10-2003