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(74) Agent: BALLARINI, Robert, J.; VOLPE AND KOENIG, P.C., United Plaza, Suite 1600, 30 S. 17th Street, Philadelphia, Pennsylvania 19103 (US).

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(71) Applicant (for all designated States except US): INTER-DIGITAL TECHNOLOGY CORPORATION [US/US]; 300 Delaware Avenue, Suite 527, Wilmington, Delaware 19801 (US).

(72) Inventors; and

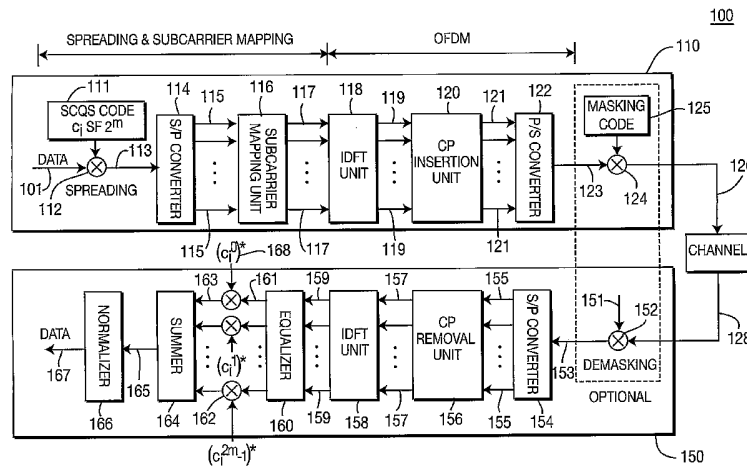
(75) Inventors/Applicants (for US only): TSAI, Yingming [—/US]; 10 Jolie Court, Booton, New Jersey 07005 (US). ZHANG, Guodong [CN/US]; 490 Main Street, Apt. C8, Farmingdale, New York 11735 (US). PAN, Jung-Lin [—/US]; 15 Court Street, Selden, New York 11784 (US).

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(54) Title: ORTHOGONAL FREQUENCY DIVISION MULTIPLEXING CODE DIVISION MULTIPLE ACCESS SYSTEM



(57) Abstract: An orthogonal frequency division multiplexing (OFDM)-code division multiple access (CDMA) system is disclosed. The system includes a transmitter and a receiver. At the transmitter, a spreading and subcarrier mapping unit spreads an input data symbol with a complex quadratic sequence code to generate a plurality of chips and maps each chip to one of a plurality of subcarriers. An inverse discrete Fourier transform is performed on the chips mapped to the subcarriers and a cyclic prefix (CP) is inserted to an OFDM frame. A parallel-to-serial converter converts the time-domain data into a serial data stream for transmission. At the receiver, a serial-to-parallel converter converts received data into multiple received data streams and the CP is removed from the received data. A discrete Fourier transform is performed on the received data streams and equalization is performed. A despreader despreads an output of the equalizer to recover the transmitted data.

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[0001] **ORTHOGONAL FREQUENCY DIVISION MULTIPLEXING -
 CODE DIVISION MULTIPLE ACCESS SYSTEM**

[0002] **FIELD OF INVENTION**

[0003] The present invention is related to a wireless communication system. More particularly, the present invention is related to an orthogonal frequency division multiplexing (OFDM)-code division multiple access (CDMA) communication system.

[0004] **BACKGROUND**

[0005] Wireless communication networks of the future will provide broadband services such as wireless Internet access to subscribers. Those broadband services require reliable and high-rate communications over time-dispersive (frequency-selective) channels with limited spectrum and intersymbol interference (ISI) caused by multipath fading. OFDM is one of the most promising solutions for a number of reasons. OFDM has high spectral efficiency and adaptive coding and modulation can be employed across subcarriers. Implementation is simplified because the baseband modulation and demodulation can be performed using simple circuits such as inverse fast Fourier transform (IFFT) circuits and fast Fourier transform (FFT) circuits. A simple receiver structure is one of the advantages of OFDM system, since in some cases only one tap equalizer is sufficient to provide excellent robustness in multipath environment. In other cases, when OFDM is used in conjunction with signal spreading across multiple subcarriers, a more advanced equalizer may be required.

[0006] OFDM has been adopted by several standards such as Digital Audio Broadcast (DAB), Digital Audio Broadcast Terrestrial (DAB-T), IEEE 802.11a/g, IEEE 802.16 and Asymmetric Digital Subscriber Line (ADSL). OFDM is being considered for adoption in standards such as Wideband Code Division Multiple Access (WCDMA) for third generation partnership project (3GPP) long term evolution, CDMA2000, Fourth Generation (4G) wireless systems, IEEE 802.11n,

IEEE 802.16, and IEEE 802.20.

[0007] Despite all of the advantages, OFDM has some disadvantages. One major disadvantage of OFDM is its inherent high peak-to-average power ratio (PAPR). The PAPR of OFDM increases as the number of subcarriers increases. When high PAPR signals are transmitted through a non-linear power amplifier, severe signal distortion will occur. Therefore, a highly linear power amplifier with power backoff is required for OFDM. As a result, the power efficiency with OFDM is low and the battery life of a mobile device implementing OFDM is limited.

[0008] Techniques for reducing the PAPR of an OFDM system have been studied extensively. These PAPR reduction techniques include coding, clipping, and filtering. The effectiveness of these methods varies and each has its own inherent trade-offs in terms of complexity, performance, and spectral efficiency.

[0009]

SUMMARY

[0010] The present invention is related to an OFDM-CDMA system. The system includes a transmitter and a receiver. At the transmitter, a spreading and subcarrier mapping unit spreads an input data symbol with a spread complex quadratic sequence (SCQS) code to generate a plurality of chips and maps each chip to one of a plurality of subcarriers. An inverse discrete Fourier transform (IDFT) or IFFT unit performs IDFT or IFFT on the chips mapped to the subcarriers and a cyclic prefix (CP) is inserted to an OFDM frame. A parallel-to-serial (P/S) converter converts the time-domain data into a serial data stream for transmission. At the receiver, a serial-to-parallel (S/P) converter converts a received data into multiple received data streams and the CP is removed from the received data. A discrete Fourier transform (DFT) or FFT unit performs DFT or FFT on the received data streams and equalization is performed. A despreader despreads an output of the equalizer to recover the transmitted data.

[0011] BRIEF DESCRIPTION OF THE DRAWINGS

[0012] A more detailed understanding of the invention may be had from the following description of a preferred embodiment, given by way of example and to be understood in conjunction with the accompanying drawing wherein:

[0013] Figure 1 is a block diagram of an OFDM-CDMA system in accordance with one embodiment of the present invention;

[0014] Figure 2 shows the code set of the spread complex quadratic sequence (SCQS) code in accordance with the present invention;

[0015] Figure 3 shows spreading and subcarrier mapping in the system of Figure 1;

[0016] Figure 4 shows an alternative interpretation of the spreading and subcarrier mapping in the system of Figure 1;

[0017] Figure 5 is a block diagram of an OFDM-CDMA system in accordance with another embodiment of the present invention;

[0018] Figure 6 is a block diagram of an OFDM-CDMA system in accordance with yet another embodiment of the present invention;

[0019] Figure 7 shows an alternative way for the frequency-domain spreading and subcarrier mapping in a system of Figure 6; and

[0020] Figure 8 is a block diagram of an exemplary time-frequency Rake combiner in accordance with the present invention.

[0021] DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

[0022] The present invention is applicable to wireless communication systems implementing OFDM and CDMA such as IEEE 802.11, IEEE 802.16, Third Generation (3G) cellular systems for long term evolution, Fourth Generation (4G) systems, satellite systems, DAB, digital video broadcasting (DVB), or the like.

[0023] The features of the present invention may be incorporated into an integrated circuit (IC) or be configured in a circuit comprising a multitude of interconnecting components.

[0024] The present invention provides an OFDM-CDMA system with an

improved PAPR and capacity. The present invention uses a special spreading code, a SCQS code, in spreading input data symbols. The SCQS code comprises two components; a quadratic phase sequence code and an orthogonal (or pseudo-orthogonal) spreading code. Examples of the quadratic phase sequence code, denoted by G , are the Newman phase code (or polyphase code), a generalized chirp-like sequence (GCL) and a Zadoff-Chu sequence. Quadratic phase sequences are called polyphase sequences as well.

[0025] To support a variable spreading factor (VSF), the sequence length of the quadratic phase sequence (or polyphase sequence) is limited as $K = 2^k$. In some special cases, (such as random access channel or uplink pilots), the sequence length of quadratic phase sequence (or polyphase sequence) can be any arbitrary integer number. Given the number of subcarriers $N = 2^n$ in the system, consider a sequence length of N as an example. Then, the generic Newman phase code or polyphase code sequence is fixed. The generic Newman phase code sequence is:

$$G_k = e^{-jk^2 \frac{\pi}{N}}, k=0, 1, \dots, N-1. \quad \text{Equation (1)}$$

[0026] More orthogonal Newman phase code sequences are created by shifting the generic Newman phase code sequence in phase. The l -th shifted version, (or DFT modulated), of the generic Newman polyphase code sequence is:

$$G_k^{(l)} = e^{-jk^2 \frac{\pi}{N}} \cdot e^{jkl \frac{2\pi}{N}}, k=0, 1, \dots, N-1, l=0, 1, \dots, N-1. \quad \text{Equation (2)}$$

Two Newman phase code sequences with different shifts are orthogonal to each other.

[0027] One example of the orthogonal (or pseudo-orthogonal) spreading code, denoted by H , is Walsh-Hadamard code, which is given by:

$$H_2 = \begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix}; \quad \text{Equation (3)}$$

$$H_{2^m} = \begin{bmatrix} H_{2^{m-1}} & H_{2^{m-1}} \\ H_{2^{m-1}} & -H_{2^{m-1}} \end{bmatrix}, \text{ for } m>1. \quad \text{Equation (4)}$$

[0028] The SCQS code is constructed by combining the quadratic phase

code and the orthogonal (or pseudo-orthogonal) spreading code. For a specific spreading factor 2^m , the SCQS code has 2^m chips. The generic quadratic phase sequence code part of the SCQS code has 2^m chips, which is:

$$\{G_i, G_{2^{n-m}+i}, \dots, G_{2^{n-m} \cdot k+i}, \dots, G_{2^{m-1}+i}\}; \quad \text{Equation (5)}$$

where $k=0, 1, \dots, 2^m - 1, i = 0, 1, \dots, 2^{n-m} - 1$.

[0029] The l -th shifted version of the quadratic phase sequence code part has 2^m chips, which is:

$$\{G_i^{(l)}, G_{2^{n-m}+i}^{(l)}, \dots, G_{2^{n-m} \cdot k+i}^{(l)}, \dots, G_{2^{m-1}+i}^{(l)}\}; \quad \text{Equation (6)}$$

where $l=0, 1, \dots, N-1, k=0, 1, \dots, 2^m - 1, i = 0, 1, \dots, 2^{n-m} - 1$.

[0030] For a specific SCQS code with spreading factor 2^m , the orthogonal (or pseudo-orthogonal) spreading code part of the SCQS code is given by one of the codes in the orthogonal (or pseudo-orthogonal) spreading code set of spreading factor 2^m . For example, the h -th code is denoted by $H_{2^m}(h, :)$.

[0031] The k -th chip of the SCQS code c_i is constructed as a product of the k -th quadratic phase sequence code of the l -th shifted version of the generic quadratic phase sequence code and the k -th chip of the h -th orthogonal (or pseudo-orthogonal) spreading code with the size of $N = 2^m$.

$$c_i^k = G_k^{(l)} \cdot H_{2^m}(h, k), k=0, 1, \dots, 2^m - 1. \quad \text{Equation (7)}$$

[0032] The code set size of the SCQS code is determined by the code set dimensions of the orthogonal (or pseudo-orthogonal) spreading code part and the quadratic phase sequence code part. The code set dimension of the quadratic phase sequence code is fixed regardless of the spreading factor and is determined by the number of different shifts, which is the number of subcarriers in the system, 2^n . The code set dimension of the orthogonal (or pseudo-orthogonal) spreading code depends on the spreading factor. For example, in the case of a Walsh-Hadamard code, the dimension equals to the spreading factor $2^m (0 \leq m \leq n)$.

[0033] Different users are assigned different SCQS codes. In order for a receiver to distinguish between different users, the SCQS codes used by two users may be different in the quadratic phase sequence code part, the orthogonal (or pseudo-orthogonal) spreading code part, or both. The code set of the SCQS code is shown in Figure 2.

[0034] Without multipath, different SCQS codes are orthogonal as long as their quadratic phase sequence code parts are different; or an orthogonal spreading code is used. Different SCQS codes are pseudo-orthogonal only when their quadratic phase sequence code parts are the same and a pseudo-orthogonal spreading code is used. In both cases, the multiple access interference (MAI) between different codes is either zero or very small.

[0035] Under the multipath fading environment, codes assigned to different users should be such that the difference in the shift of quadratic phase sequence code part should be as large as possible. Codes assigned to different users should be such that if the difference in the shift of the quadratic phase sequence code part of two codes is not less than the maximum delay spread of the multipath channel, there is no MAI between the two codes. Therefore, the corresponding orthogonal (or pseudo-orthogonal) spreading code part can be assigned to be the same. Optionally, the difference in the shift of the quadratic phase sequence code part may be limited to be at most the maximum delay spread of the multipath channel. This will create more codes with perfect MAI immunity. This is achievable as long as the number of users in the system is no more than N/L , where N is the number of subcarriers and L is the multipath channel maximum delay spread.

[0036] If the difference in the shift of the quadratic phase sequence code part of two codes is less than the maximum delay spread of the multipath channel, the corresponding orthogonal (or pseudo-orthogonal) spreading code part should be different in order to reduce the MAI that cannot be cancelled by the difference in the shift of the quadratic phase sequence code part.

[0037] In this way, the MAI can be reduced as compared to the conventional CDMA system since the correlation between orthogonal codes is

further reduced by the correlation of two quadratic phase sequence codes. For an interference-limited system (such as CDMA), reduced MAI implies increased system capacity.

[0038] An OFDM-CDMA system of the present invention comprises a transmitter and a receiver. The transmitter comprises a spreading and subcarrier mapping portion and an OFDM portion. The spreading and subcarrier mapping portion performs spreading of input data symbols into a plurality of chips and mapping of the chips to one of a plurality of subcarriers. The OFDM portion performs conventional OFDM operation. The spreading may be performed in the frequency-domain, in the time-domain or both, which will be explained in detail hereinafter.

[0039] Figure 1 is a block diagram of an OFDM-CDMA system 100 in accordance with a first embodiment of the present invention. The system 100 comprises a transmitter 110 and a receiver 150. The transmitter 110 comprises a spreader 112, a serial-to-parallel (S/P) converter 114, a subcarrier mapping unit 116, an IDFT unit 118, a cyclic prefix (CP) insertion unit 120, a parallel-to-serial (P/S) converter 122 and an optional mixer 124. The spreader 112 spreads input data symbols 101 in frequency-domain using the SCQS code 111. The procedure of spreading and subcarrier mapping is shown in Figure 3. The spreading factor used by the SCQS code c_i is $2^m (0 \leq m \leq n)$. One user can use all of 2^n subcarriers in the system. Therefore, the number of data symbols that can be transmitted by one user in one OFDM frame is 2^{n-m} . Each data symbol $d(i)$ 101 is spread by the spreading code c_i 111 into 2^m chips 113. The 2^m chips 113 are then converted into 2^m parallel chips 115 by the S/P converter 114 and each chip is mapped to one of the subcarriers 117 by the subcarrier mapping unit 116 in an equal-distance. The distance between each subcarrier used by chips of the same data symbol is 2^{n-m} subcarriers. Chips of different data symbols are mapped to subcarriers in the system sequentially such that the chips of data symbol $d(i)$ are mapped to subcarriers $2^{n-m} \cdot k + i$,

($k = 0, 1, \dots, 2^m - 1, i = 0, 1, \dots, 2^{n-m} - 1$).

[0040] Figure 4 shows an alternative embodiment for spreading and subcarrier mapping. Instead of the spreader 112, a repeater 402 is used to repeat each data symbol $d(i)$ 2^m times at the chip rate. The repeated data symbols 404 are converted into 2^m parallel symbols 407 by the S/P converter 406 and each symbol is mapped to one of the 2^m subcarriers of equal distance by the subcarrier mapping and weighting unit 408 sequentially. The distance between each subcarrier is 2^{n-m} subcarriers. Chips of different data symbols are mapped to subcarriers in the system sequentially such that the chips of data symbol $d(i)$ are mapped to subcarriers $2^{n-m} \cdot k + i$, ($k = 0, 1, \dots, 2^m - 1, i = 0, 1, \dots, 2^{n-m} - 1$). A symbol mapped on each subcarrier $2^{n-m} \cdot k + i$ is weighted by an SCQS code such that a symbol on subcarrier $2^{n-m} \cdot k + i$ is multiplied with the k -th chip of the SCQS code, denoted by c_i^k .

[0041] Referring back to Figure 1, chips 117 mapped on subcarriers are fed into the IDFT unit 118 to be converted into time-domain data 119. A cyclic prefix (CP) is then added by the CP insertion unit 120 to the end of each OFDM frame. The time-domain data with CP 121 is then converted by the P/S converter 122 into a serial data 123 and transmitted over the wireless channel. It should be noted that the IDFT operation may be replaced by IFFT or other similar operations and the CP insertion may be performed after the IDFT output is converted into a serial data stream by the P/S converter 122 and the CP removal may be performed before the received signals are converted to a parallel data stream by the S/P converter 154.

[0042] Due to the structure of spread data, the IDFT operation can be simplified. The output 119 of the IDFT unit 118 comprises data symbols shifted by a particular phase. The phase is a function of corresponding input data subcarrier and data symbol indexes. Therefore, the IDFT operation can be replaced by the computation of the phase shift, which requires less computation.

[0043] For example, assume $n/2 < m \leq n$ and the orthogonal (or pseudo-

orthogonal) spreading code part of the SCQS code are $\{1, 1, \dots, 1\}$. Then, the h -th output of the IDFT unit 118 is given as follows:

$$IDFT(h) = d(i) \cdot e^{j \frac{(p \cdot 2^{n-m} + i)^2 - 2^{n-2}}{2^n} \pi}; \quad \text{Equation (8)}$$

where the value of h satisfies the following condition:

$$h = 2^{n-m} \cdot p + i, \quad p = 0, 1, \dots, 2^m - 1, \quad i = 0, 1, \dots, 2^{n-m} - 1.$$

[0044] It is optional to perform the masking operation at the transmitter 110 and the corresponding demasking operation at the receiver 150. The purpose of masking is to reduce the inter-cell MAI. At the transmitter 110, the mixer 124 multiplies the data 123 with a masking code 125 before transmission. The corresponding demasking operation is performed at the receiver 150. A mixer 152 multiplies the received signals 128 with the conjugate 151 of the masking code 125 to generate a demasked data stream 153.

[0045] Referring to Figure 1, the receiver 150 comprises an optional mixer 152, an S/P converter 154, a CP removing unit 156, a DFT unit 158, an equalizer 160 and a despreader (including multipliers 162, a summer 164 and a normalizer 166). The time-domain received data 128 are converted into parallel data stream 155 by the S/P converter 154 and the CP is removed by the CP removing unit 156. The performance of these operations may be switched as explained hereinabove. The output 157 from the CP removing unit 156 is then fed into the DFT unit 158 to be converted into frequency-domain data 159. Equalization on the frequency-domain data 159 is performed by the equalizer 160. As in a conventional OFDM system, a simple one-tap equalizer may be used for the frequency-domain data 159 at each subcarrier. It should be noted that the DFT operation may be replaced by an FFT operation or other similar operation.

[0046] Due to the structure of spread data, the DFT operation can also be simplified. The outputs 159 of the DFT unit are data symbols shifted by a particular phase. The phase is a function of corresponding input data subcarrier and data symbol indexes. Therefore, the DFT operation can be replaced by the computation of the phase shift, which requires less computation. The way it is done is similar, but opposite, to the IDFT operation at the transmitter side.

[0047] The equalized data is despread at the frequency-domain. The output 161 at each subcarrier after equalization is multiplied by the multipliers 162 with the conjugate 168 of the corresponding chip of the SCQS code, c_i^k , $k = 0, 1, \dots, 2^m - 1$, used at the transmitter 110. Then, the multiplication outputs 163 at all subcarriers are summed up by the summer 164 and the summed output 165 is normalized by the normalizer 166 by the spreading factor of the SCQS code to recover the data 167.

[0048] The receiver 150 may further include a block linear equalizer or a joint detector (not shown) for processing the output of the despreader. Any type of block linear equalizer or joint detector may be used. One conventional configuration for a block linear equalizer or a joint detector is the minimum mean square error (MMSE) block linear equalizer. In this case, a channel matrix H is established and computed for subcarriers, and equalization is performed using the established channel matrix such that:

$$\vec{d} = (H^H H + \sigma^2 I)^{-1} H^H \vec{r}; \quad \text{Equation (9)}$$

where H is the channel matrix, \vec{r} is the received signal in subcarriers and \vec{d} is the equalized data vector in subcarriers.

[0049] For uplink operation, it is preferred to keep a constant envelope after IDFT operation, which allows use of an efficient and inexpensive power amplifier. In order to keep a constant envelope, the following conditions for a system with $N=2^n$ subcarriers have to be met. First, the spreading factor 2^m is limited by $\lfloor n/2 \rfloor \leq m \leq n$, wherein the term $\lfloor a \rfloor$ means the smallest integer larger than a . Second, for spreading factor 2^m , only a fraction of orthogonal codes are used to combine with the quadratic phase sequence codes to generate the SCQS codes that yield constant envelope. For example, in the case of Newman phase code and Hadamard code, only the first $2^{\lceil m/2 \rceil}$ codes of the Hadamard code sets (of size 2^m) are used to combine with the Newman phase sequence code to generate the SCQS codes. The term $\lceil b \rceil$ means the largest integer smaller than b .

[0050] As stated above, as long as the number of users in the system is no more than N/L , there is no MAI and there is no need to implement multi-user detection (MUD). When the number of users in the system is more than N/L , then there will be MAI and MUD may be implemented. The MAI will be more benign than conventional CDMA system with the same number of users.

[0051] Suppose that there are M users in the system. The number of users for MUD in the conventional CDMA system will be M . However, the number of users for MUD in the OFDM-CDMA system in accordance with the present invention will be $\lceil M/L \rceil$, which is reduced by a scale of L as compared to a conventional CDMA system. In this way, the complexity of MUD operation is much lower than the MUD in a prior art CDMA system. It is also possible to use multiple antennas at the transmitter and/or receiver.

[0052] Figure 5 is a block diagram of an OFDM-CDMA system 500, (multi-carrier direct sequence (MC-DS) CDMA system), in accordance with a second embodiment of the present invention. The system 500 comprises a transmitter 510 and a receiver 550. The transmitter 510 comprises an S/P converter 512, a plurality of multipliers 514, a sub-carrier mapping unit 516, an IDFT unit 518, a P/S converter 520, a CP insertion unit 522 and an optional mixer 524. If there are $N=2^n$ subcarriers in the system 500, the N consecutive data symbols 501 of the user i are converted from serial to N parallel symbols 513 by the S/P converter 512. The j -th data symbol of the N parallel data symbols 513 of the user i is denoted by $d^j(i)$, where $j = 0, 1, \dots, N-1$. The SCQS code used by the user i is denoted by c_i . Each of the N parallel data symbols 513 is spread in time-domain using the SCQS code c_i 511. The spreading factor of the SCQS code c_i is 2^m ($0 \leq m \leq n$), therefore each data symbol 513 is spread by the SCQS code c_i 511 into 2^m chips 515.

[0053] At each chip duration, one chip of each of the N data symbols $d^j(i)$ is transmitted on its corresponding subcarrier j . One user can use all of 2^n subcarriers in the system. Therefore, the number of data symbols that can be

transmitted by one user in one OFDM frame is 2^n .

[0054] The chips 515 are mapped to subcarriers by the subcarrier mapping unit 516. Chips 517 on subcarriers are fed into the IDFT unit 518, and converted into time-domain data 519. The time-domain data 519 are converted from parallel into serial data 521 by the P/S converter 520, and a CP is added to the end of each frame by the CP insertion unit 522. The data with CP 523 is transmitted over the wireless channel. It is equivalent to perform the conventional DS-CDMA operation on each subcarrier independently using the SCQS code, and DS-CDMA signals on subcarriers are transmitted in parallel using OFDM structure.

[0055] The receiver 550 comprises a CP removal unit 554, an S/P converter 556, a DFT unit 558, an equalizer 560, a plurality of rake combiners 562, and a P/S converter 564. First, the CP is removed by the CP removing unit 554 from the received data 528 via the wireless channel. The data 555 is then converted from serial to parallel data 557 by the S/P converter 556. The parallel data 557 is fed into the DFT unit 558, and converted to frequency-domain data 559. Then, equalization is applied to the frequency-domain data 559 by the equalizer 560. As in a conventional OFDM system, a simple one-tap equalizer may be used at each subcarrier.

[0056] Data 561 on each subcarrier after equalization is recovered by Rake combiners 562, (which include despanders), in the time-domain. Then, parallel data symbols 563 yielded by each Rake combiners 562 are parallel-to-serial converted by the P/S converter 564 to recover the transmitted data.

[0057] As in the first embodiment of Figure 1, it is optional to perform a masking operation at the transmitter 510 and the corresponding demasking operation at the receiver 550 to reduce the intercell MAI. The mixer 524 multiplies output 523 from the CP insertion unit 522 with a masking code 525 before transmission. The mixer 552 of the receiver 550 multiplies the received signals 528 with the conjugate 551 of the masking code used at the transmitter 510.

[0058] Figure 6 is a block diagram of an OFDM-CDMA system 600 in

accordance with a third embodiment of the present invention. The system 600 comprises a transmitter 610 and a receiver 650. The transmitter 610 includes an S/P converter 612, a plurality of multipliers 614, a plurality of repeaters 616, a plurality of S/P converters 618, a subcarrier mapping and weighting unit 620, an IDFT unit 622, a P/S converter 624, a CP insertion unit 626 and an optional mixer 628. In accordance with the third embodiment, the input data symbol is spread twice, once at the time-domain and the other at the frequency-domain. Assume the total number of subcarriers is 2^n and the spreading factors used in the time-domain and frequency-domain spreading are 2^p and 2^m , respectively. The N_T consecutive data symbols 601 of the user i are converted from serial to parallel N_T symbols 613 by the S/P converter 612. The value of N_T equals to 2^{n-m} . The j -th data symbol of the N_T parallel data symbols 613 of the user i is denoted by $d^j(i)$, where $j = 0, 1, \dots, N_T-1$. The time-domain spreading code 611 used by the user i is denoted by $H_{2^p}(i, :)$. Each of the N_T parallel data symbols 613 is then spread in the time-domain by the multipliers 614 by multiplying the symbols 613 with the time-domain spreading code $H_{2^p}(i, :)$ 611. The spreading factor of the time domain spreading code $H_{2^p}(i, :)$ is 2^p as defined in Equations (3) and (4). Each data symbol 613 is spread into 2^p chips and N_T parallel 2^p chip streams 615 are generated.

[0059] After the time-domain spreading, a frequency-domain spreading is performed. Given the user i , for each chip stream j , (corresponding to the j -th data symbols of the N_T data symbols), at each chip duration, each chip of the N_T chip streams is repeated 2^m times by the repeater 616 and the 2^m repeated chips are converted into parallel 2^m chips 619 by the S/P converter 618. The 2^m chips are then mapped to 2^m equal-distant subcarriers sequentially by the subcarrier mapping and weighting unit 620. The distance between each subcarrier is 2^{n-m} subcarriers. Subcarrier mapping is performed sequentially such that the repeated chips from the j -th chip stream are mapped to subcarriers $2^{n-m} \cdot k + j$,

($k = 0, 1, \dots, 2^m - 1, j = 0, 1, \dots, 2^{n-m} - 1$). Before the IDFT operation, a chip on each subcarrier $2^{n-m} \cdot k + j$ is weighted by the k -th chip of the SCQS code c_i , denoted by c_i^k .

[0060] One user can use all of 2^n subcarriers in the system. Therefore, the number of data symbols that can be transmitted by one user in one OFDM frame is 2^{n-m} .

[0061] Figure 7 shows an alternative way for the frequency-domain spreading and subcarrier mapping in a system of Figure 6. Instead of repeating the chips 2^m times, the chips 615 are directly spread by the frequency-domain spreading code c_i^k . Given the user i , for each chip stream j , (corresponding to the j -th data symbols of the N_T data symbols), at each chip duration, each of the chips 615 is spread by the SCQS code c_i^k 703 into 2^m chips 704 by the multipliers 702 and the frequency-domain spread chips 704 are converted into 2^m parallel chips 707 by the S/P converter 706. These parallel chips 707 are then mapped to 2^m equal-distant subcarriers 709 by the subcarrier mapping unit 708 sequentially, as explained hereinabove. The distance between each subcarrier is 2^{n-m} subcarriers. Subcarrier mapping is performed sequentially such that the repeated chips from the j -th chip stream are mapped to subcarriers $2^{n-m} \cdot k + j$, ($k = 0, 1, \dots, 2^m - 1, j = 0, 1, \dots, 2^{n-m} - 1$).

[0062] Referring again to Figure 6, chips 621 mapped on subcarriers are fed into the IDFT unit 622, and converted into time-domain data 623. The time-domain data 623 is converted from parallel data into serial data 625 by the P/S converter 624, and a CP is added to the end of each frame of the data 625 by the CP insertion unit 626. The data with the CP 627 is transmitted over the wireless channel.

[0063] The receiver 650 includes an optional mixer 652, a CP removal unit 654, an S/P converter 656, a DFT unit 658, an equalizer 660, a plurality of time-frequency Rake combiners 662 and a P/S converter 664. At the receiver 650 side,

the CP is removed by the CP removal unit 654 from the received data 632 via the wireless channel. The data 655 is then converted from serial to parallel data 657 by the S/P converter 656. The parallel data 657 is fed into the DFT unit 658, and converted to frequency-domain data 659. Then, equalization is applied to the frequency-domain data 659 by the equalizer 660. As in a conventional OFDM system, a simple one-tap equalizer may be used at each subcarrier.

[0064] After equalization, data 661 on each subcarrier is recovered by time-frequency Rake combiners 662, which will be explained in detail hereinafter. Parallel data symbols 663 yielded by each of the time-frequency Rake combiners 662 are then parallel-to-serial converted by the P/S converter 664 to recover the transmitted data.

[0065] A time-frequency Rake combiner 662 is a Rake combiner that performs processing at both the time and frequency domains in order to recover the data that is spread in both the time and frequency domains at the transmitter. Figure 8 shows exemplary time-frequency Rake combiners 662. It should be noted that the time-frequency Rake combiners 662 may be implemented in many different ways and the configuration shown in Figure 8 is provided as an example, not as a limitation, to those of ordinary skill in the art.

[0066] Each time-frequency Rake combiner 662 comprises a subcarrier grouping unit 802, a despreader 804 and a Rake combiner 806. For each data symbol j ($j = 0, 1, \dots, 2^{n-m} - 1$) of N_T consecutive data symbols, the subcarrier grouping unit 802 collects the following chips on subcarriers 661 $2^{n-m} \cdot k + j$, ($k = 0, 1, \dots, 2^m - 1$), totaling 2^m chips. Then, the despreader 804 performs frequency-domain despreading to the chips on the 2^m subcarriers. The despreader 804 includes a plurality of multipliers 812 for multiplying conjugate 813 of the SCQS codes to the collected chips 811, a summer 815 for summing the multiplication outputs 814, and a normalizer 817 for normalizing the summed output 816. After the frequency-domain despreading, chips on 2^n subcarriers become chips on N_T parallel chip streams 818. To recover the j -th data symbol of the user i , time-domain Rake combining is performed by the Rake combiner 806

on the corresponding chip stream 818.

[0067] Referring again to Figure 6, it is optional to perform a masking operation at the transmitter 610 and the corresponding demasking operation at the receiver 650 to reduce the intercell MAI. The mixer 628 multiplies output 627 from the CP insertion unit 626 with a masking code 630 before transmission. The mixer 652 of the receiver 650 multiplies the received signals 632 with the conjugate 651 of the masking code used at the transmitter 610.

[0068] For all the embodiments described hereinbefore, a predetermined data vector $\{d(i)\}$, (i.e., pre-known signals), may be transmitted. In this way, the uplink transmitted signals can be used as a preamble for Random Access Channel (RACH) or uplink pilot signals. For example, a predetermined data vector $\{d(i)\}$ of all 1s, $\{1, 1, \dots, 1\}$, may be transmitted.

[0069] Although the features and elements of the present invention are described in the preferred embodiments in particular combinations, each feature or element can be used alone without the other features and elements of the preferred embodiments or in various combinations with or without other features and elements of the present invention.

* * *

CLAIMS

What is claimed is:

1. An orthogonal frequency division multiplexing (OFDM) - code division multiple access (CDMA) system comprising:

a transmitter comprising:

a spreading and subcarrier mapping unit for spreading an input data symbol with a spread complex quadratic sequence (SCQS) code to generate a plurality of chips and mapping each chip to one of a plurality of subcarriers;

an inverse discrete Fourier transform (IDFT) unit for performing IDFT on the chips mapped to the subcarriers to generate time-domain data;

a parallel-to-serial (P/S) converter for converting the time-domain data into a serial data stream for transmission; and

a cyclic prefix (CP) insertion unit for inserting a CP into the data; and

a receiver for receiving a wireless signal from the transmitter, the receiver comprising:

a CP remover for removing the CP from data in the wireless signal;

a serial-to-parallel (S/P) converter for converting received data into multiple received data streams;

a discrete Fourier transform (DFT) unit for performing DFT on the received data streams;

an equalizer for performing equalization on an output of the DFT unit;

and

a despreader for despreading an output of the equalizer.

2. The system of claim 1 wherein the spreading and subcarrier mapping unit comprises:

a multiplier for multiplying the input data symbol with the SCQS code to spread the input data symbol to generate the plurality of chips;

an S/P converter for converting the chips into multiple parallel chips; and

a subcarrier mapping unit for mapping each chip to one of the subcarriers.

3. The system of claim 1 wherein the spreading and subcarrier mapping unit comprises:

a repeater for repeating the input data symbol multiple times at a chip rate;
an S/P converter for converting the repeated input data symbols into multiple parallel symbols; and

a subcarrier mapping and weighting unit for mapping each of the repeated input symbols to one of the plurality of subcarriers and multiplying each of the repeated input symbols with a corresponding chip of the SCQS code.

4. The system of claim 1 wherein the spreading and subcarrier mapping unit comprises:

an S/P converter for converting N input data symbols into N parallel symbols;
 N multipliers for multiplying each of N input data symbols with the SCQS code to spread the input data symbols; and

a subcarrier mapping unit for mapping one chip of each symbol to one of N subcarriers at each chip duration.

5. The system of claim 1 wherein the spreading and subcarrier mapping unit comprises:

a first S/P converter for converting N_T input data symbols into N_T parallel input data symbols;

N_T multipliers for multiplying each of the N_T input data symbols with a time-domain spreading code, each input data symbol being spread into SF_T chips in time-domain, SF_T being a time-domain spreading factor;

N_T repeaters for repeating each of the SF_T chips SF_F times, SF_F being a frequency-domain spreading factor;

N_T second S/P converters, each second S/P converter for converting the SF_F repeated chips into SF_F parallel chips; and

a subcarrier mapping and weighting unit for mapping each chip to one of the plurality of subcarriers and multiplying each chip with a corresponding chip of the SCQS code.

6. The system of claim 1 wherein the spreading and subcarrier mapping unit comprises:

a first S/P converter for converting serial N_T input data symbols into N_T parallel input data symbols;

N_T first multipliers for multiplying each of the N_T input data symbols with a time-domain spreading code, each input data symbol being spread into SF_T chips in time-domain, SF_T being a time-domain spreading factor;

N_T second multipliers for multiplying each of the SF_T chips obtained in time-domain with the SCQS code to spread the chips, each chips being spread into SF_F chips in frequency-domain, SF_F being a frequency-domain spreading factor;

N_T second S/P converters, each second S/P converter for converting the SF_F chips obtained from each of the SF_T chips into SF_F parallel chips; and

a subcarrier mapping unit for mapping each chip to one of the subcarriers.

7. The system of claim 1 wherein the SCQS code is constructed by combining a generic quadratic phase sequence code and an orthogonal spreading code.

8. The system of claim 7 wherein the SCQS code is constructed by chip-by-chip multiplication of a shifted version of quadratic phase sequence code having 2^m chips with one of orthogonal spreading codes with spreading factor of 2^m .

9. The system of claim 8 wherein the quadratic phase sequence code is one of a Newman phase code sequence, a generalized chirp-like sequence (GCL) and a Zadoff-Chu sequence and the orthogonal spreading code is a Walsh-Hadamard code.

10. The system of claim 8 wherein the chip streams are mapped to subcarriers separated by 2^{n-m} subcarriers among a total of 2^n subcarriers.

11. The system of claim 8 wherein different users are assigned different SCQS codes that are different in at least one of the quadratic phase sequence code and the orthogonal spreading code.

12. The system of claim 8 wherein different users are assigned different SCQS codes with a shift as large as possible in the quadratic phase sequence code.

13. The system of claim 8 wherein the shift of the quadratic phase sequence code is limited to a maximum delay spread of a channel.

14. The system of claim 9 wherein the spreading factor 2^m is limited by $\lfloor n/2 \rfloor \leq m \leq n$ and only first $2^{\lceil m/2 \rceil}$ codes of the Walsh-Hadamard codes are used to combine with the Newman phase sequence code to generate the SCQS codes, wherein $\lfloor a \rfloor$ means a smallest integer larger than a and $\lceil b \rceil$ means a largest integer smaller than b .

15. The system of claim 1 wherein the IDFT and the DFT operation is performed by computing a phase shift using a corresponding input data subcarrier index and data symbol index.

16. The system of claim 1 wherein the transmitter further comprising a mixer for multiplying a masking code to the serial data stream for transmission and the

receiver further comprising a mixer for multiplying a conjugate of the masking code to the received data.

17. The system of claim 1 wherein the orthogonal spreading code is a pseudo-orthogonal spreading code.

18. The system of claim 1 wherein the IDFT and DFT are performed by an inverse fast Fourier transform (IFFT) and a fast Fourier transform (FFT), respectively.

19. The system of claim 1 wherein multi-user detection (MUD) is further performed on an output of the despreader.

20. The system of claim 1 further comprising a block linear equalizer for performing block linear equalization (BLE) on an output of the despreader.

21. The system of claim 1 further comprising a joint detector for performing a joint detection on an output of the despreader.

22. The system of claim 1 wherein at least one of the transmitter and the receiver comprises multiple antennas.

23. The system of claim 1 wherein the input data symbols are predetermined and known to the receiver.

24. The system of claim 23 wherein the transmitted signals generated from a predetermined data vector are used as one of a preamble for random access channel (RACH) and pilot signals.

25. A method for transmitting and receiving data using an orthogonal frequency division multiplexing (OFDM)-code division multiple access (CDMA) system, the method comprising:

at a transmitter,

spreading an input data symbol with a spread complex quadratic sequence (SCQS) code to generate a plurality of chips;

mapping each chip to one of a plurality of subcarriers;

performing an inverse discrete Fourier transform (IDFT) on the chips mapped to the subcarriers to generate a time-domain data;

converting the time-domain data into a serial data stream for transmission; and

inserting a cyclic prefix (CP) to the data; and

at a receiver,

receiving data transmitted by the transmitter;

removing the CP from the received data;

converting the received data into multiple data streams;

performing a discrete Fourier transform (DFT) on the multiple data streams;

performing equalization on a DFT output; and

despreading the equalized DFT output by multiplying a complex conjugate of the SCQS code used at transmission with the equalization output and by summing multiplication results.

26. The method of claim 25 wherein the spreading and subcarrier mapping is performed by the steps of:

multiplying the input data symbol with the SCQS code to spread the input data symbol to generate the plurality of chips;

converting the chips into multiple parallel chips; and

mapping each chip to one of the subcarriers.

27. The method of claim 25 wherein the spreading and subcarrier mapping is performed by the steps of:

repeating the input data symbol multiple times at a chip rate;
converting the repeated input data symbols into multiple parallel symbols;
mapping each of the repeated input symbols to one of the plurality of subcarriers; and
multiplying each of the repeated input symbols with a corresponding chip of the SCQS code.

28. The method of claim 25 wherein the spreading and subcarrier mapping is performed by the steps of:

converting N input data symbols into N parallel symbols;
multiplying each of N input data symbols with the SCQS code to spread the input data symbols; and
mapping one chip of each symbol to one of N subcarriers at each chip duration.

29. The method of claim 25 wherein the spreading and subcarrier mapping is performed by the steps of:

converting N_T input data symbols into N_T parallel input data symbols;
multiplying each of the N_T input data symbols with a time-domain spreading code, each input data symbol being spread into SF_T chips in time-domain, SF_T being a time-domain spreading factor;
repeating each of the SF_T chips SF_F times, SF_F being a frequency-domain spreading factor;
converting the SF_F repeated chips into SF_F parallel chips;
mapping each chip to one of the plurality of subcarriers; and
multiplying each chip with a corresponding chip of the SCQS code.

30. The method of claim 25 wherein the spreading and subcarrier mapping is performed by the steps of:

converting serial N_T input data symbols into N_T parallel input data symbols;
multiplying each of the N_T input data symbols with a time-domain spreading code, each input data symbol being spread into SF_T chips in time-domain, SF_T being a time-domain spreading factor;

multiplying each of the SF_T chips obtained in time-domain with the SCQS code to spread the chips, each chips being spread into SF_F chips in frequency-domain, SF_F being a frequency-domain spreading factor;

converting the SF_F chips obtained from each of the SF_T chips into SF_F parallel chips; and

mapping each chip to one of the subcarriers.

31. The method of claim 25 wherein the SCQS code is constructed by combining a generic quadratic phase sequence code and an orthogonal spreading code.

32. The method of claim 31 wherein the SCQS code is constructed by chip-by-chip multiplication of a shifted version of quadratic phase sequence code having 2^m chips with one of orthogonal spreading codes with spreading factor of 2^m .

33. The method of claim 32 wherein the quadratic phase sequence code is one of a Newman phase code sequence, a generalized chirp-like sequence (GCL) and a Zadoff-Chu sequence and the orthogonal spreading code is a Walsh-Hadamard code.

34. The method of claim 32 wherein the chip streams are mapped to subcarriers separated by 2^{n-m} subcarriers among a total of 2^n subcarriers.

35. The method of claim 32 wherein different users are assigned different SCQS codes that are different in at least one of the quadratic phase sequence code and the orthogonal spreading code.

36. The method of claim 32 wherein different users are assigned different SCQS codes with a shift as large as possible in the quadratic phase sequence code.

37. The method of claim 32 wherein the shift of the quadratic phase sequence code is limited to a maximum delay spread of a channel.

38. The method of claim 33 wherein the spreading factor 2^m is limited by $\lfloor n/2 \rfloor \leq m \leq n$ and only first $2^{\lceil m/2 \rceil}$ codes of the Walsh-Hadamard codes are used to combine with the Newman phase sequence code to generate the SCQS codes, wherein $\lfloor a \rfloor$ means a smallest integer larger than a and $\lceil b \rceil$ means a largest integer smaller than b .

39. The method of claim 25 wherein the IDFT and the DFT operation is performed by computing a phase shift using a corresponding input data subcarrier index and data symbol index.

40. The method of claim 25 wherein the transmitter further performs multiplying a masking code to the serial data stream for transmission and the receiver further performs multiplying a conjugate of the masking code to the received data.

41. The method of claim 25 wherein the orthogonal spreading code is a pseudo-orthogonal spreading code.

42. The method of claim 25 wherein the IDFT and DFT are performed by an inverse fast Fourier transform (IFFT) and a fast Fourier transform (FFT), respectively.

43. The method of claim 25 wherein multi-user detection (MUD) is further performed on despreading output.

44. The method of claim 25 wherein at the receiver block linear equalization (BLE) is further performed on the despreading output.

45. The method of claim 25 wherein at the receiver a joint detection is further performed on the despreading output.

46. The method of claim 25 wherein at least one of the transmitter and the receiver comprises multiple antennas.

47. The method of claim 25 wherein the input data symbols are predetermined and known to the receiver.

48. The method of claim 47 wherein the transmitted signals generated from a predetermined data vector are used as one of a preamble for random access channel (RACH) and pilot signals.

49. In an orthogonal frequency division multiplexing (OFDM)-code division multiple access (CDMA) wireless communication system, a transmitter comprising:

- a spreading and subcarrier mapping unit for spreading an input data symbol with a spread complex quadratic sequence (SCQS) code to generate a plurality of chips and mapping each chip to one of a plurality of subcarriers;
- an inverse discrete Fourier transform (IDFT) unit for performing IDFT on the chips mapped to the subcarriers to generate time-domain data;
- a parallel-to-serial (P/S) converter for converting the time-domain data into a serial data stream for transmission; and

a cyclic prefix (CP) insertion unit for inserting a CP into the data; and

50. The transmitter of claim 49 wherein the spreading and subcarrier mapping unit comprises:

a multiplier for multiplying the input data symbol with the SCQS code to spread the input data symbol to generate the plurality of chips;

an S/P converter for converting the chips into multiple parallel chips; and

a subcarrier mapping unit for mapping each chip to one of the subcarriers.

51. The transmitter of claim 49 wherein the spreading and subcarrier mapping unit comprises:

a repeater for repeating the input data symbol multiple times at a chip rate;

an S/P converter for converting the repeated input data symbols into multiple parallel symbols; and

a subcarrier mapping and weighting unit for mapping each of the repeated input symbols to one of the plurality of subcarriers and multiplying each of the repeated input symbols with a corresponding chip of the SCQS code.

52. The transmitter of claim 49 wherein the spreading and subcarrier mapping unit comprises:

an S/P converter for converting N input data symbols into N parallel symbols;

N multipliers for multiplying each of N input data symbols with the SCQS code to spread the input data symbols; and

a subcarrier mapping unit for mapping one chip of each symbol to one of N subcarriers at each chip duration.

53. The transmitter of claim 49 wherein the spreading and subcarrier mapping unit comprises:

a first S/P converter for converting N_T input data symbols into N_T parallel input data symbols;

N_T multipliers for multiplying each of the N_T input data symbols with a time-domain spreading code, each input data symbol being spread into SF_T chips in time-domain, SF_T being a time-domain spreading factor;

N_T repeaters for repeating each of the SF_T chips SF_F times, SF_F being a frequency-domain spreading factor;

N_T second S/P converters, each second S/P converter for converting the SF_F repeated chips into SF_F parallel chips; and

a subcarrier mapping and weighting unit for mapping each chip to one of the plurality of subcarriers and multiplying each chip with a corresponding chip of the SCQS code.

54. The transmitter of claim 49 wherein the spreading and subcarrier mapping unit comprises:

a first S/P converter for converting serial N_T input data symbols into N_T parallel input data symbols;

N_T first multipliers for multiplying each of the N_T input data symbols with a time-domain spreading code, each input data symbol being spread into SF_T chips in time-domain, SF_T being a time-domain spreading factor;

N_T second multipliers for multiplying each of the SF_T chips obtained in time-domain with the SCQS code to spread the chips, each chips being spread into SF_F chips in frequency-domain, SF_F being a frequency-domain spreading factor;

N_T second S/P converters, each second S/P converter for converting the SF_F chips obtained from each of the SF_T chips into SF_F parallel chips; and

a subcarrier mapping unit for mapping each chip to one of the subcarriers.

55. The transmitter of claim 49 wherein the SCQS code is constructed by combining a generic quadratic phase sequence code and an orthogonal spreading code.

56. The transmitter of claim 55 wherein the SCQS code is constructed by chip-by-chip multiplication of a shifted version of quadratic phase sequence code having 2^m chips with one of orthogonal spreading codes with spreading factor of 2^m .

57. The transmitter of claim 55 wherein the quadratic phase sequence code is one of a Newman phase code sequence, a generalized chirp-like sequence (GCL) and a Zadoff-Chu sequence and the orthogonal spreading code is a Walsh-Hadamard code.

58. The transmitter of claim 55 wherein the chip streams are mapped to subcarriers separated by 2^{n-m} subcarriers among a total of 2^n subcarriers.

59. The transmitter of claim 55 wherein different users are assigned different SCQS codes that are different in at least one of the quadratic phase sequence code and the orthogonal spreading code.

60. The transmitter of claim 55 wherein different users are assigned different SCQS codes with a shift as large as possible in the quadratic phase sequence code.

61. The transmitter of claim 55 wherein the shift of the quadratic phase sequence code is limited to a maximum delay spread of a channel.

62. The transmitter of claim 56 wherein the spreading factor 2^m is limited by $\lfloor n/2 \rfloor \leq m \leq n$ and only first $2^{\lceil m/2 \rceil}$ codes of the Walsh-Hadamard codes are used to combine with the Newman phase sequence code to generate the SCQS codes, wherein $\lfloor a \rfloor$ means a smallest integer larger than a and $\lceil b \rceil$ means a largest integer smaller than b .

63. The transmitter of claim 49 wherein the IDFT operation is performed by computing a phase shift using a corresponding input data subcarrier and data symbol indexes.

64. The transmitter of claim 49 wherein the transmitter further comprises a mixer for multiplying a masking code to the serial data stream for transmission.

65. The transmitter of claim 49 wherein the orthogonal spreading code is a pseudo-orthogonal spreading code.

66. The transmitter of claim 49 wherein the IDFT are performed by an inverse fast Fourier transform (IFFT).

67. The transmitter of claim 49 wherein the transmitter comprises multiple antennas.

68. The transmitter of claim 49 wherein the input data symbols are predetermined and known to a receiver.

69. The transmitter of claim 68 wherein the transmitted signals generated from a predetermined data vector are used as one of a preamble for random access channel (RACH) and pilot signals.

70. In an orthogonal frequency division multiplexing (OFDM)-code division multiple access (CDMA) wireless communication system where a transmitter spreads an input data symbol with a spread complex quadratic sequence (SCQS) code to generate a plurality of chips and maps the chips to a plurality of subcarriers using OFDM, a receiver comprising:

a CP remover for removing a CP from received data;

a serial-to-parallel (S/P) converter for converting the received data into multiple received data streams;

a discrete Fourier transform (DFT) unit for performing DFT on the multiple received data streams;

an equalizer for performing equalization on an output of the DFT unit; and

a despreader for despreading an output of the equalizer.

71. The receiver of claim 70 wherein multi-user detection (MUD) is further performed on an output of the despreader.

72. The receiver of claim 70 further comprising a block linear equalizer for performing block linear equalization (BLE) on an output of the despreader.

73. The receiver of claim 70 further comprising a joint detector for performing a joint detection on an output of the despreader.

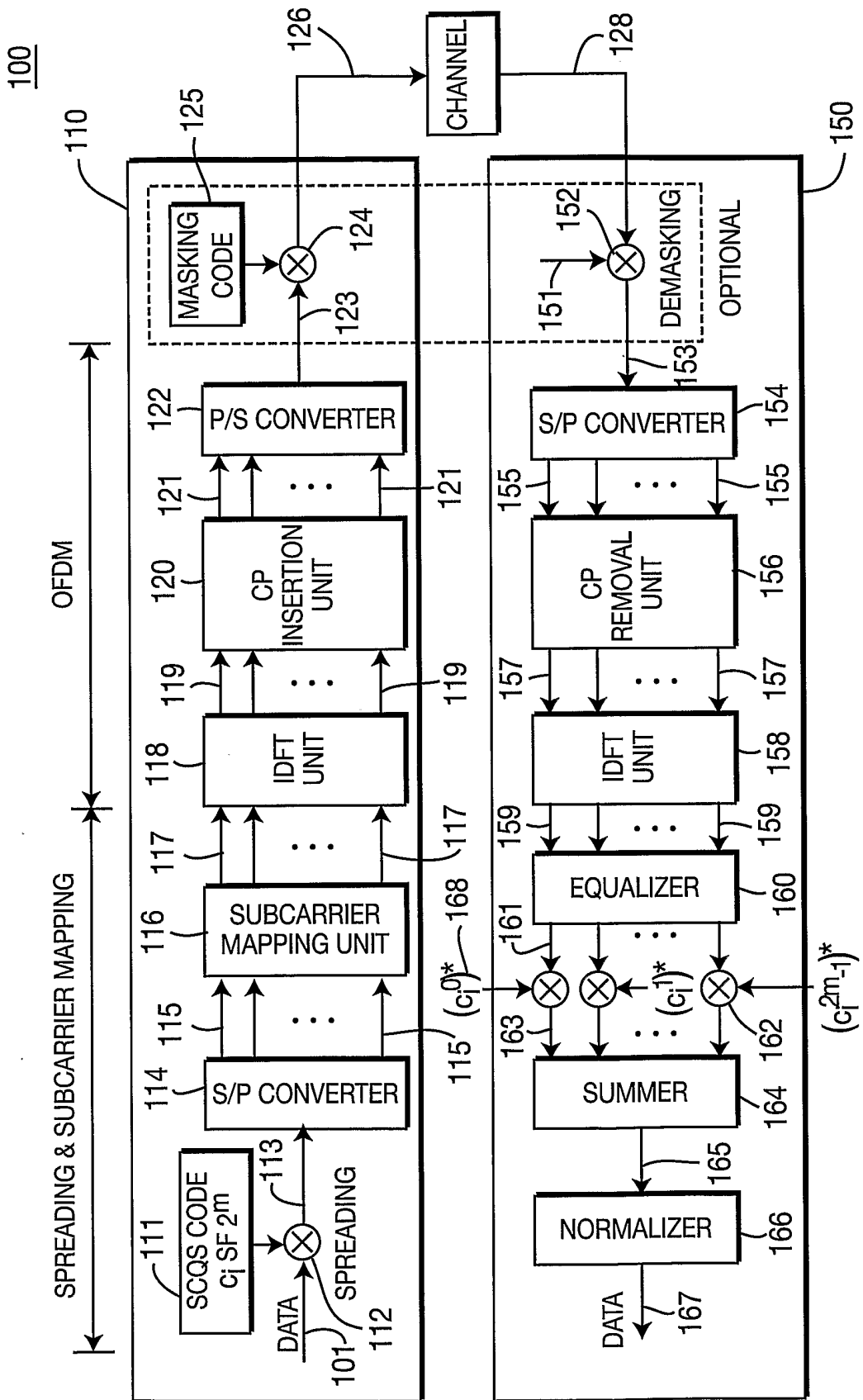


FIG. 1

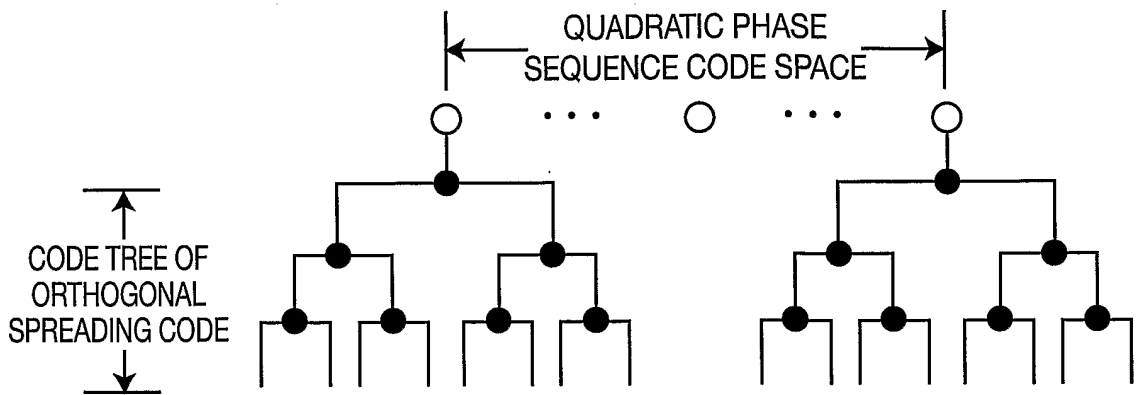


FIG. 2

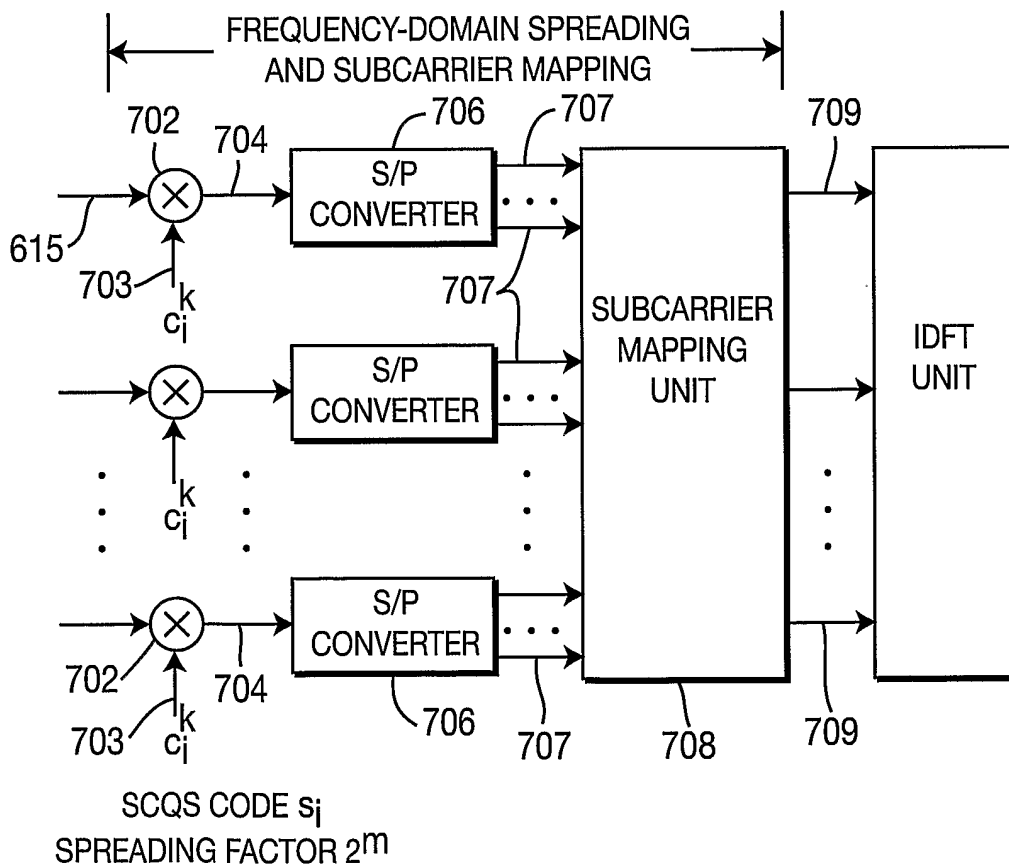


FIG. 7

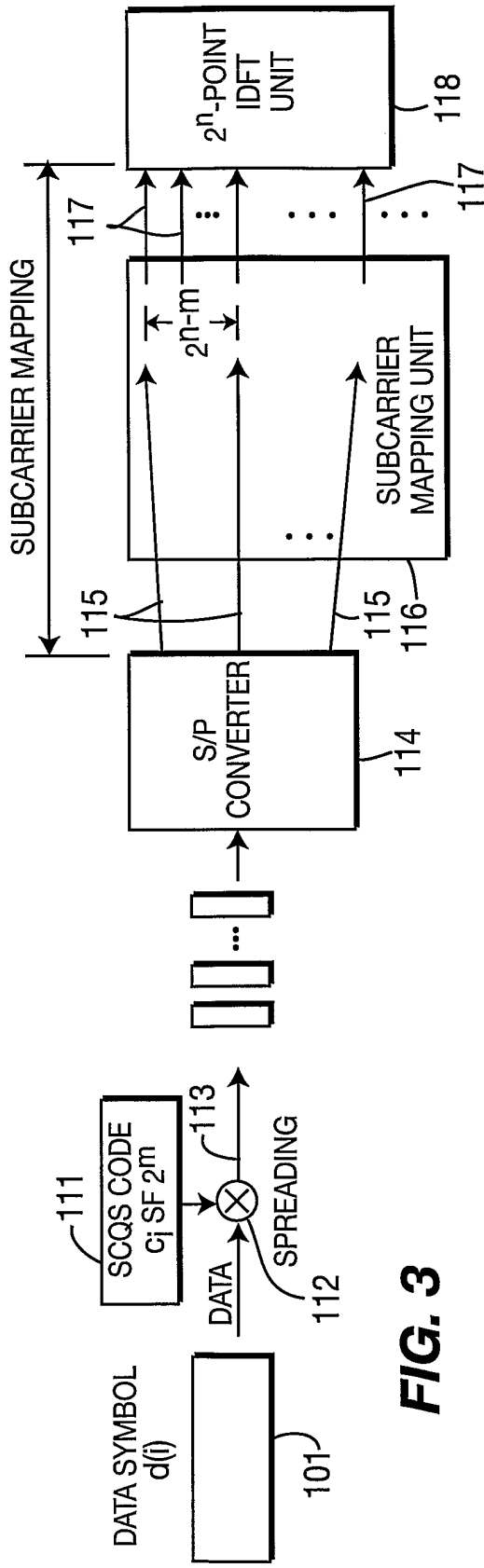


FIG. 3

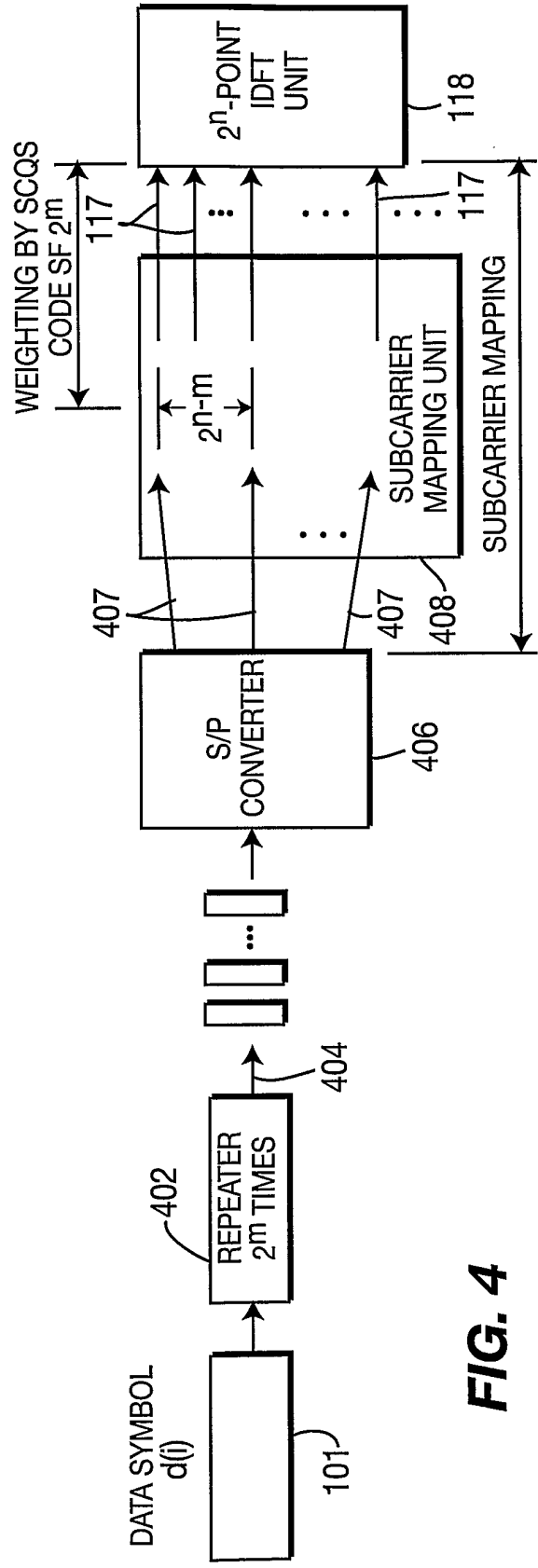


FIG. 4

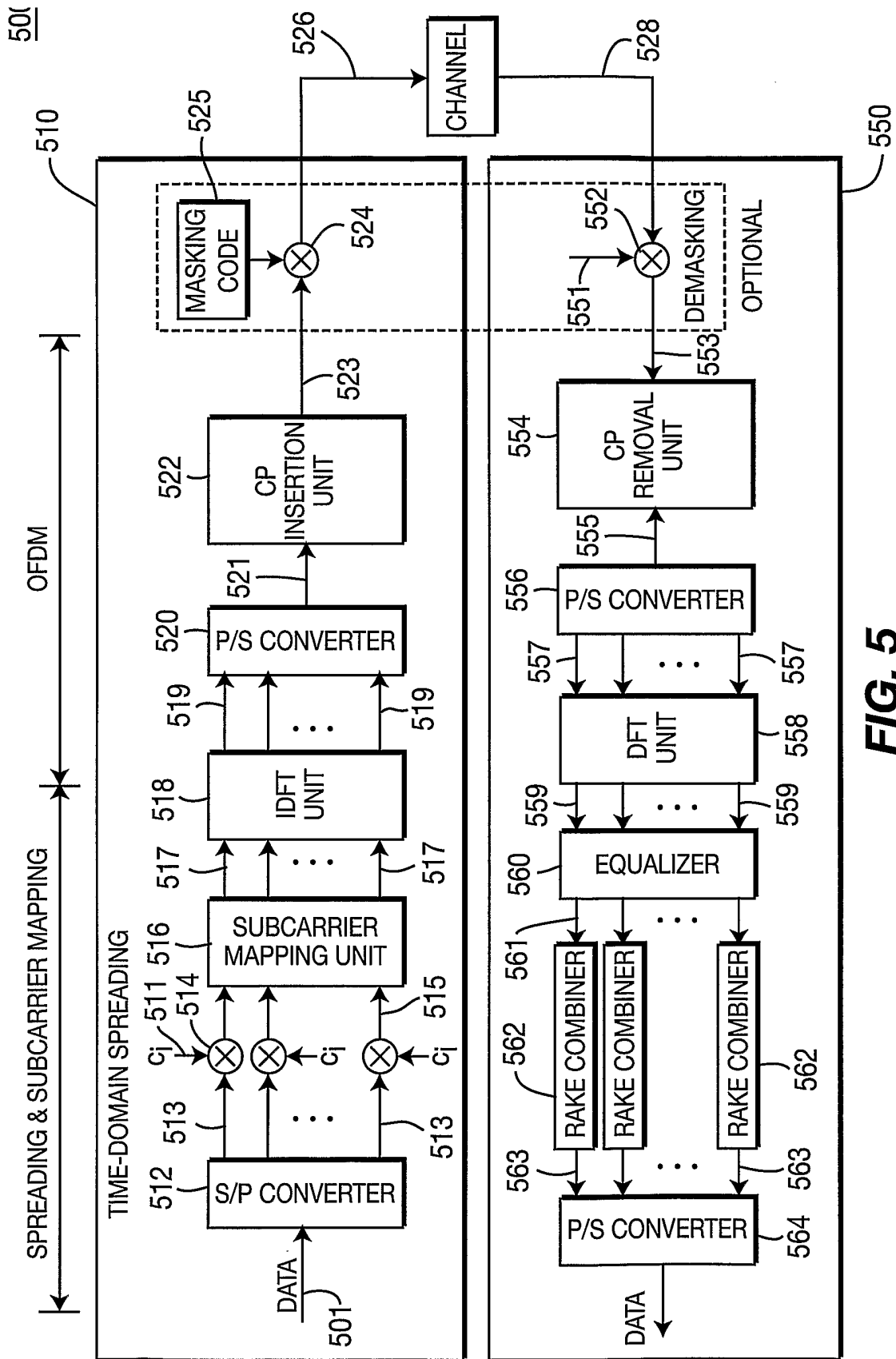


FIG. 5

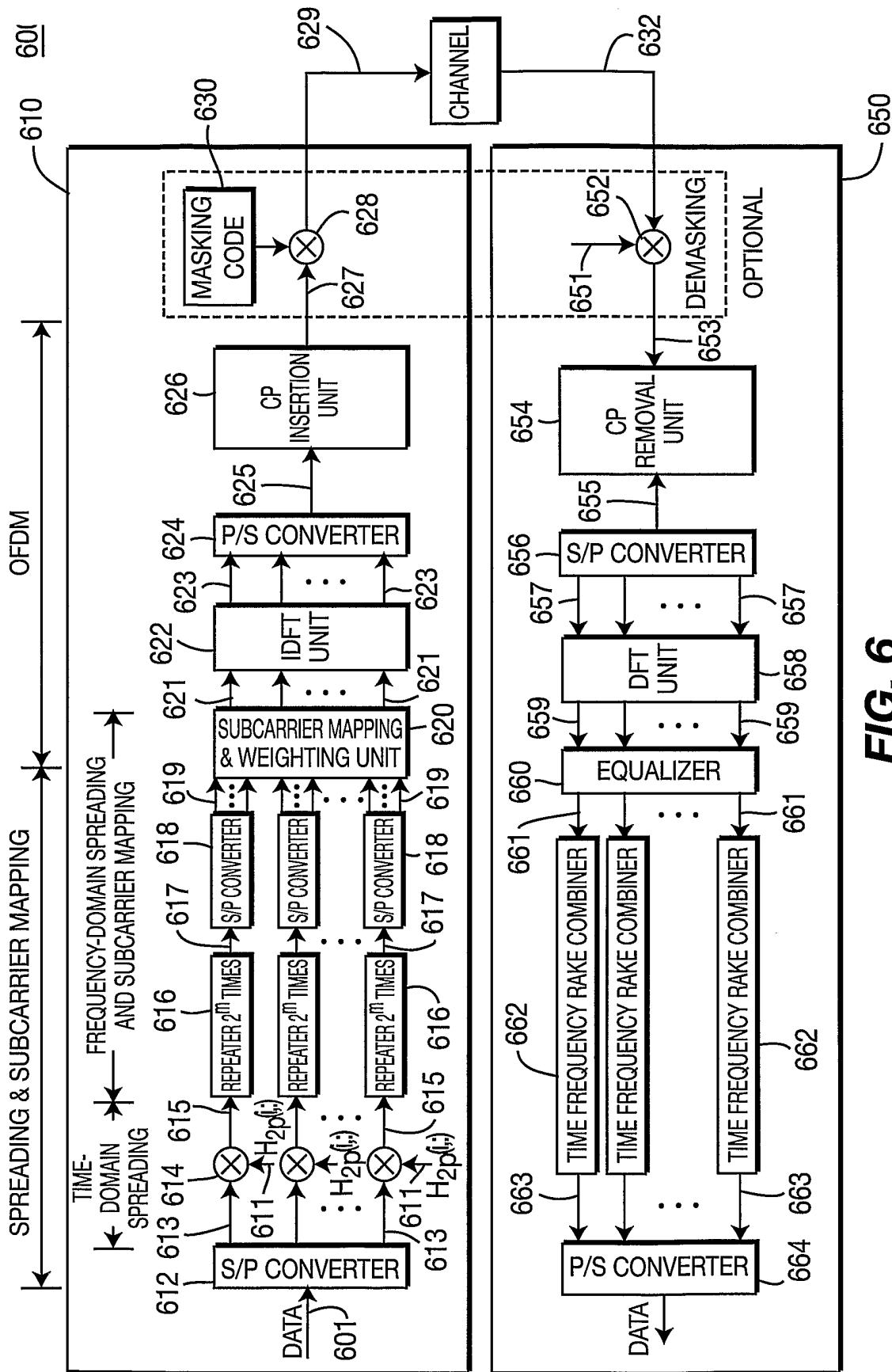


FIG. 6

