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[Continued on next page]

(54) Title: RATE-COMPATIBLE SHORTENED QUASI-CYCLIC LOW-DENSITY PARITY-CHECK (LDPC) CODES

$$H_5^1 = \begin{bmatrix} 0 & 0 & 0 & 0 & 1 \\ 1 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 \end{bmatrix} \quad H_5^\infty = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \end{bmatrix}$$

Length $mz \times nz$ parity-check matrix H

$$H = \begin{bmatrix} H_z^{s_{11}} & H_z^{s_{12}} & \dots & H_z^{s_{1,n-1}} & H_z^{s_{1n}} \\ H_z^{s_{21}} & H_z^{s_{22}} & \dots & H_z^{s_{2,n-1}} & H_z^{s_{2n}} \\ \vdots & \vdots & \ddots & \vdots & \vdots \\ H_z^{s_{m-1,1}} & H_z^{s_{m-1,2}} & \dots & H_z^{s_{m-1,n-1}} & H_z^{s_{m-1,n}} \\ H_z^{s_{m1}} & H_z^{s_{m2}} & \dots & H_z^{s_{m,n-1}} & H_z^{s_{mn}} \end{bmatrix}$$

Expansion factor z and a base matrix

$$S_{m \times n} = \begin{bmatrix} s_{11} & s_{12} & \dots & s_{1,n-1} & s_{1n} \\ s_{21} & s_{22} & \dots & s_{2,n-1} & s_{2n} \\ \vdots & \vdots & \ddots & \vdots & \vdots \\ s_{m-1,1} & s_{m-1,2} & \dots & s_{m-1,n-1} & s_{m-1,n} \\ s_{m1} & s_{m2} & \dots & s_{m,n-1} & s_{mn} \end{bmatrix}$$

(57) Abstract: An embodiment of the present invention provides an apparatus, comprising a transceiver capable of encoding and decoding a unified quasi-cyclic low-density parity-check (QC-LDPC) code structure for variable code rates and sizes using a unified base matrix definition. QC-LDPC codes form a special class of structured LDPC codes whose parity check matrices comprise permutation or, shifted identity matrices. The unified base matrix definition may be a concatenation of multiple square matrices $S_{m \times m} = (S_{m \times m}^R | S_{m \times m}^{R-1} | \dots | S_{m \times m}^3 | S_{m \times m}^2 | S_{m \times m}^1)$ and the base matrix for rate $(r-1)/r$ may be $S_{m \times m}^r = (S_{m \times m}^r | S_{m \times m}^{r-1} | \dots | S_{m \times m}^3 | S_{m \times m}^2 | S_{m \times m}^1)$ for $r=2,3,\dots,R$.



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RATE-COMPATIBLE SHORTENED QUASI-CYCLIC LOW-DENSITY PARITY-CHECK (LDPC) CODES

5 BACKGROUND

[0001] Wireless communication has become prevalent throughout society creating the need for faster and more reliable wireless communication techniques. Although not limited in this respect, several techniques may be adopted in wireless standards such as the Institute for Electronic and Electrical Engineers
10 (IEEE) 802.11n, 802.16e, and 802.15.3a standards. In an attempt to improve the reliability of these communication techniques, they may employ forward error correction capabilities such as quasi-cyclic low-density parity-check (QC-LDPC) codes which have been proposed as a strong forward error correction (FEC) candidate with low complexity and high performance. However, there are
15 shortcomings to these FEC techniques when variable code rates and sizes are used.

[0002] Thus, a strong need exists for an apparatus and method capable of improved wireless communication with improved FEC that overcomes the aforementioned shortcomings.

20

BRIEF DESCRIPTION OF THE DRAWINGS

[0003] The subject matter regarded as the invention is particularly pointed out and distinctly claimed in the concluding portion of the specification. The
25 invention, however, both as to organization and method of operation, together with

objects, features, and advantages thereof, may best be understood by reference to the following detailed description when read with the accompanying drawings in which:

5 [0004] FIG. 1 illustrates a cyclic permutation matrix H_z^s and a length $mz \times nz$ parity-check matrix H as well as a base matrix.

[0005] It will be appreciated that for simplicity and clarity of illustration, elements illustrated in the figures have not necessarily been drawn to scale. For example, the dimensions of some of the elements are exaggerated relative to other elements for clarity. Further, where considered appropriate, reference numerals have been repeated among the figures to indicate corresponding or analogous elements.

DETAILED DESCRIPTION

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[0006] In the following detailed description, numerous specific details are set forth in order to provide a thorough understanding of the invention. However, it will be understood by those skilled in the art that the present invention may be practiced without these specific details. In other instances, well-known methods, procedures, components and circuits have not been described in detail so as not to obscure the present invention.

20 [0007] Some portions of the detailed description that follows are presented in terms of algorithms and symbolic representations of operations on data bits or binary digital signals within a computer memory. These algorithmic descriptions

and representations may be the techniques used by those skilled in the data processing arts to convey the substance of their work to others skilled in the art.

[0008] An algorithm is here, and generally, considered to be a self-consistent sequence of acts or operations leading to a desired result. These

5 include physical manipulations of physical quantities. Usually, though not necessarily, these quantities take the form of electrical or magnetic signals capable of being stored, transferred, combined, compared, and otherwise manipulated. It has proven convenient at times, principally for reasons of common usage, to refer to these signals as bits, values, elements, symbols, characters, terms, numbers or the like. It should be understood, however, that all
10 of these and similar terms are to be associated with the appropriate physical quantities and are merely convenient labels applied to these quantities.

[0009] Unless specifically stated otherwise, as apparent from the following discussions, it is appreciated that throughout the specification discussions utilizing

15 terms such as "processing," "computing," "calculating," "determining," or the like, refer to the action and/or processes of a computer or computing system, or similar electronic computing device, that manipulate and/or transform data represented as physical, such as electronic, quantities within the computing system's registers and/or memories into other data similarly represented as physical quantities within
20 the computing system's memories, registers or other such information storage, transmission or display devices.

[0010] Embodiments of the present invention may include apparatuses for

performing the operations herein. An apparatus may be specially constructed for the desired purposes, or it may comprise a general purpose computing device
25 selectively activated or reconfigured by a program stored in the device. Such a

program may be stored on a storage medium, such as, but not limited to, any type of disk including floppy disks, optical disks, compact disc read only memories (CD-ROMs), magnetic-optical disks, read-only memories (ROMs), random access memories (RAMs), electrically programmable read-only memories (EPROMs),
5 electrically erasable and programmable read only memories (EEPROMs), magnetic or optical cards, or any other type of media suitable for storing electronic instructions, and capable of being coupled to a system bus for a computing device.

[0011] The processes and displays presented herein are not inherently

10 related to any particular computing device or other apparatus. Various general purpose systems may be used with programs in accordance with the teachings herein, or it may prove convenient to construct a more specialized apparatus to perform the desired method. The desired structure for a variety of these systems will appear from the description below. In addition, embodiments of the present
15 invention are not described with reference to any particular programming language. It will be appreciated that a variety of programming languages may be used to implement the teachings of the invention as described herein. In addition, it should be understood that operations, capabilities, and features described herein may be implemented with any combination of hardware (discrete or
20 integrated circuits) and software.

[0012] Use of the terms "coupled" and "connected", along with their derivatives, may be used. It should be understood that these terms are not intended as synonyms for each other. Rather, in particular embodiments, "connected" may be used to indicate that two or more elements are in direct
25 physical or electrical contact with each other. "Coupled" may be used to indicate

that two or more elements are in either direct or indirect (with other intervening elements between them) physical or electrical contact with each other, and/or that the two or more elements co-operate or interact with each other (e.g. as in a cause an effect relationship).

5 **[0013]** It should be understood that embodiments of the present invention may be used in a variety of applications. Although the present invention is not limited in this respect, the devices disclosed herein may be used in many apparatuses such as in the transmitters and receivers of a radio system. Radio systems intended to be included within the scope of the present invention include, 10 by way of example only, cellular radiotelephone communication systems, satellite communication systems, two-way radio communication systems, one-way pagers, two-way pagers, personal communication systems (PCS), personal digital assistants (PDA's), wireless local area networks (WLAN), personal area networks (PAN, and the like).

15 **[0014]** Quasi-cyclic low-density parity-check (QC-LDPC) codes have been proposed as a strong forward error correction (FEC) candidate with low complexity and high performance. An embodiment of the present invention provides a QC-LDPC structure that is capable of accommodating codes of multiple rates and sizes.

20 **[0015]** An LDPC code may be characterized by a binary parity-check matrix H with a low density of 1's. A structured LDPC code may be one where the locations of the 1's in its parity-check matrix follow a certain pattern. QC-LDPC codes may form a special class of structured codes whose parity-check matrices may comprise cyclic permutation matrices or, shifted identity matrices.

25 **[0016]** Turning now to FIG. 1, shown generally as 100, a cyclic permutation

matrix H_z^s is generated by shifting the diagonal of a $z \times z$ identity matrix to the left by s times. Here z is called the expansion factor or scale factor, and s is called the shift. The symbol H_z^∞ may be used to denote the special case of zero-matrix 110. An example is illustrated in FIG. 1 at 105.

5 [0017] A length $mz \times nz$ parity-check matrix H may be constructed as shown at 115. In an embodiment of the present invention, H may be uniquely determined by the expansion factor z and a base matrix with its code rate being $(n-m)/n$ as shown at 120. Code rates of $1/2$, $2/3$, $3/4$, $5/6$ and $7/8$ may be typically used in wireless communication systems, although the present invention is not
10 limited in this respect.

[0018] In some communication standards, for example, but not limited to, wireless communication standards 802.16e and 802.11n, it may be desired for each LDPC code rate to have a family of codes of different code sizes. This may be achieved by expanding a single base matrix with different expansion factors.
15 However, this approach may still require a base matrix definition for each code rate.

[0019] An embodiment of the present invention provides a unified base matrix definition for multiple codes rates. This base matrix definition may be a concatenation of multiple square matrices

20
$$S_{m \times Rm} = (S_{m \times m}^R | S_{m \times m}^{R-1} | \dots | S_{m \times m}^3 | S_{m \times m}^2 | S_{m \times m}^1)$$

and the base matrix for rate $(r-1)/r$ may be

$$S_{m \times rm} = (S_{m \times m}^r | S_{m \times m}^{r-1} | \dots | S_{m \times m}^3 | S_{m \times m}^2 | S_{m \times m}^1)$$

for $r=2,3,\dots,R$.

[0020] An embodiment of the present invention also provides a method of forward error correction, comprising employing a transceiver capable of a unified quasi-cyclic low-density parity-check structure for variable code rates and sizes which uses a unified base matrix definition.

5 [0021] Further, this base matrix definition may be a concatenation of multiple square matrices

$$S_{m \times Rm} = (S_{m \times m}^R | S_{m \times m}^{R-1} | \dots | S_{m \times m}^3 | S_{m \times m}^2 | S_{m \times m}^1)$$

and the base matrix for rate (r-1)/r may be

$$S_{m \times rm} = (S_{m \times m}^r | S_{m \times m}^{r-1} | \dots | S_{m \times m}^3 | S_{m \times m}^2 | S_{m \times m}^1)$$

10 for r=2,3,...,R.

[0022] An embodiment of the present invention may further provide an article comprising a storage medium having stored thereon instructions, that, when executed by a computing platform, results in providing forward error correction, by controlling a transceiver capable of a unified quasi-cyclic low-density parity-check structure for variable code rates and sizes which uses a unified base matrix definition. Further, this base matrix definition may be a concatenation of multiple square matrices

$$S_{m \times Rm} = (S_{m \times m}^R | S_{m \times m}^{R-1} | \dots | S_{m \times m}^3 | S_{m \times m}^2 | S_{m \times m}^1)$$

and the base matrix for rate (r-1)/r may be

20
$$S_{m \times rm} = (S_{m \times m}^r | S_{m \times m}^{r-1} | \dots | S_{m \times m}^3 | S_{m \times m}^2 | S_{m \times m}^1)$$

for r=2,3,...,R.

[0023] QC-LDPC codes may be decoded using layered decoding techniques to achieve increased potential decoding throughput. Higher potential

throughput can be achieved by further reducing the size of the base matrices, and more precisely, the row length m .

[0024] In an embodiment of the present invention, row length $m \geq 4$ may be the minimal requirement to achieve good performance, thus an embodiment of the

5 present invention provides the base matrix sizes 4×8 for rate $\frac{1}{2}$, 4×12 for rate $\frac{2}{3}$, 4×16 for rate $\frac{3}{4}$, 4×24 for rate $\frac{5}{6}$, and 4×32 for rate $\frac{7}{8}$. Further, an embodiment of the present invention provides, although is not limited to, the use of a unified base matrix definition. The definition may be, but again is not limited to:

10

$$S_{4 \times 32} = (S_{4 \times 4}^8 | S_{4 \times 4}^7 | S_{4 \times 4}^6 | S_{4 \times 4}^5 | S_{4 \times 4}^4 | S_{4 \times 4}^3 | S_{4 \times 4}^2 | S_{4 \times 4}^1)$$

for rate $\frac{7}{8}$, and

$$S_{4 \times 24} = (S_{4 \times 4}^6 | S_{4 \times 4}^5 | S_{4 \times 4}^4 | S_{4 \times 4}^3 | S_{4 \times 4}^2 | S_{4 \times 4}^1)$$

15

for rate $\frac{5}{6}$, and

$$S_{4 \times 16} = (S_{4 \times 4}^4 | S_{4 \times 4}^3 | S_{4 \times 4}^2 | S_{4 \times 4}^1)$$

for rate $\frac{3}{4}$, and

20

$$S_{4 \times 12} = (S_{4 \times 4}^3 | S_{4 \times 4}^2 | S_{4 \times 4}^1)$$

for rate $\frac{2}{3}$, and

$$S_{4 \times 8} = \left(S_{4 \times 4}^2 \mid S_{4 \times 4}^1 \right)$$

for rate $\frac{1}{2}$.

[0025] While certain features of the invention have been illustrated and
5 described herein, many modifications, substitutions, changes, and equivalents will
now occur to those skilled in the art. It is, therefore, to be understood that the
appended claims are intended to cover all such modifications and changes as fall
within the true spirit of the invention.

Claims:

1. An apparatus, comprising:

a transceiver capable of a unified quasi-cyclic low-density parity-check structure for variable code rates and sizes using a unified base matrix definition.

5

2. The apparatus of claim 1, wherein the base matrix definition is a concatenation of multiple square matrices

$$S_{m \times Rm} = (S_{m \times m}^R | S_{m \times m}^{R-1} | \dots | S_{m \times m}^3 | S_{m \times m}^2 | S_{m \times m}^1)$$

and the base matrix for rate (r-1)/r is

10
$$S_{m \times rm} = (S_{m \times m}^r | S_{m \times m}^{r-1} | \dots | S_{m \times m}^3 | S_{m \times m}^2 | S_{m \times m}^1)$$

for r=2,3,...,R.

3. The apparatus of claim 2, wherein the row length m of said unified base matrix definition is a minimum of 4.

15

4. The apparatus of claim 3, wherein base matrix sizes are 4×8 for rate $\frac{1}{2}$, 4×12 for rate $\frac{2}{3}$, 4×16 for rate $\frac{3}{4}$, 4×24 for rate $\frac{5}{6}$, and 4×32 for rate $\frac{7}{8}$.

5. The apparatus of claim 4, wherein said unified base matrix definition is:

20
$$S_{4 \times 32} = (S_{4 \times 4}^8 | S_{4 \times 4}^7 | S_{4 \times 4}^6 | S_{4 \times 4}^5 | S_{4 \times 4}^4 | S_{4 \times 4}^3 | S_{4 \times 4}^2 | S_{4 \times 4}^1) \text{ for rate } \frac{7}{8}.$$

6. The apparatus of claim 4, wherein said unified base matrix definition is:

$$S_{4 \times 24} = (S_{4 \times 4}^6 | S_{4 \times 4}^5 | S_{4 \times 4}^4 | S_{4 \times 4}^3 | S_{4 \times 4}^2 | S_{4 \times 4}^1) \text{ for rate } 5/6.$$

7. The apparatus of claim 4, wherein said unified base matrix definition is:

$$S_{4 \times 16} = (S_{4 \times 4}^4 | S_{4 \times 4}^3 | S_{4 \times 4}^2 | S_{4 \times 4}^1) \text{ for rate } \frac{3}{4}.$$

5

8. The apparatus of claim 4, wherein said unified base matrix definition is:

$$S_{4 \times 12} = (S_{4 \times 4}^3 | S_{4 \times 4}^2 | S_{4 \times 4}^1) \text{ for rate } \frac{2}{3}.$$

9. The apparatus of claim 4, wherein said unified base matrix definition is:

10 $S_{4 \times 8} = (S_{4 \times 4}^2 | S_{4 \times 4}^1) \text{ for rate } \frac{1}{2}.$

10. A method of forward error correction, comprising:

employing a transceiver capable of a unified quasi-cyclic low-density parity-check structure for variable code rates and sizes which uses a unified base matrix definition.

15

11. The method of claim 10, further comprising using a base matrix definition is a concatenation of multiple square matrices

$$S_{m \times Rm} = (S_{m \times m}^R | S_{m \times m}^{R-1} | \dots | S_{m \times m}^3 | S_{m \times m}^2 | S_{m \times m}^1)$$

- 20 and the base matrix for rate $(r-1)/r$ is

$$S_{m \times rm} = (S_{m \times m}^r | S_{m \times m}^{r-1} | \dots | S_{m \times m}^3 | S_{m \times m}^2 | S_{m \times m}^1)$$

for $r=2,3,\dots,R$.

13. An article comprising a storage medium having stored thereon instructions, that, when executed by a computing platform: results in providing forward error correction, by controlling a transceiver capable of a unified quasi-cyclic low-density parity-check structure for variable code rates and sizes which uses a unified base matrix definition.

14. The article of claim 13, wherein said unified base matrix definition may be a concatenation of multiple square matrices

$$S_{m \times Rm} = (S_{m \times m}^R | S_{m \times m}^{R-1} | \dots | S_{m \times m}^3 | S_{m \times m}^2 | S_{m \times m}^1)$$

10 and the base matrix for rate $(r-1)/r$ may be

$$S_{m \times rm} = (S_{m \times m}^r | S_{m \times m}^{r-1} | \dots | S_{m \times m}^3 | S_{m \times m}^2 | S_{m \times m}^1)$$

for $r=2,3,\dots,R$.

1/1

$$\begin{array}{ccc}
 \diagup 105 & \diagup 100 & \diagup 110 \\
 H_5^1 = \begin{bmatrix} 0 & 0 & 0 & 0 & 1 \\ 1 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 \end{bmatrix} & & H_5^\infty = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \end{bmatrix}.
 \end{array}$$

Length $mz \times nz$ parity-check matrix H

$$H = \begin{bmatrix} H_z^{s_{11}} & H_z^{s_{12}} & \cdots & H_z^{s_{1,n-1}} & H_z^{s_{1n}} \\ H_z^{s_{21}} & H_z^{s_{22}} & \cdots & H_z^{s_{2,n-1}} & H_z^{s_{2n}} \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ H_z^{s_{m-1,1}} & H_z^{s_{m-1,2}} & \cdots & H_z^{s_{m-1,n-1}} & H_z^{s_{m-1,n}} \\ H_z^{s_{m1}} & H_z^{s_{m2}} & \cdots & H_z^{s_{m,n-1}} & H_z^{s_{mn}} \end{bmatrix}. \quad \diagup 115$$

Expansion factor z and a base matrix

$$S_{m \times n} = \begin{bmatrix} s_{11} & s_{12} & \cdots & s_{1,n-1} & s_{1n} \\ s_{21} & s_{22} & \cdots & s_{2,n-1} & s_{2n} \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ s_{m-1,1} & s_{m-1,2} & \cdots & s_{m-1,n-1} & s_{m-1,n} \\ s_{m1} & s_{m2} & \cdots & s_{m,n-1} & s_{mn} \end{bmatrix} \quad \diagup 120$$

FIG. 1

INTERNATIONAL SEARCH REPORT

International application No

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A. CLASSIFICATION OF SUBJECT MATTER
H03M13/11

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

B. FIELDS SEARCHEDMinimum documentation searched (classification system followed by classification symbols)
H03M

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)

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C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	CLASSON B. ET AL.: "LDPC coding for OFDMA PHY" IEEE 802.16E SESSION #33, SEOUL, KOREA, 30 August 2004 (2004-08-30), pages 1-17, XP002371218 Retrieved from the Internet: URL: http://www.ieee802.org/16/tge/contrib/C80216e-04_278r1.pdf [retrieved on 2006-03-08] page 7 - page 8 ----- -/--	1-14



Further documents are listed in the continuation of Box C.



See patent family annex.

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Date of the actual completion of the international search

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INTERNATIONAL SEARCH REPORT

International application No

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C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
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