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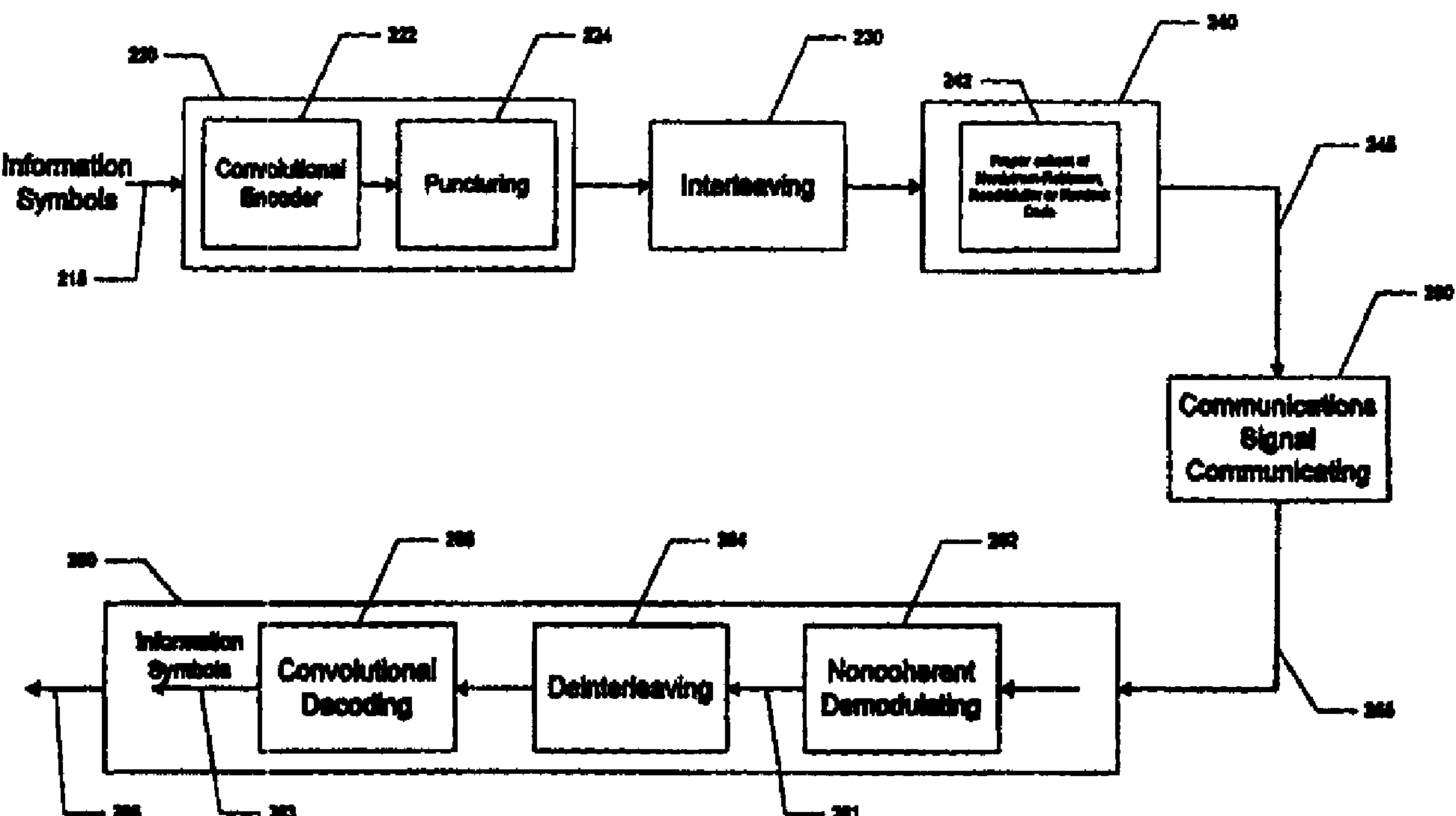
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(54) Titre : SYSTEMES ET PROCEDES DE TELECOMMUNICATIONS EMPLOYANT UNE SEGMENTATION DE DEBIT
DE CODE AVEC MODULATION NON ORTHOGONALE
(54) Title: COMMUNICATIONS SYSTEMS AND METHODS EMPLOYING CODE RATE PARTITIONING WITH
NONORTHOGONAL MODULATION



(57) Abrégé/Abstract:

Information is processed to produce a plurality of information symbols. The plurality of information symbols are encoded according to a concatenation of an error correction code and a nonorthogonal modulation code to produce a modulated communications signal. The modulated communications signal is communicated over a communication medium, and communications signal processing means process the communicated modulated communications signal to produce information. Preferably, the

(57) Abrégé(suite)/Abstract(continued):

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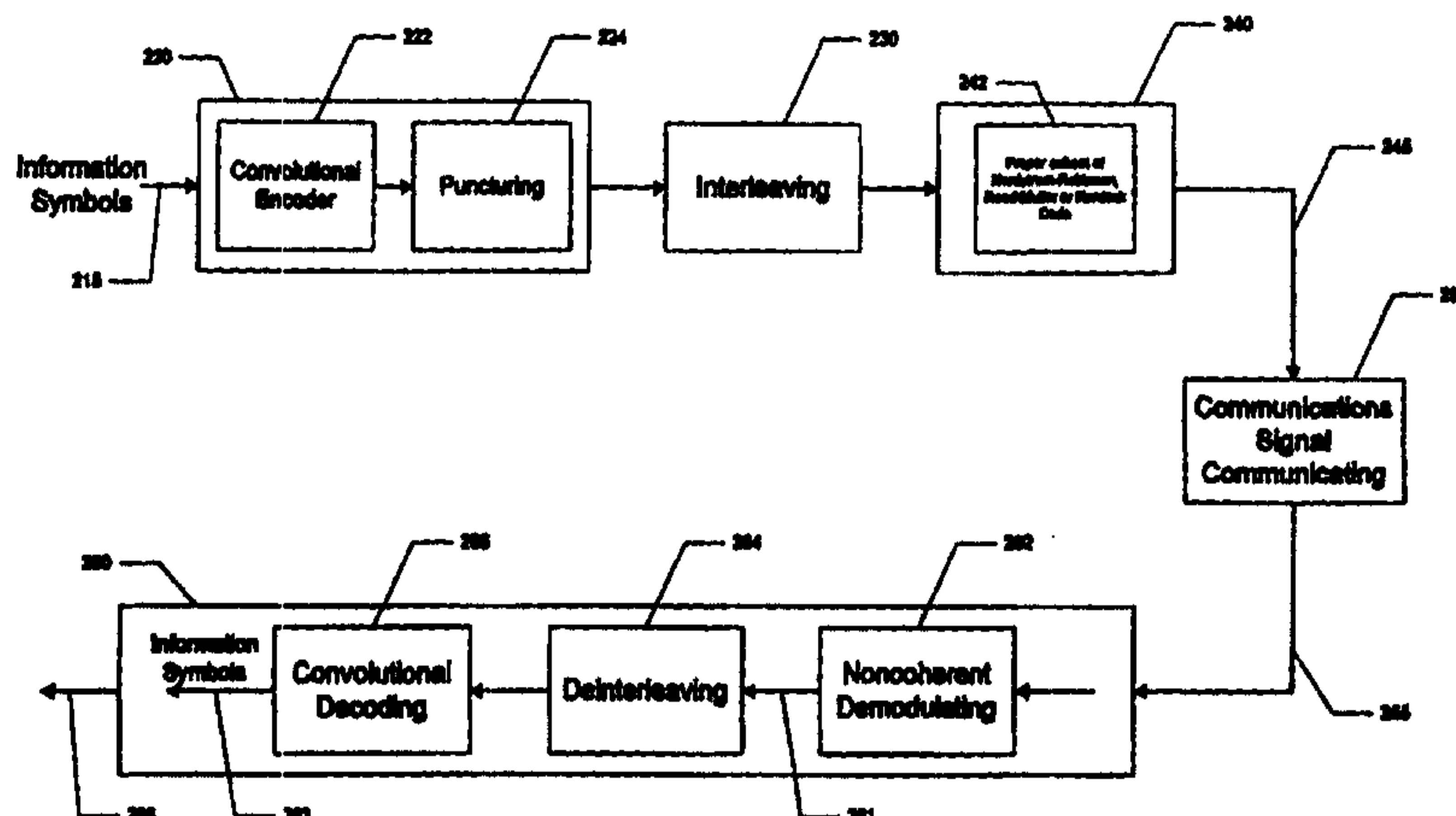
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(54) Title: COMMUNICATIONS SYSTEMS AND METHODS EMPLOYING CODE RATE PARTITIONING WITH NONORTHOGONAL MODULATION



(57) Abstract

Information is processed to produce a plurality of information symbols. The plurality of information symbols are encoded according to a concatenation of an error correction code and a nonorthogonal modulation code to produce a modulated communications signal. The modulated communications signal is communicated over a communication medium, and communications signal processing means process the communicated modulated communications signal to produce information. Preferably, the information symbols are encoded according to an error correction code, preferably a convolutional code, to produce a plurality of coded symbols. The plurality of coded symbols are preferably interleaved to produce a plurality of interleaved coded symbols. The interleaved coded symbols are then modulated according to a nonorthogonal code to produce the modulated communications signal. Preferably, the coded symbols are modulated according to a proper subset of one of a Nordstrom-Robinson code, a Reed-Muller code, or a Kerdock code, the proper subset being operable to produce a modulated communications signal from a signal set such that the communications signal noncoherently demodulates to produce a unique output for each signal in the signal set, and the communications signal processing means includes noncoherent demodulating means for noncoherently demodulating the communicated modulated communications signal.

COMMUNICATIONS SYSTEMS AND METHODS EMPLOYING CODE RATE PARTITIONING WITH NONORTHOGONAL MODULATION

Field of the Invention

The present invention relates to communications systems and methods, in particular, to coding systems and methods in communications systems.

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Background of the Invention

In many communications systems, for example, wireless communications systems such as mobile satellite radiotelephone systems, it is generally desirable to use as little signal power as necessary to 10 communicate signals. Toward this end, many communications systems utilize error correction coding to improve signal-to-noise ratio without requiring an increase in signal power. As illustrated in Figure 1, in a typical wireless communications system, information represented by information symbols 105 is first encoded according to an error control code, for example, in a 15 convolutional encoder 110. The coded symbols 115 output from the convolutional coder 110 are then typically interleaved in an interleaver 120, which reorders the coded symbols 115 to produce a plurality of interleaved coded symbols 125. The interleaved coded symbols 125 are then typically orthogonally modulated by an orthogonal modulator 130 to produce a 20 communications signal 135 which is then communicated over a communications medium 140. An orthogonal modulator 130 is typically employed because the orthogonally modulated communications signal 135 can be demodulated in a noncoherent fashion at a receiver.

The convolutional encoder 110 and the orthogonal demodulator 130 25 produce an overall code rate and minimum distance for the communications signal 135. The convolutional encoder 110 typically employs a rate k/n convolutional code, i.e., a code which produces n coded symbols 115 for each k information symbols 105 input into the encoder 110, and generally has a minimum Hamming distance $d_{1,mln}$ associated therewith. The orthogonal

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modulator 130 typically employs a set of p orthogonal block modulation vectors of length l for input vectors of length m , producing a code rate of m/l and a minimum distance of $d_{2,\min}$. When combined as illustrated in Figure 1, the convolutional encoder 110 and the orthogonal modulator 130 produce an overall code rate of $k/n * m/l$ and a minimum distance of $d_{1,\min} * d_{2,\min}$.

Techniques exist for improving the error-correcting performance in communications systems including, for example, lowering the rate of the convolutional encoder 110 or the orthogonal modulator 130 to provide greater redundancy. Other techniques involve techniques such as the use of high-order signaling alphabet in combination with direct sequence spread-spectrum modulation, as described in Published International Application WO 95/22859 by Cafarella et al. (international filing date February 3, 1995). Such techniques can result in lower efficiency and greater complexity in receiver design. Due to bandwidth and power constraints, there is an ever present need to provide improved signal-to-noise performance without requiring undue additional complexity in receiver design, increased signal power, decreased rate and the like.

Summary of the Invention

In light of the foregoing, it is an object of the present invention to provide error correction coding and modulation systems and methods which provide improved signal-to-noise performance.

It is another object of the present invention to provide error correction coding and modulation systems and methods which may be utilized with noncoherent demodulation techniques.

These and other objects, features and advantages are provided according to the present invention by communications systems and methods in which information symbols are encoded according to a concatenation of a error correcting code, preferably a convolutional code, and a nonorthogonal modulation code to produce a modulated communications signal representing the information symbols. The nonorthogonal modulation code preferably corresponds to one of a

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Nordstrom-Robinson, a Reed-Muller and a Kerdock code, representing a union of selected translations of an orthogonal code set. More preferably, the nonorthogonal modulation code represents a signal set such that when the communications signal is noncoherently demodulated, a unique output is produced for each code in the set. In this manner, less

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complex demodulation techniques can be employed.

The present invention stems from the recognition that a coding scheme having improved distance characteristics over a conventional concatenation of an error correcting code and an orthogonal modulation can be achieved by 5 replacing the orthogonal modulation code with a selected nonorthogonal modulation code which represents an expansion of an orthogonal code which can be demodulated without undue complexity using modified noncoherent orthogonal demodulation techniques. By utilizing nonorthogonal modulation vectors, the present invention allows a decreased code rate to be utilized for 10 the error correcting code while maintaining a desired overall code rate and increasing overall minimum distance.

In particular, in a communications system according to the present invention, information processing means process information to produce a plurality of information symbols. Means are provided to encode the plurality 15 of information symbols according to a concatenation of an error correction code and a nonorthogonal modulation code to produce a modulated communications signal. Communications signal communicating means communicate the modulated communications signal over a communications medium, and communications signal processing means process the 20 communicated modulated communications signal to produce information. Preferably, the convolutional code is punctured to thereby provide a desired overall coding rate. More optimal partitioning between error correction encoding and modulation may thereby be provided.

Preferably, the means for encoding comprises error correction 25 encoding means for encoding the plurality of information symbols according to an error correction code to produce a plurality of coded symbols, and nonorthogonal modulating means for modulating the plurality of coded symbols according to a nonorthogonal modulation code to produce a modulated communications signal. The coded symbols produced by the error 30 correction encoding means preferably are interleaved before modulation in the nonorthogonal modulating means. According to a preferred embodiment, the nonorthogonal modulating means modulate the plurality of coded symbols according to a nonorthogonal modulation code representing a union of

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translations of a set of orthogonal code vectors according to a predetermined translation which produces one of a Nordstrom-Robinson code, a Reed-Muller code, and a Kerdock code, the predetermined translation including a plurality of vectors which map the orthogonal code to the nonorthogonal code.

5 Preferably, the nonorthogonal modulating means modulates the coded symbols according to a proper subset of a nonorthogonal modulation code, the proper subset being operable to produce a modulated communications signal from a signal set such that the communications signal noncoherently demodulates to produce a unique output for each signal in the signal set.

10 The communications signal processing means preferably includes noncoherent demodulating means for noncoherently demodulating the communicated modulated communications signal.

15 The noncoherent demodulating means preferably includes means for processing the communicated modulated communications signal to produce a plurality of received communications symbols, and means for translating the plurality of received communications symbols according to the translation vectors which produce the nonorthogonal modulation code to produce a plurality of groups of communications symbols, a respective group corresponding to a respective one of the translation vectors of the

20 nonorthogonal code. Means are also preferably provided for correlating each group of communications symbols with the set of orthogonal code vectors to produce decision information for each group, and for combining the decision information for the groups of communications symbols to produce a second plurality of information symbols. Efficient demodulation of the

25 nonorthogonally modulated communications signal is thereby provided.

Brief Description of the Drawings

Some of the objects and advantages of the present invention having been stated, others will be more fully understood from the detailed description that follows and by reference to the accompanying drawings in which:

Figure 1 is a schematic diagram illustrating a communications system according to the prior art;

Figure 2 is a schematic diagram illustrating a communications system

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according to the present invention;

Figure 3 is a schematic diagram illustrating a preferred embodiment of a communications system according to the present invention;

5 Figure 4 is a schematic diagram illustrating a preferred embodiment for processing a modulated communications signal according to the present invention; and

Figure 5 is a flowchart illustration of operations for communicating information according to the present invention.

10

Detailed Description of Preferred Embodiments

The present invention now will be described more fully hereinafter with reference to the accompanying drawings, in which embodiments of the invention are shown. This invention may, however, be embodied in many different forms and should not be construed as limited to the embodiments 15 set forth herein; rather, these embodiments are provided so that this disclosure will be thorough and complete, and will fully convey the scope of the invention to those skilled in the art. In the drawings, like numbers refer to like elements throughout.

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Overview

As will be appreciated by those skilled in the art, in a typical conventional communication scheme such as the one illustrated in Figure 1, information may be protected by an error control code, e.g., a convolutional code. For an input information sequence of binary symbols $b_i \in \{+1, -1\}$, the 25 convolutional code produces a coded symbol sequence $\{c_j\}$ including symbols which are a function of the input sequence b_i . For a rate 1/2 convolutional code, for example, the coded bits c_{2i} and c_{2i+1} are some function of b_i, \dots, b_{i-M+1} where M is the memory of the code, i.e., the rate 1/2 code produces two coded symbols for each input information symbol.

30

Those skilled in the art will also understand that in addition to the rate of the code, an important measure of the performance of a code is the minimum Hamming and Euclidean distance of the code, representing a measure of the separation between two possible codewords in the code. For

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example, consider a typical orthogonal modulation scheme, in which a sequence of symbols input into a modulator are mapped onto a signal set including p vectors of length p that are orthogonal, each component of the vectors being commonly known as a "chip." If $\mathbf{s}_i = (s_{i,1}, \dots, s_{i,p})$ for $i = 1, \dots, p$ are these vectors, with $s_{j,i} \in \{\pm 1\}$, then

$$\sum_{i=1}^p s_{i,l} s_{m,i} = \begin{cases} p, & l=m \\ 0, & l \neq m \end{cases}.$$

For example, if $p=16$, these vectors are:

10 $\mathbf{s}_1 = \{+1, +1, +1, +1, +1, +1, +1, +1, +1, +1, +1, +1, +1, +1, +1, +1\};$
 $\mathbf{s}_2 = \{+1, -1, +1, -1, +1, -1, +1, -1, +1, -1, +1, -1, +1, -1, +1, -1\};$
 $\mathbf{s}_3 = \{+1, +1, -1, -1, +1, +1, -1, -1, +1, +1, -1, -1, +1, +1, -1, -1\};$
 $\mathbf{s}_4 = \{+1, -1, -1, +1, +1, -1, -1, +1, +1, -1, -1, +1, +1, -1, -1, +1\};$
 $\mathbf{s}_5 = \{+1, +1, +1, +1, -1, -1, -1, +1, +1, +1, +1, -1, -1, -1, -1, -1\};$
 $\mathbf{s}_6 = \{+1, -1, +1, -1, -1, +1, -1, +1, +1, -1, +1, -1, -1, +1, -1, +1\};$
 $\mathbf{s}_7 = \{+1, +1, -1, -1, -1, +1, +1, +1, +1, -1, -1, -1, -1, +1, +1, +1\};$
 $\mathbf{s}_8 = \{+1, -1, -1, +1, -1, +1, +1, -1, +1, -1, +1, -1, +1, +1, +1, -1\};$
 $\mathbf{s}_9 = \{+1, +1, +1, +1, +1, +1, +1, +1, -1, -1, -1, -1, -1, -1, -1, -1\};$
 $\mathbf{s}_{10} = \{+1, -1, +1, -1, +1, -1, +1, -1, -1, +1, -1, +1, -1, +1, -1, +1\};$
 $\mathbf{s}_{11} = \{+1, +1, -1, -1, +1, +1, -1, -1, -1, +1, +1, -1, -1, +1, +1, +1\};$
 $\mathbf{s}_{12} = \{+1, -1, -1, +1, +1, -1, -1, +1, -1, +1, +1, -1, -1, +1, +1, -1\};$
 $\mathbf{s}_{13} = \{+1, +1, +1, +1, -1, -1, -1, -1, -1, -1, +1, +1, +1, +1, +1\};$
 $\mathbf{s}_{14} = \{+1, -1, +1, -1, -1, +1, -1, +1, -1, +1, -1, +1, +1, -1, +1, -1\};$
 $\mathbf{s}_{15} = \{+1, +1, -1, -1, -1, +1, +1, -1, -1, +1, +1, +1, +1, +1, -1, -1\};$ and
 $\mathbf{s}_{16} = \{+1, -1, -1, +1, -1, +1, +1, -1, -1, +1, +1, +1, -1, -1, +1, +1\}.$

25

The squared Euclidean distance between two distinct codewords is defined as:

$$d_{l,m}^2 = \sum_{j=1}^p (s_{l,j} - s_{m,j})^2$$

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For orthogonal modulation vectors:

$$d_{l,m}^2 = 2p, \text{ for } l \neq m.$$

For the above example in which $p=16$, the minimum squared Euclidean distance is thus 32.

5 As is well-known by those skilled in the art, an orthogonal modulation code is conventionally used in communications systems, as an orthogonally modulated signal may be demodulated in a noncoherent fashion, i.e., decision statistics for received symbols can be derived without knowing the phase of the received signal. For example, when a convolutional code with minimum 10 Hamming distance d_{\min} is followed by a long interleaver and then orthogonally modulated according to an orthogonal modulation code as described above with distance $2p$ and rate $1/4$, the overall squared Euclidean distance is $2pd_{\min}$. The rate of the concatenation of the convolutional code and the 15 orthogonal modulation code in bits/chip is $1/4 * 1/n$ where $1/n$ is the rate of the convolutional code, e.g., for a rate $1/2$ convolutional code, the overall rate becomes $1/8$.

Increasing the size of the modulation signal set is generally desirable because using a larger modulation code set can increase the rate of communication without substantially increasing the likelihood of a decoder 20 error or substantially degrading reliability, thus enabling the use of lower rate convolutional codes. Thus, performance of a coding scheme can be adjusted by varying the size of the signal set used for modulation and varying the rate of the convolutional code such that the overall rate of communications is the same as that provided by a conventional combination of a convolutional 25 encoder and an orthogonal modulator. However, although a larger modulation signal set can be created including complementary codes, i.e., codes which are negatives of one another, these codes produce signals representing 180 degree phase shifts from one another, and thus produce signals which are not amenable to noncoherent demodulation. For this 30 reason, it generally is preferable to use a proper subset of modulation vectors such that none of the modulation vectors has a complement within the

subset.

According to the present invention, the original orthogonal code set is expanded by adding selected translates of the original orthogonal vectors to the modulation code set. For the example given above, the orthogonal signal set for 16 vectors can be expanded to 128 vectors by using the following 5 translation vectors which produce a subcode of the length 16 Nordstrom-Robinson code:

$$b_1 = \{+1, +1, +1, +1, +1, +1, +1, +1, +1, +1, +1, +1, +1, +1, +1, +1\};$$

$$b_2 = \{+1, +1, +1, -1, +1, +1, +1, -1, +1, +1, -1, -1, +1, -1, +1, -1\};$$

$$b_3 = \{+1, +1, +1, +1, +1, -1, -1, +1, +1, +1, -1, -1, +1, -1, +1, -1\};$$

$$b_4 = \{+1, +1, +1, -1, +1, +1, -1, +1, +1, +1, -1, +1, +1, -1, -1, -1\};$$

$$b_5 = \{+1, +1, +1, +1, +1, +1, -1, -1, +1, -1, +1, -1, -1, +1, +1, -1\};$$

$$b_6 = \{+1, +1, +1, -1, +1, -1, -1, +1, -1, -1, -1, -1, -1, -1, +1\};$$

$$b_7 = \{+1, +1, +1, +1, +1, -1, +1, -1, +1, -1, +1, +1, +1, -1, -1\}; \text{ and}$$

$$b_8 = \{+1, +1, +1, -1, +1, -1, +1, +1, +1, +1, +1, -1, +1, -1, -1\}.$$

The new code includes all vectors of the form:

$$(s_{l,1}b_{m,1}, s_{l,2}b_{m,2}, \dots, s_{l,16}b_{m,16})$$

for $l=1, \dots, 16$ and $m=1, \dots, 8$, i.e., $16*8=128$ code words. Those skilled in the

art will appreciate that this construction is not unique, and that there may be other possible vectors b_1, \dots, b_8 that will give an equivalent or identical code.

To allow for noncoherent demodulation, a subset (or subcode) is preferably selected for use in nonorthogonal modulation such that no two vectors of the nonorthogonal modulation code produce antipodal signals. The number of vectors can be further expanded from 128 to 1024, producing a new code which is a subset of the linear Reed-Muller code of length 16 and rate 11/16. Removing complements, a subset of this code is produced having a rate of 10/16. The Nordstrom-Robinson code of length 16 can also be generalized to lengths that are even powers of two (e.g. 64, 256) to produce codes known as Kerdock codes.

Relationships between the orthogonal codes and these expanded nonorthogonal codes can be summarized as follows:

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BO(5,16) ⊂ NR(8,16) ⊂ RM(11,16) ⊂ RM(15,16)

and

O(4,16) ⊂ NR*(7,16) ⊂ RM*(10,16) ⊂ RM*(14,16).

5 BO(5,16) represents a biorthogonal code, i.e. an orthogonal code including complementary code words, having a code of length 16 and including 2^5 codewords, found by taking the 16 vectors s_1-s_{16} listed above and adding the negatives of each vector to produce 32 vectors. NR(8,16) code represents the standard Nordstrom-Robinson code of length 16, which

10 includes 2^8 vectors and produced by taking the 32 vectors from the biorthogonal code BO(5,16) and adding translates corresponding to the eight translation vectors listed above. RM(11,16) represents the Reed-Muller code of length 16 with 2^{11} codewords. The RM(15,16) code is the Reed-Muller code of length 16 with 2^{15} codewords. As the number of codewords in the

15 code increases, the code distance decreases, i.e., code BO(5,16) has distance 8, code NR(8,16) has distance 6, code RM(11,16) has distance 4, and code RM(15,16) code has distance 2.

Because noncoherent demodulation is preferred, however, subsets of these various codes are preferably used. Half of the codewords are removed

20 from the sets such that no two codewords produce antipodal signals. This reduces the number of codes in the sets and reduces the rate of transmission, but does not change the minimum distance between codewords. Thus, the orthogonal code O(4,16) represents half of the biorthogonal code B(5,16), i.e., the 16 vectors s_1-s_{16} listed above. Similarly,

25 the code NR*(7,16) is a subset of the Nordstrom-Robinson code NR(8,16), the RM*(10,16) is a subset of the RM(11,16) code, and the RM*(14,16) code is a subset of the RM(15,16) code.

According to the present invention, the use of a selectively expanded modulation signal set allows the use of a lower rate convolutional code, thus

30 providing greater error protection. For example, replacing the original combination of an orthogonal code set O(4,16) having the rate 1/4 and a rate 1/2 convolutional code, with the nonorthogonal Nordstrom-Robinson code set NR*(7,16) having a rate 7/16 and a lower rate convolutional code with rate

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$2/7$, can be used to produce the same overall code rate of $(2/7) * (7/16) = 1/8$.

The squared Euclidean distance associated with the Nordstrom-Robinson code NR*(7,16) is $6*4=24$, compared to the squared Euclidean distance $8*4=32$ of the original orthogonal code O(4,16). The punctured convolutional

5 code with rate $2/7$ and memory 4 has distance 13 compared to the original rate 1/2 code with distance 7. Thus, assuming sufficient interleaving, the new combination of codes has distance $24*13=312$, compared to the old scheme with distance $32*7=224$, corresponding to a 1.44dB gain in additive white Gaussian noise at high signal-to-noise ratio.

10 Tables 1 and 2 illustrate the effect of expanding the modulation code set and modifying the convolutional code as described above for codes of length 16 and 64, respectively:

Table 1

Modulation Code			Convolutional Code			Overall		
Length	Rate	Distance/4	Memory	Rate	Distance	Overall Rate	Overall Distance	
15	16	4/16	8	4	1/2	7	1/8	56
	16	7/16	6	4	2/7	13	1/8	78
	16	10/16	4	4	1/5	20	1/8	80
	16	14/16	2	4	1/7	28	1/8	56
20	16	4/16	8	5	1/2	8	1/8	64
	16	7/16	6	5	2/7	16	1/8	96
	16	10/16	4	5	1/5	22	1/8	88
	16	14/16	2	5	1/7	32	1/8	64
25	16	4/16	8	6	1/2	10	1/8	80
	16	7/16	6	6	2/7	16	1/8	96
	16	10/16	4	6	1/5	25	1/8	100
	16	14/16	2	6	1/7	36	1/8	72
30	16	4/16	8	7	1/2	10	1/8	80
	16	7/16	6	7	2/7	19	1/8	114
	16	10/16	4	7	1/5	28	1/8	112
	16	14/16	2	7	1/7	40	1/8	80

Table 2

Modulation Code			Convolutional Code			Overall		
Length	Rate	Distance/4	Memory	Rate	Distance	Overall Rate	Overall Distance	
5	64	6/64	32	4	1/3	12	1/32	384
	64	11/64	28	4	2/11	21	1/32	588
	64	6/64	32	5	1/3	13	1/32	416
	64	11/64	28	5	2/11	24	1/32	672
10	64	6/64	32	6	1/3	15	1/32	480
	64	11/64	28	6	2/11	28	1/32	784
	64	6/64	32	7	1/3	16	1/32	512
	64	11/64	28	7	2/11	31	1/32	868

For the length 16 modulation vectors shown in Table 1, assuming additive white Gaussian noise, a rate 2/7 convolutional code of memory 7 combined with a (7,16) Nordstrom-Robinson code produces a coding gain of 1.54dB over orthogonal modulation with a rate 1/2 convolutional code. For the length 64 modulation vectors shown in Table 2, a rate 2/11 convolutional code of memory 7 combined with a (11, 64) Kerdock code produces a performance gain estimated at $10 \log_{10} (4*868/4*512) = 2.3$ dB over orthogonal modulation with a rate 1/3 convolutional code.

A demodulator for demodulating the nonorthogonally modulated communications signal can be implemented by augmentation of a receiver used for orthogonally modulated signals. Assuming the preferred noncoherent demodulation, the demodulator processes the received signal by first applying a noncoherent matched filter to each chip of the modulation, and then performing a fast Haddamard transform to obtain decision statistics for the orthogonal vector subset, e.g., s_1-s_{16} , of the nonorthogonal modulation code. Decision statistics for the other vectors in the modulation code may be obtained by translating the received vector and then performing a fast Haddamard transform to produce decision statistics corresponding to each vector translation. Decision information about a symbol can then be obtained by comparing the decision statistics from each subset.

Implementation

Referring now to Figure 2, in a communications system 200 according to the present invention, information 205 is processed by information processing means 210 to produce a plurality of information symbols 215.

- 5 Error correction encoding means 220 encode the plurality of information symbols 215 according to an error correction code to produce a plurality of error-correction encoded symbols 225. Nonorthogonal modulating means 240 modulate error correction encoded symbols, preferably interleaved error correction encodes symbols 235 interleaved by interleaving means 230,
- 10 according to a nonorthogonal modulation code to produce a modulated communications signal 245. The modulated communications signal 245 is communicated over a communications medium by communications signal communicating means 250. The communicated modulated communications signal 250 is processed by communications signal processing means 260 to
- 15 produce information 265.

As illustrated in Figure 3, the error correction encoding means 220 preferably includes a convolutional encoder 222 which encodes the plurality of information symbols 215 according to a convolutional code, which may in turn may be followed by puncturing means 224, e.g., a puncture table or the like, which punctures the output of the convolutional encoder 222 to produce a desired rate for the error-correction encoding means 220. Those skilled in the art will appreciate, however, that other error correcting codes, such as block codes, may be used with the present invention.

- 20 Interleaved error correction encoded symbols 235 produced by interleaving means 230 are modulated in a nonorthogonal modulating means 240, preferably using a nonorthogonal modulation code or signal set 242 which is a proper subset of one of a Nordstrom-Robinson code, a Reed Muller code and a Kerdock code, more preferably a subset which includes only one of each complementary pair of vectors, i.e., vectors which produce antipodal signals. The modulated communications signal 245 thereby produced is then communicated over a communications medium by communications signal communicating means 250. Communications signal processing means 260 preferably includes a noncoherent demodulating
- 25
- 30

means 262 for noncoherently demodulating the communicated modulated communications signal 255 to produce demodulated communications symbols 261. The demodulated communications symbols 261 may then deinterleaved by deinterleaving means 264 and convolutionally decoded in a convolutional 5 decoder 266, for example, a Viterbi algorithm, to produce information symbols 263 which may be further processed to recover information 265.

Those skilled in the art will appreciate that the elements described above may include various communications system components. It will be understood that the information processing means 210, error-correction 10 encoding means 220, interleaving means 230 and nonorthogonal modulating means 240 may include special purpose hardware, software running on general purpose computers or other data processing hardware, or combinations thereof. These elements may be implemented using, for example, commonly-used communications hardware such as amplifiers, 15 multiplexers, gate arrays or other application-specific integrated circuits (ASICs), microprocessors, digital signal processor (DSP) chips and the like, the operation of which is well-known to those skilled in the art and need not be described in greater detail herein. It will also be understood that communications signal communicating means 250 may be implemented using 20 special-purpose hardware, software running on data processors, or combinations thereof, and may include commonly used communications components such as multiplexers, mixers, amplifiers, antennas, receivers, and the like, the operation of which is well-known to those skilled in the art and need not be discussed in greater detail herein. Similarly, communications 25 signal processing means 260 may include special-purpose hardware, software running on data processors or combinations thereof, and may include such commonly-used components as amplifiers, filters, analog-to-digital converters (A/D's), ASICs, DSP chips and the like, the operation of which is well-known to those skilled in the art and need not be discussed in 30 greater detail herein.

Figure 4 illustrates means 262 for noncoherently demodulating a communications signal 255 which is modulated according to the nonorthogonal modulation scheme described above to produce information

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symbols 445 corresponding to the coded symbols 235 input into the nonorthogonal modulating means 240 of Figures 2 and 3. A noncoherent matched filter 410 is applied to the communications signal 255, and the complex output of the matched filter sampled by sampling means 420 to produce a plurality of received communications symbols 425. The received communications symbols 425 are then correlated in correlating means 430 against the vectors of the nonorthogonal modulation code by which the communications signal 255 was modulated, to produce decision information 435a-m representing the degree of correlation of received communications symbols with the code vectors of the nonorthogonal code. The decision information 435a-m is then input into a decision means 440 to produce information symbols 445, representing an estimate of the coded information symbols 235 before modulation in the nonorthogonal modulating means 240 of Figures 2 and 3. In this manner, decoding of the communications signal 255 is provided.

The correlating means 430 preferably includes a plurality of code vector translators 432a-m which translate the received communications symbols 435 according to the translation vectors used to produce the nonorthogonal modulation code employed in the nonorthogonal modulating means 240 of Figures 2 and 3, as described above. Those skilled in the art will appreciate that because these translation vectors map an orthogonal code to the nonorthogonal code such that the orthogonal code is a subset of the nonorthogonal code, one of the translators 432a-m corresponds to a unity translation and therefore in practice does not require an actual translation.

Orthogonal vector correlators 434a-m correlate the translated received communications symbols with the orthogonal subset of the nonorthogonal modulation code to produce the decision information 435a-m, for example, by computing fast Haddamard transforms for each of the translated vector outputs 433a-m using what is commonly referred to as a "Green machine" algorithm, as described in *The Theory of Error-Correcting Codes*, by F.J. MacWilliams et al., North-Holland Publishing Co., 1978, pp. 419-426.

Figure 5 illustrates operations for communicating information over a communications medium according to the present invention (Block 500).

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Information is processed to produce a plurality of information symbols (Block 510). The plurality of information symbols are encoded according to an error-correction code, preferably a convolutional code, to produce a plurality of coded symbols (Block 520). The plurality of symbols is then preferably interleaved to produce a plurality of interleaved coded symbols (Block 530).
5 The plurality of interleaved coded symbols are then modulated according to a nonorthogonal modulation code, preferably a proper subset of one of a Nordstrom-Robinson code, a Reed-Muller code or a Kerdock code from which complementary code vectors have been eliminated to allow noncoherent 10 demodulation, to produce a modulated communications signal (Block 540). The modulated communications signal is then communicated over the communications medium (Block 550). The communicated modulated communications signal is then processed, preferably by noncoherent demodulation techniques, to produce information (Block 560), e.g. coded 15 symbol likelihoods. These likelihoods may be deinterleaved and further decoded.

Those skilled in the art will appreciate that variations to the above operations may be performed according to the present invention. For example, it will be understood that although convolutional encoding is preferred for the error correction encoding operation (Block 520), other types 20 of error correction coding, for example, block coding, may be used in lieu of convolutional coding. It will also be understood that although the interleaving operation (Block 530) is preferred, the present invention may be performed without interleaving. Similarly, although using a proper subset of one of the 25 aforementioned nonorthogonal codes in which complementary code vectors have been eliminated is preferred in order to enable less complex noncoherent demodulation techniques. It is not required to obtain the benefits of the present invention.

In the drawings and specification, there have been disclosed typical 30 embodiments of the invention and, although specific terms are employed, they are used in a generic and descriptive sense only and not for purposes of limitation, the scope of the invention being set forth in the following claims.

The embodiments of the invention in which an exclusive property or privilege is claimed are defined as follows:

1. A method of producing a communications signal, the method comprising the steps of:
encoding a plurality of information symbols according to a concatenation of an error correction code and a nonorthogonal modulation code to produce a modulated communications signal, wherein the nonorthogonal modulation code represents a union of translations of an orthogonal code.
2. A method according to claim 1, wherein said step of encoding comprises the steps of:
encoding the plurality of information symbols according to the error correction code to produce a plurality of coded symbols; and
modulating the plurality of coded symbols according to the nonorthogonal modulation code to produce the modulated communications signal.
3. A method according to claim 2, wherein said step of modulating comprises the step of modulating the plurality of coded symbols according to the nonorthogonal modulation code representing a translation of a set of orthogonal code vectors according to a predetermined translation which produces one of a Nordstrom-Robinson code, a Reed-Muller code, or a Kerdock code.
4. A method according to claim 2, wherein said step of modulating comprises the step of modulating the plurality of coded symbols according to one of a Nordstrom-Robinson code, a Reed-Muller code, or a Kerdock code.
5. A method according to claim 2, wherein said step of modulating comprises the step of modulating the plurality of coded symbols according to a proper subset of the nonorthogonal modulation code.
6. A method according to claim 1, wherein said step of encoding comprises the step of encoding the plurality of information symbols according to a

concatenation of a convolutional code and the nonorthogonal modulation code to produce the modulated communications signal.

7. A method according to claim 6, wherein said step of encoding comprises the step of encoding the plurality of information symbols according to a concatenation of a punctured convolutional code and the nonorthogonal modulation code to produce the modulated communications signal.

8. A method according to claim 2, wherein said step of modulating is preceded by the step of interleaving the plurality of coded symbols to produce a plurality of interleaved coded symbols, and wherein said step of modulating comprises the step of modulating the plurality of interleaved coded symbols to produce the modulated communications signal.

9. A method according to claim 2, further comprising the steps of:
communicating the modulated communications signal over a communications medium; and
processing the communicated modulated communications signal to produce information.

10. A method according to claim 9:
wherein said step of modulating comprises the step of modulating the plurality of coded symbols according to a proper subset of the nonorthogonal modulation code, the proper subset being operable to produce the modulated communications signal from a signal set such that the communications signal noncoherently demodulates to produce a respective unique output for a respective signal in the signal set; and
wherein said step of processing the communicated modulated communications signal comprises the step of noncoherently demodulating the communicated modulated communications signal.

11. A method according to claim 10:

wherein said step of modulating comprises the step of modulating the plurality of coded symbols according to the nonorthogonal modulation code representing a union of translations of a set of orthogonal code vectors according to a predetermined set of translation vectors which produces one of a Nordstrom-Robinson code, a Reed-Muller code, or a Kerdock code, the translation including a plurality of translation vectors; and

wherein said step of noncoherently demodulating comprises the steps of:
processing the communicated modulated communications signal to produce a plurality of received communications symbols;
translating the plurality of received communications symbols according to the translation vectors to produce a plurality of groups of communications symbols, a respective group corresponding to a respective one of the translation vectors;
correlating each group of communications symbols with the set of orthogonal code vectors to produce decision information for each group;
and
combining the decision information for the groups of communications symbols to produce a plurality of information symbols.

12. An apparatus for producing a communications signal, the apparatus comprising:
an encoder operative to encode a plurality of information symbols according to a concatenation of an error correction code and a nonorthogonal modulation code to produce a modulated communications signal, wherein the nonorthogonal modulation code represents a union of translations of an orthogonal code.
13. An apparatus according to claim 12, wherein said encoder comprises:
error correction encoding means for encoding the plurality of information symbols according to the error correction code to produce a plurality of coded symbols; and
nonorthogonal modulating means, responsive to said error correction encoding means, for modulating the plurality of coded symbols according to the

nonorthogonal modulation code to produce the modulated communications signal.

14. An apparatus according to claim 13, wherein said nonorthogonal modulating means comprises means for modulating the plurality of coded symbols according to the nonorthogonal modulation code representing a translation of a set of orthogonal code vectors according to a predetermined translation which produces one of a Nordstrom-Robinson code, a Reed-Muller code, or a Kerdock code.

15. An apparatus according to claim 13, wherein said nonorthogonal modulating means comprises means for modulating the plurality of coded symbols according to one of a Nordstrom-Robinson code, a Reed-Muller code, or a Kerdock code.

16. An apparatus according to claim 13, wherein said nonorthogonal modulating means comprises means for modulating the plurality of coded symbols according to a proper subset of the nonorthogonal modulation code.

17. An apparatus according to claim 12, wherein said encoder comprises means for encoding the plurality of information symbols according to a concatenation of a convolutional code and the nonorthogonal modulation code to produce the modulated communications signal.

18. An apparatus according to claim 17, wherein said means, for encoding the plurality of information symbols according to the concatenation of the convolutional code and the nonorthogonal modulation code, comprises means for encoding the plurality of information symbols according to a concatenation of a punctured convolutional code and the nonorthogonal modulation code to produce the modulated communications signal.

19. An apparatus according to claim 13, further comprising interleaving means, responsive to said error correction encoding means, for interleaving the

plurality of coded symbols to produce a plurality of interleaved coded symbols, and wherein said nonorthogonal modulating means comprises means for modulating the plurality of interleaved coded symbols to produce the modulated communications signal.

20. An apparatus according to claim 13, further comprising:

communications signal communicating means, responsive to said means for encoding the plurality of information symbols according to a concatenation of the error correction code and the nonorthogonal modulation code, for communicating the modulated communications signal over the communications medium; and

communications signal processing means, responsive to said communications signal communicating means, for processing the communicated modulated communications signal to produce information.

21. An apparatus according to claim 19 or 20:

wherein said nonorthogonal modulating means comprises means for modulating the plurality of coded symbols according to a proper subset of the nonorthogonal modulation code, the proper subset being operable to produce the modulated communications signal from a signal set such that the communications signal noncoherently demodulates to produce a unique output for each signal in the signal set; and

wherein said communications signal processing means comprises noncoherent demodulating means for noncoherently demodulating the communicated modulated communications signal.

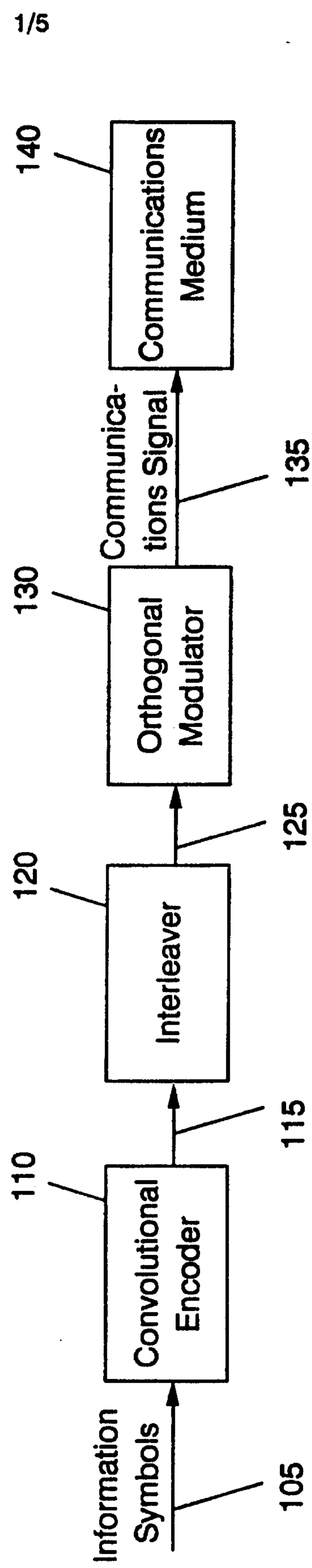
22. An apparatus according to claim 21:

wherein said nonorthogonal modulating means comprises means for modulating the plurality of coded symbols according to the nonorthogonal modulation code representing a union of translations of a set of orthogonal code vectors according to a predetermined set of translation vectors which produces one of a Nordstrom-Robinson code, a Reed-Muller code, or a Kerdock code, the translation including a plurality of translation vectors; and

wherein said noncoherent demodulating means comprises:

means for processing the communicated modulated communications signal to produce a plurality of received communications symbols; means, responsive to said means for processing the communicated modulated communications signal to produce the plurality of received communications symbols, for translating the plurality of received communications symbols according to the translation vectors to produce a plurality of groups of communications symbols, a respective group corresponding to a respective one of the translation vectors; means, responsive to said means for translating, for correlating each group of communications symbols with the set of orthogonal code vectors to produce decision information for each group; and means, responsive to said means for correlating, for combining the decision information for the groups of communications symbols to produce a plurality of information symbols.

FIG. 1
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FIG. 2

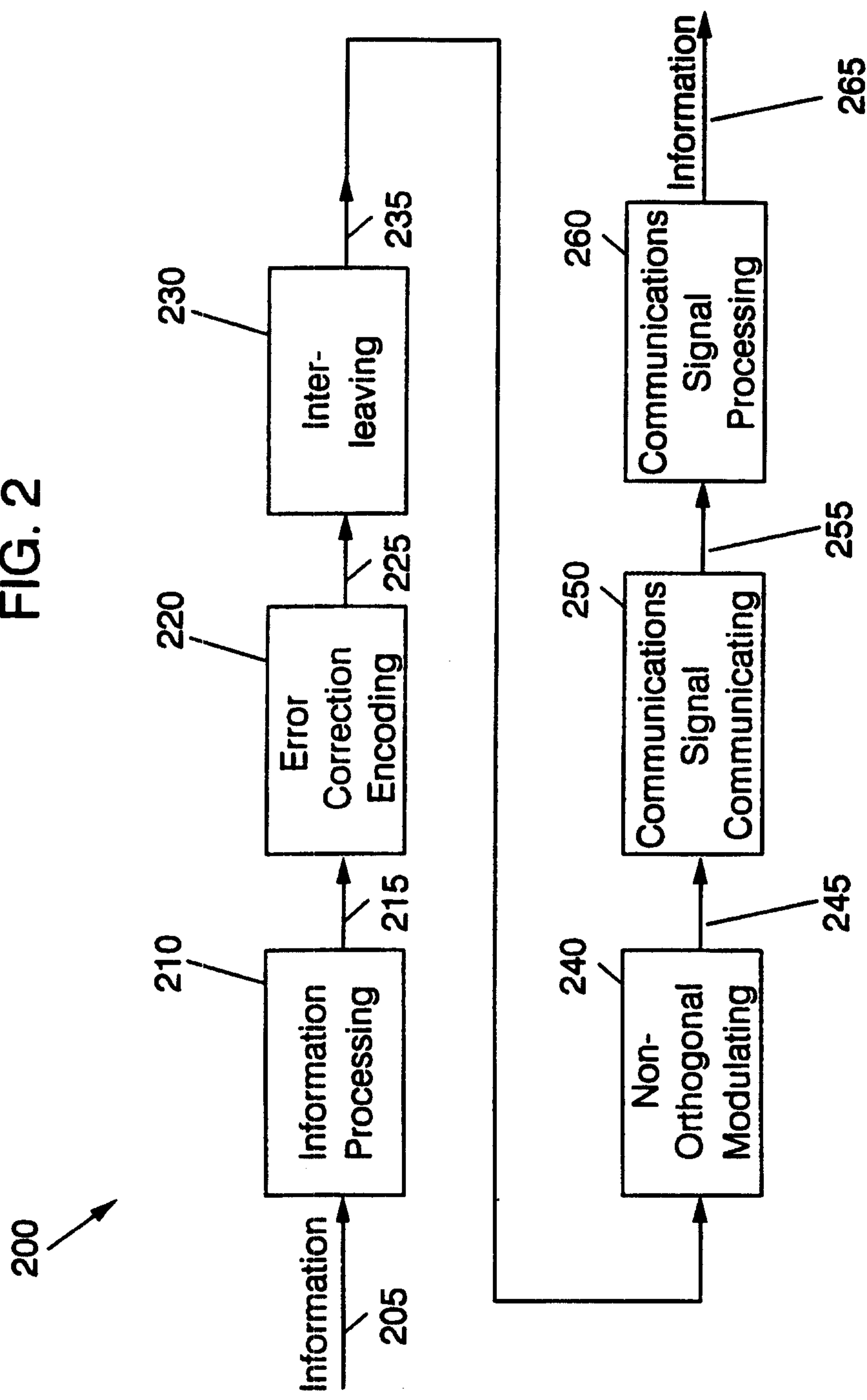
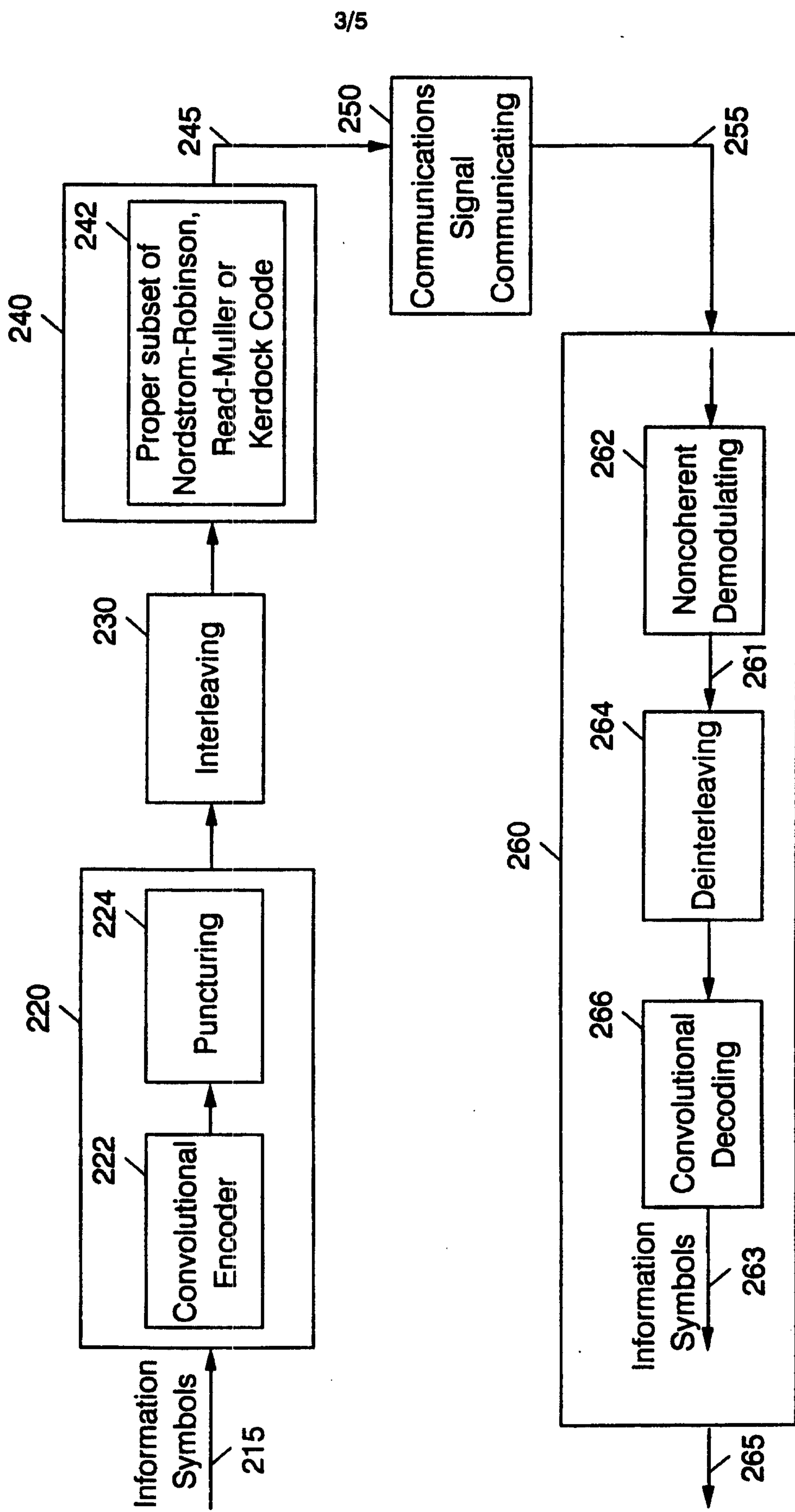


FIG. 3



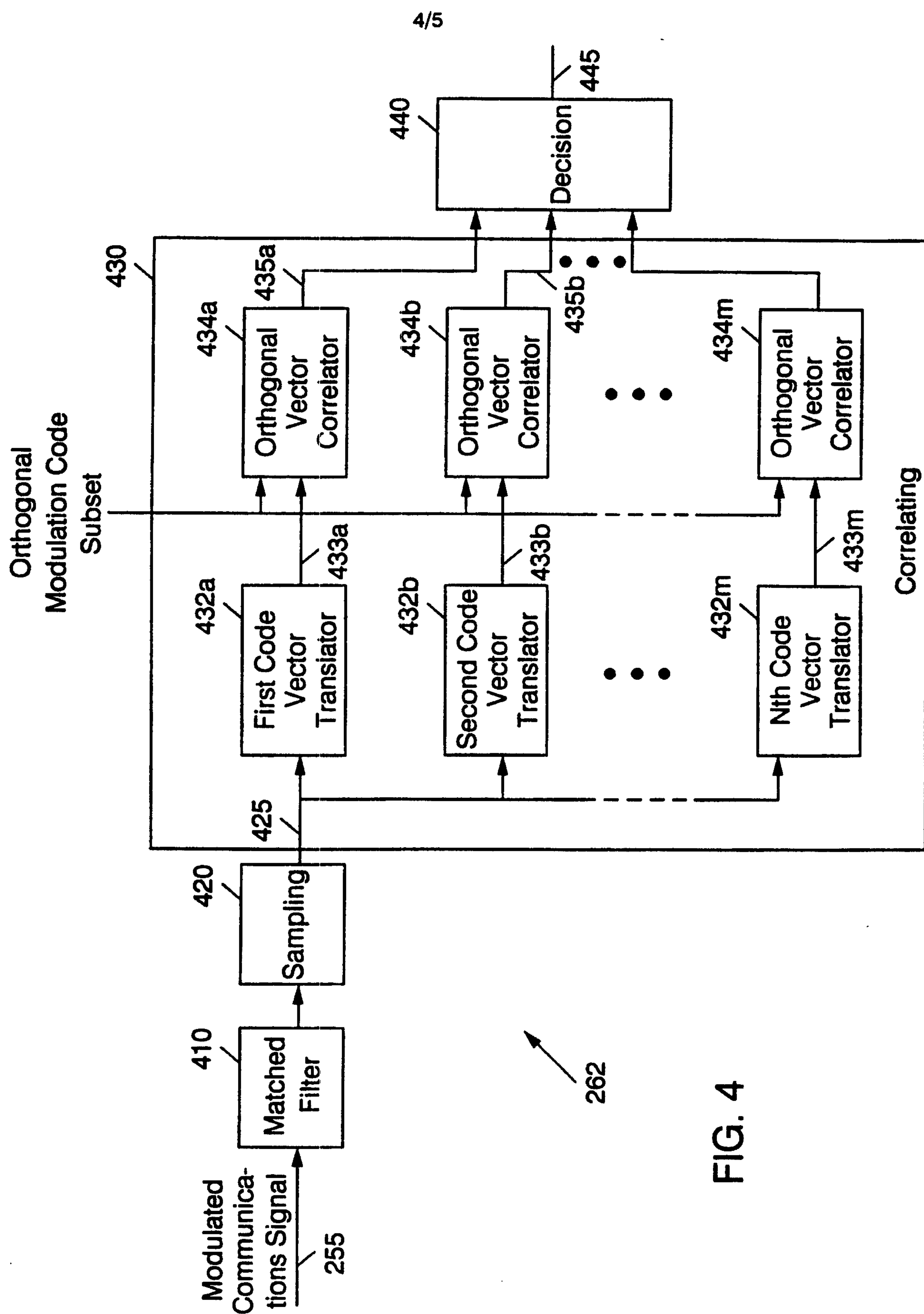


FIG. 4

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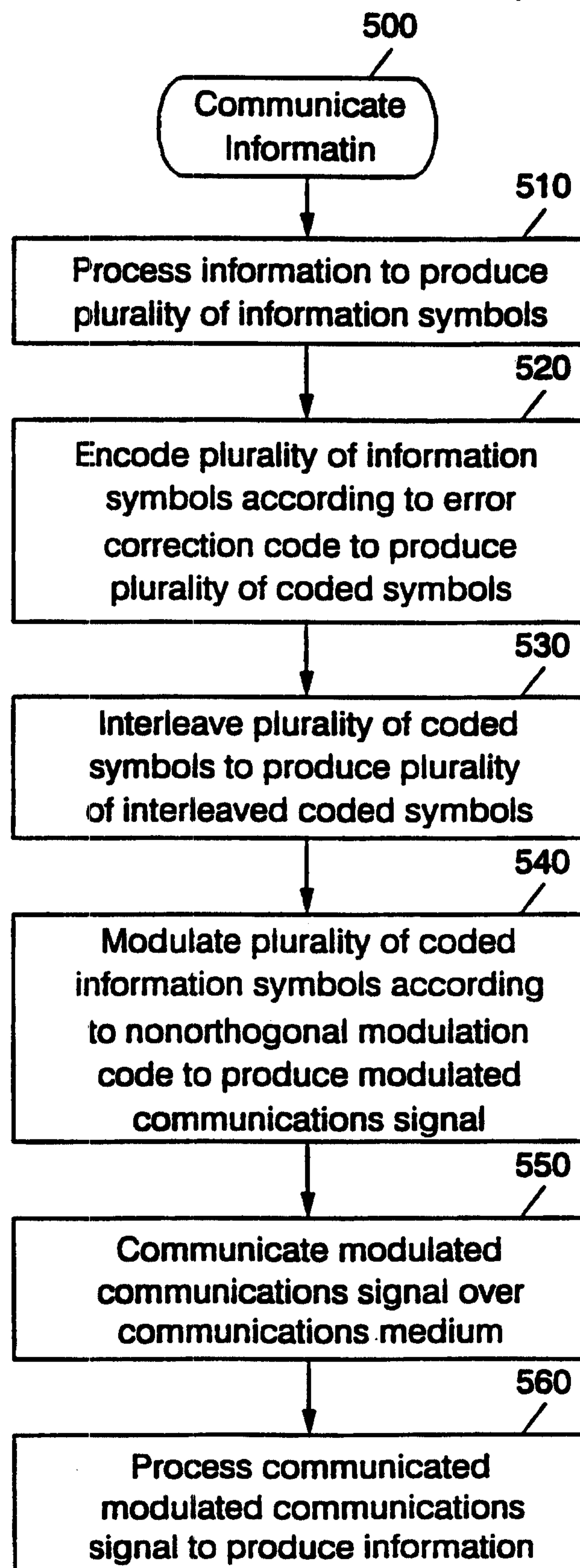


FIG. 5

