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(54) **APPARATUS AND METHODS FOR PROVIDING EFFICIENT SPACE-TIME STRUCTURES FOR PREAMBLES, PILOTS AND DATA FOR MULTI-INPUT, MULTI-OUTPUT COMMUNICATIONS SYSTEMS**

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(51) **Int. Cl.**

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H04B 7/02	(2006.01)
H04J 11/00	(2006.01)

(52) **U.S. Cl.** **375/260**; 375/267; 375/299; 370/208

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See application file for complete search history.

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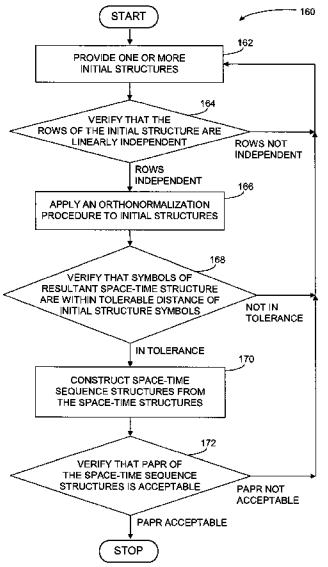
(57) **ABSTRACT**

Apparatus and methods for providing efficient space-time structures for preambles, pilots and data for multi-input, multi-output (MIMO) communications systems are provided. One such embodiment includes providing a computer program that includes logic configured to provide an initial structure. The computer program further includes logic configured to verify that the rows of the initial structure are linearly independent and logic configured to apply an orthonormalization procedure to the initial structure to obtain a space-time structure. Methods are also provided for providing efficient space-time structures for preambles, pilots and data for MIMO communications systems.

35 Claims, 7 Drawing Sheets



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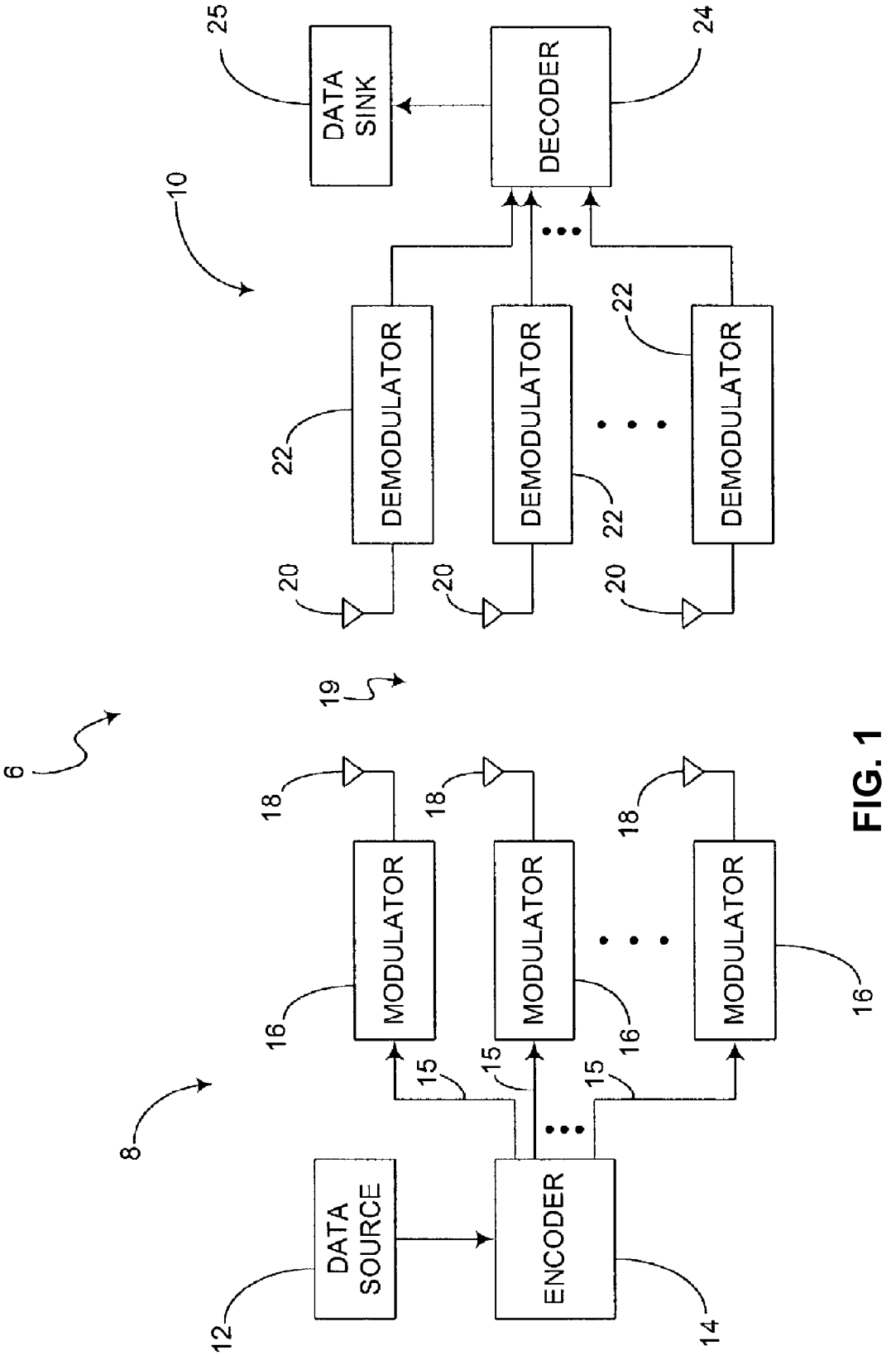
DATA SOURCE
ENCODER
MODULATOR
DEMODULATOR
DECODER
DATA SINK
6
8
10
12
14
15
16
18
19
20
22
24
25

FIG. 1

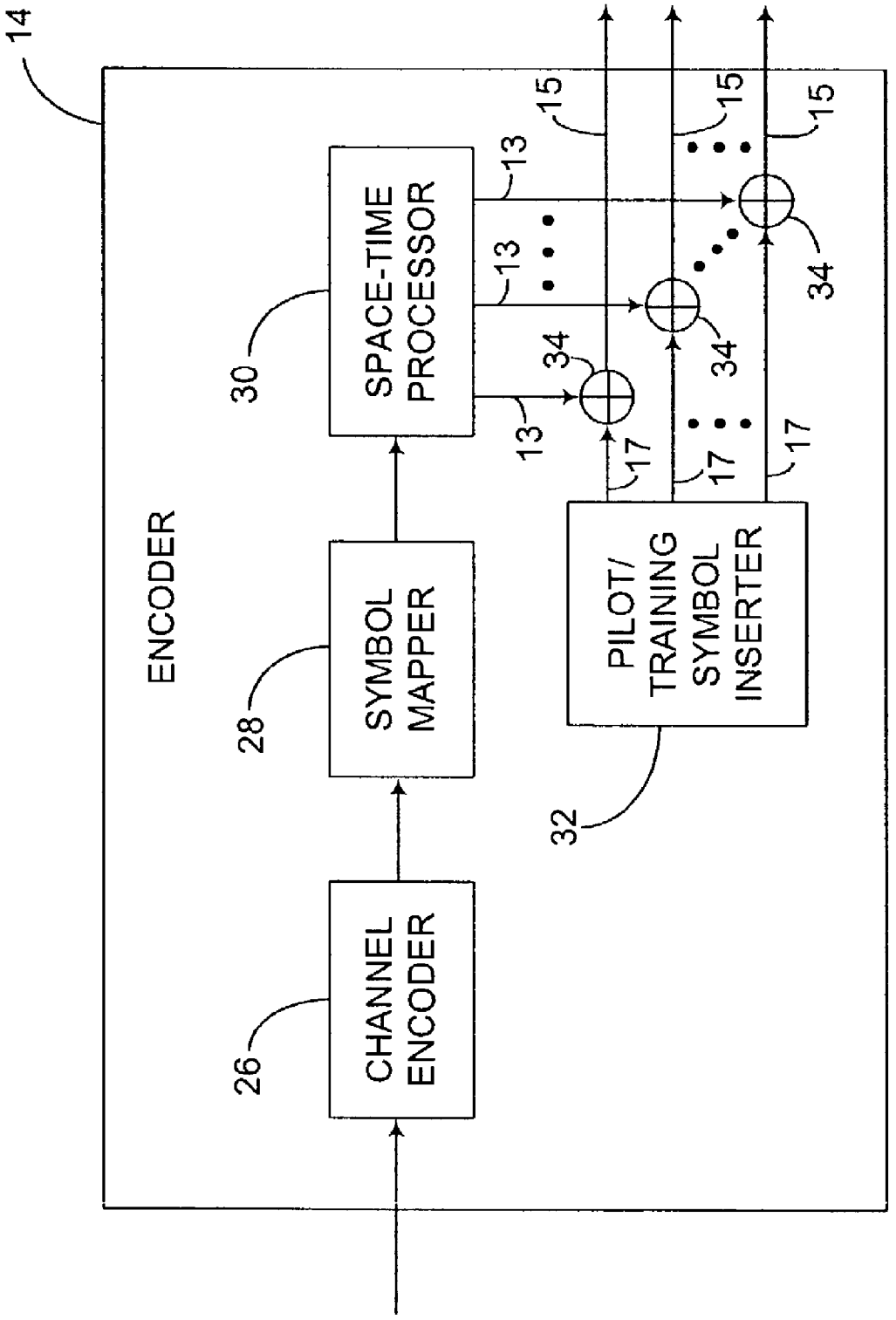
14
ENCODER
CHANNEL ENCODER
26
SYMBOL MAPPER
28
SPACE-TIME PROCESSOR
30
PILOT/ TRAINING SYMBOL INSERTER
32
13
15
17
34

FIG. 2

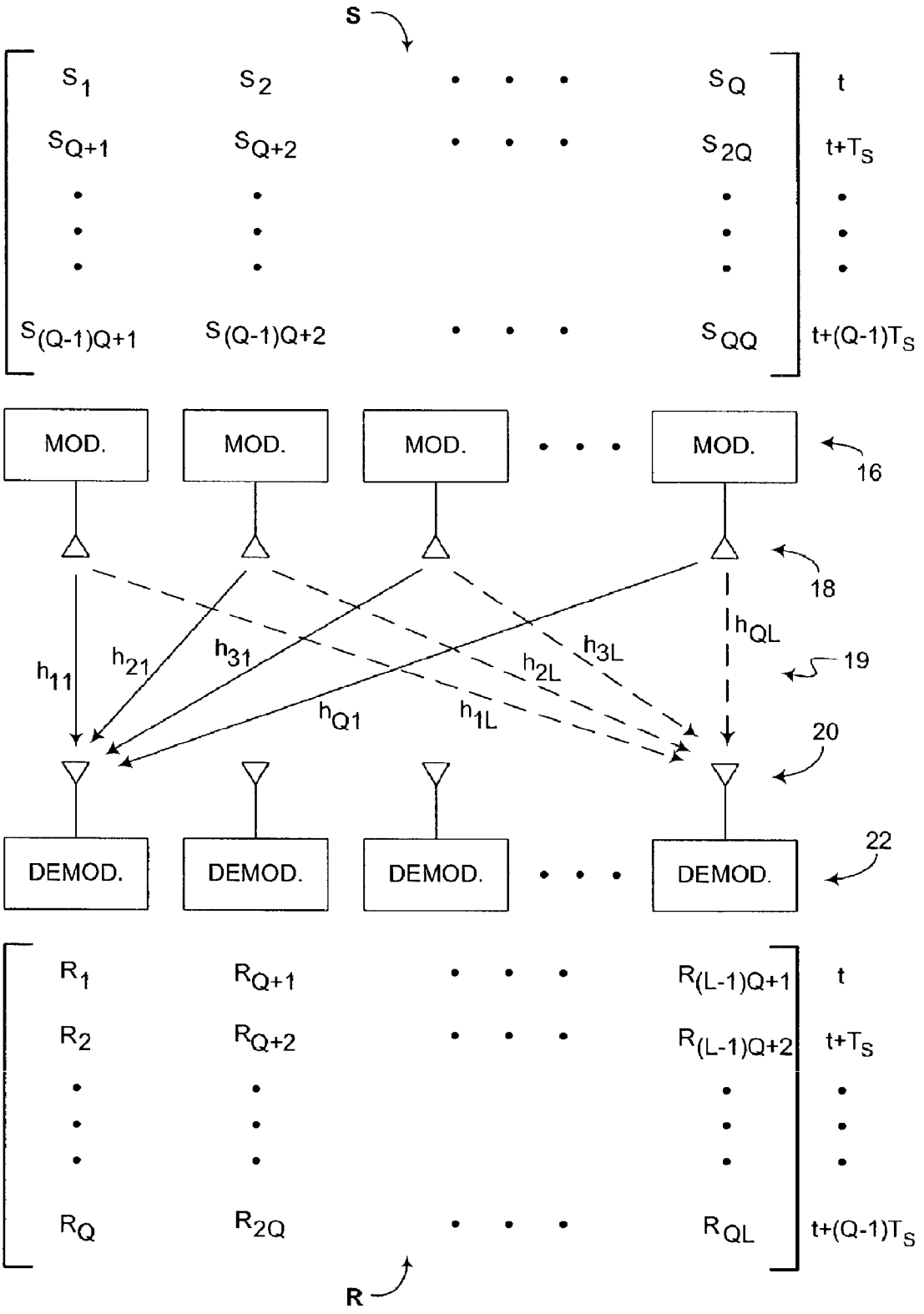
S
S_1 S_2 S_Q t
S_{Q+1} S_{Q+2} S_{2Q} $t+T_S$
$S_{(Q-1)Q+1}$ $S_{(Q-1)Q+2}$ S_{QQ} $t+(Q-1)T_S$
MOD.
MOD.
MOD.
MOD.
16
18
h_{11}
h_{21}
h_{31}
h_{Q1}
h_{1L}
h_{2L}
h_{3L}
h_{QL}
19
20
DEMOD.
DEMOD.
DEMOD.
DEMOD.
22
R_1 R_{Q+1} $R_{(L-1)Q+1}$ t
R_2 R_{Q+2} $R_{(L-1)Q+2}$ $t+T_S$
R_Q R_{2Q} R_{QL} $t+(Q-1)T_S$
R

FIG. 3

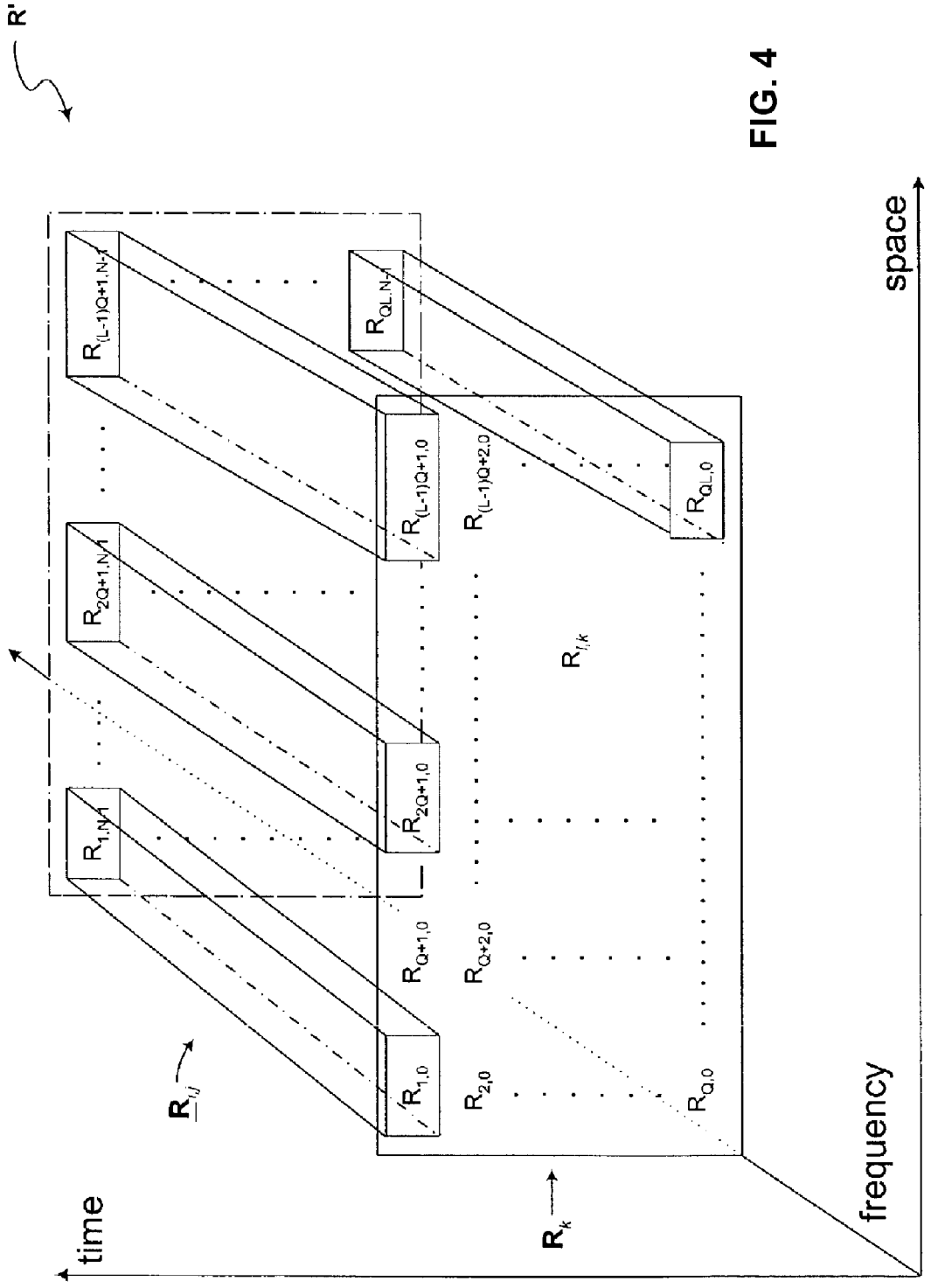
R'
time
frequency
space
$R_{i,j}$
R_k
$R_{1,N-1}$
$R_{2Q+1,N-1}$
$R_{(L-1)Q+1,N-1}$
$R_{QL,N-1}$
$R_{1,0}$
$R_{2Q+1,0}$
$R_{(L-1)Q+1,0}$
$R_{QL,0}$
$R_{Q+1,0}$
$R_{Q+2,0}$
$R_{2,0}$
$R_{Q,0}$
$R_{(L-1)Q+2,0}$
$R_{i,k}$

FIG. 4

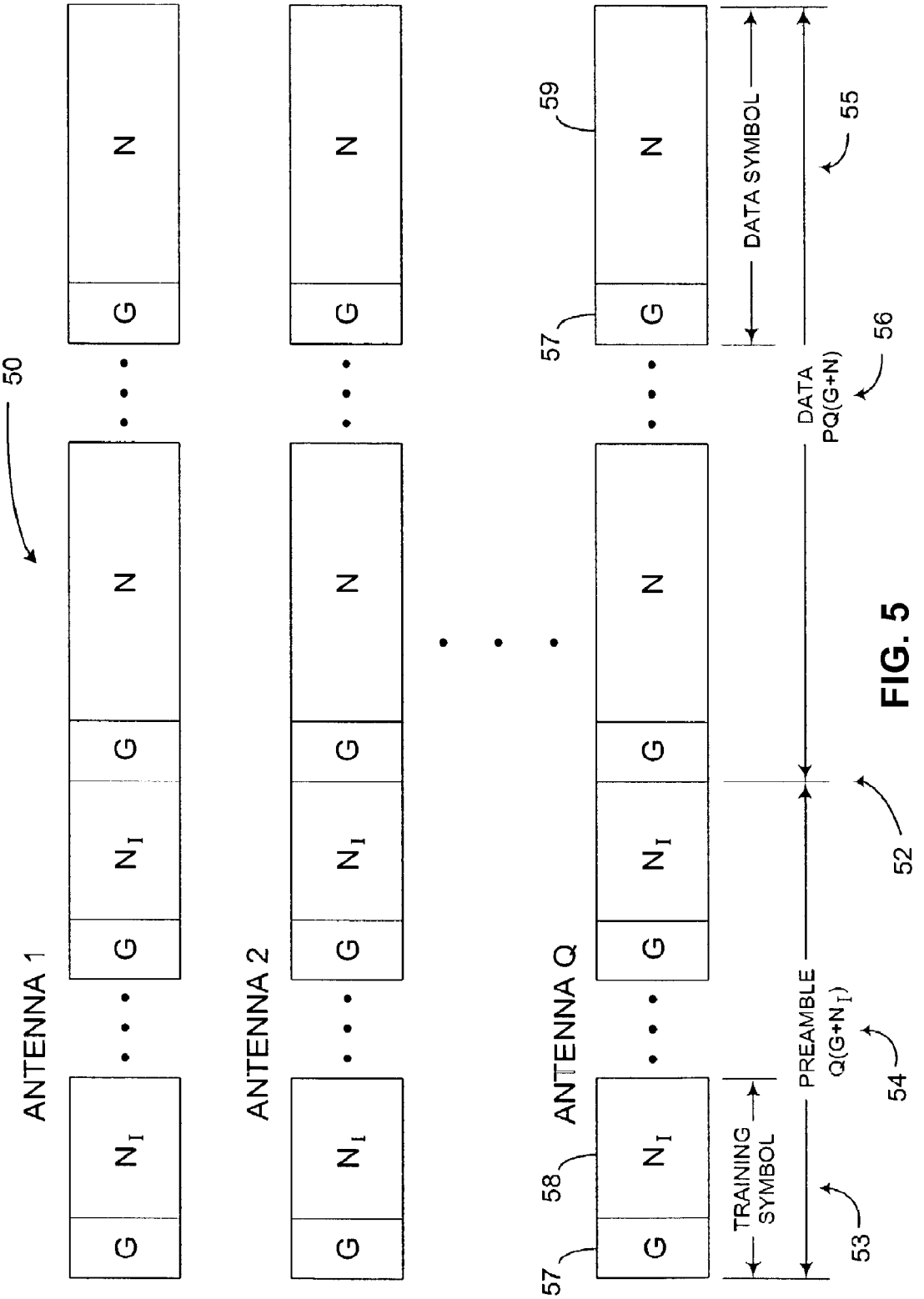
50
ANTENNA 1
ANTENNA 2
ANTENNA Q
G
N
N_I
52
53
54
55
56
57
58
59
TRAINING SYMBOL
PREAMBLE
$Q(G+N_I)$
DATA
$PQ(G+N)$
DATA SYMBOL

FIG. 5

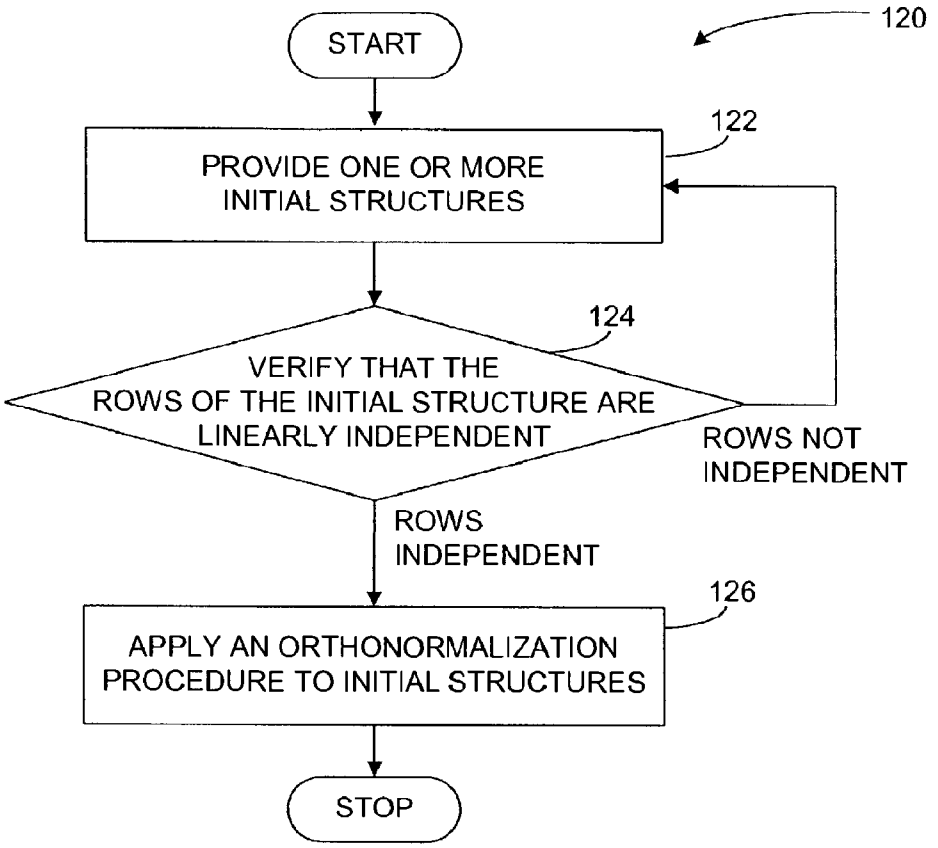
120
START
122
PROVIDE ONE OR MORE INITIAL STRUCTURES
124
VERIFY THAT THE ROWS OF THE INITIAL STRUCTURE ARE LINEARLY INDEPENDENT
ROWS NOT INDEPENDENT
ROWS INDEPENDENT
126
APPLY AN ORTHONORMALIZATION PROCEDURE TO INITIAL STRUCTURES
STOP

FIG. 6

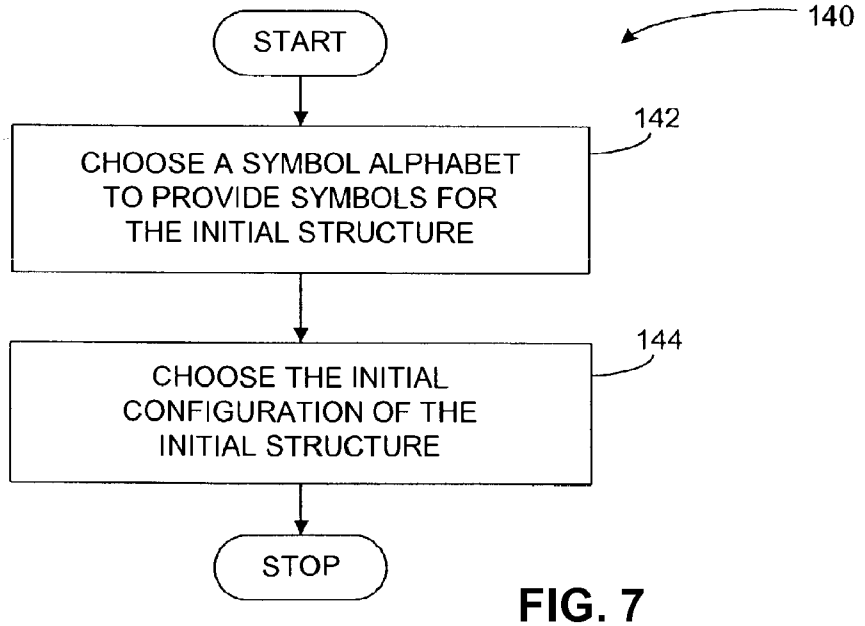
140
START
142
CHOOSE A SYMBOL ALPHABET TO PROVIDE SYMBOLS FOR THE INITIAL STRUCTURE
144
CHOOSE THE INITIAL CONFIGURATION OF THE INITIAL STRUCTURE
STOP

FIG. 7

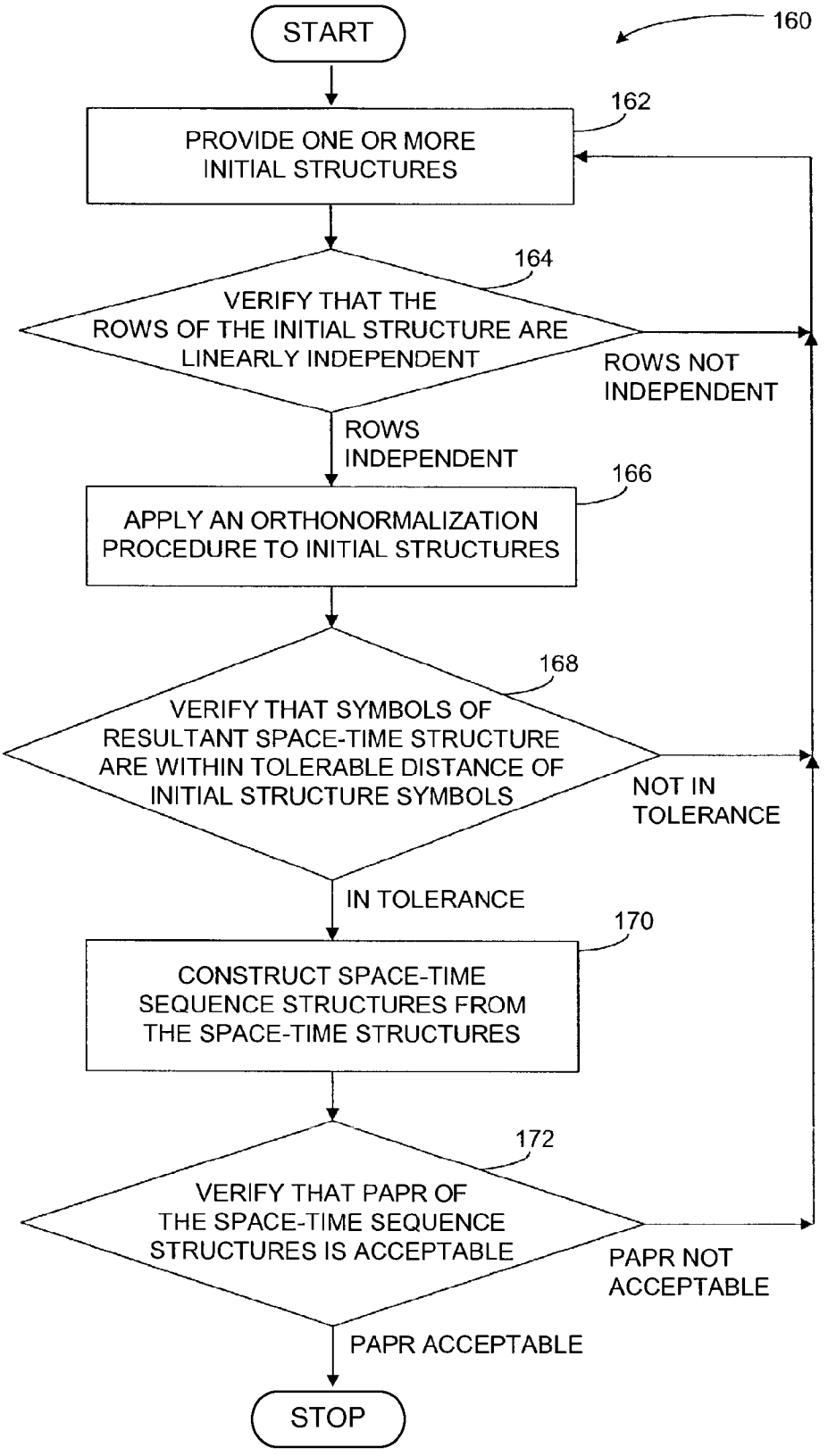
START
160
162
PROVIDE ONE OR MORE INITIAL STRUCTURES
164
VERIFY THAT THE ROWS OF THE INITIAL STRUCTURE ARE LINEARLY INDEPENDENT
ROWS NOT INDEPENDENT
ROWS INDEPENDENT
166
APPLY AN ORTHONORMALIZATION PROCEDURE TO INITIAL STRUCTURES
168
VERIFY THAT SYMBOLS OF RESULTANT SPACE-TIME STRUCTURE ARE WITHIN TOLERABLE DISTANCE OF INITIAL STRUCTURE SYMBOLS
NOT IN TOLERANCE
IN TOLERANCE
170
CONSTRUCT SPACE-TIME SEQUENCE STRUCTURES FROM THE SPACE-TIME STRUCTURES
172
VERIFY THAT PAPR OF THE SPACE-TIME SEQUENCE STRUCTURES IS ACCEPTABLE
PAPR NOT ACCEPTABLE
PAPR ACCEPTABLE
STOP

FIG. 8

APPARATUS AND METHODS FOR PROVIDING EFFICIENT SPACE-TIME STRUCTURES FOR PREAMBLES, PILOTS AND DATA FOR MULTI-INPUT, MULTI-OUTPUT COMMUNICATIONS SYSTEMS

Matter enclosed in heavy brackets [ ] appears in the original patent but forms no part of this reissue specification; matter printed in italics indicates the additions made by reissue.

CROSS-REFERENCE TO RELATED APPLICATIONS

[This application claims priority to co-pending U.S. provisional application entitled, "Efficient Training and Synchronization Sequence Structures for MIMO OFDM," having serial No. 60/322,786, filed Sep. 17, 2001, which is entirely incorporated herein by reference.]

This is a broadening Reissue application of U.S. patent application Ser. No. 10/245,090, filed Sep. 17, 2002 (now U.S. Pat. No. 7,269,224, granted Sep. 11, 2007). U.S. patent application Ser. No. 10/245,090 claims priority to U.S. Provisional Patent Application No. 60/322,786, filed on Sep. 17, 2001, and entitled "Efficient Training and Synchronization Sequence Structures for MIMO OFDM," which is entirely incorporated herein by reference.

This application is related to co-pending U.S. provisional application entitled "Preamble Structures for SISO and MIMO OFDM Systems," having Ser. No. 60/327,145, filed on Oct. 4, 2001, which is entirely incorporated herein by reference.

TECHNICAL FIELD OF THE INVENTION

The present invention is generally related to communications systems and, more particularly, to Multi-Input, Multi-Output (MIMO) communications systems.

BACKGROUND OF THE INVENTION

Significant developments in communications have been made by the introduction of technologies that increase system operating efficiency (i.e., system "throughput"). One example of these technologies is the use of two or more transmit antennas and two or more receive antennas (i.e., multiple antennas) in a wireless communications system that employs multiple frequencies (i.e., multiple carriers). Such systems are typically referred to as Multi-Input, Multi-Output (MIMO) communications systems. In contrast, traditional wireless communications systems typically employ one transmit antenna and one receive antenna operating at a single signal-carrier frequency (SC), and such systems are referred to accordingly as Single-Input, Single-Output (SISO) systems.

In the operation of MIMO communications systems, signals are typically transmitted over a common path (i.e., a channel) by multiple antennas. The signals are typically pre-processed to avoid interference from other signals in the common channel. There are several techniques that may be used to pre-process the signals in this regard, and some of these techniques may be combined to further improve system throughput. One such technique, known as Space-Time Processing (STP), processes and combines "preambles" and "data symbols" into "space-time signal structures." Wireless

communications systems typically transmit data or information (e.g., voice, video, audio, text, etc.) as formatted signals, known as data symbols (or information symbols), which are typically organized into groups, known as data frames (or information frames).

Training symbols (or preamble symbols) are another type of symbol, which are typically added as prefixes to data symbols (e.g., at the beginning of data frames), to enable training (i.e., synchronization) of the data symbols between the transmitters and receivers of a MIMO communications system. These training symbol prefixes can be referred to as preambles or preamble structures. The combination of the preambles and data symbols can be referred to as space-time signal structures. Space-time structures may also be constructed using STP for preambles and data symbols individually. Furthermore, pilot structures (or pilots) are space-time structures that are also constructed by STP and have the same structure as preambles, although they are periodically arranged within groups of data symbols for different purposes. Certain properties incorporated into space-time signal structures make it possible to recover the data symbols from them through post-processing by a receiver, for example. Moreover, the formation and processing of space-time signal structures in a wireless communications system may provide increased strength (i.e., gain) in the recovered signal, which typically enhances the performance of the communications system.

Another technique that may be used to pre-process signals in MIMO communications systems is called Frequency Division Multiplexing (FDM). FDM involves dividing the frequency spectrum of a wireless communications system into sub-channels and transmitting modulated data or information (i.e., formatted signals for voice, video, audio, text, etc.) over these sub-channels at multiple signal-carrier frequencies ("sub-carrier frequencies"). Orthogonal Frequency Division Multiplexing (OFDM) has emerged as a popular form of FDM in which the sub-carrier frequencies are spaced apart by precise frequency differences. The application of OFDM technologies in SISO communications systems (i.e., SISO OFDM systems) provides the capability, among others, to transmit and receive relatively large amounts of information. The application of OFDM in MIMO communications systems (i.e., MIMO OFDM systems) provides the added capability of increased capacity to transmit and receive information using, generally, the same amount of bandwidth (i.e., transmission line capacity) as used in SISO OFDM systems. MIMO OFDM communications systems also offer improved performance to overcome some of the difficulties experienced in other FDM communications systems, such as performance degradation due to multiple versions of a transmitted signal being received over various transmission paths (i.e., multi-path channel interference).

In wireless communications systems (e.g., SISO or MIMO), synchronization of data symbols is typically required in both time and frequency. Estimation of noise variance and channel parameters is also typically required. Thus, efficient preamble structures and pilot structures for use in wireless communications systems should provide both synchronization and parameter estimation. Furthermore, efficient preamble structures and pilot structures should possess a low peak-to-average power ratio (PAPR) (i.e., at or approaching unity) to facilitate efficient system operation. In their application to MIMO communications systems, however, existing preamble structures and pilot structures have shortcomings in their capability to provide the foregoing functions of time and frequency synchronization, estimation of noise variance and channel parameters, and low PAPR. For

example, the IEEE Standard 802.11a preamble structure includes a short sequence, which provides time synchronization and coarse frequency offset estimation, followed by a long sequence, which provides fine frequency and channel estimation. Although this preamble has direct application to SISO communications systems, it is not directly applicable to MIMO communications systems to provide the above mentioned functions, without the need for significant modifications.

Existing techniques for space-time processing of preamble symbols, pilot symbols, and data symbols into space-time structures also have shortcomings in their applications to MIMO communications systems. For example, existing space-time structures (i.e., preamble, pilot, or data) are typically limited to applications in MIMO communications systems that employ two, four, or eight transmit antennas. However, MIMO communications systems may be required that employ other numbers of transmit antennas to satisfy various applications. As another example, existing space-time structures do not support the "full diversity" performance of MIMO communications systems. That is, existing space-time structures do not support the optimal signal transmission performance that MIMO communications systems can provide. For example, a MIMO communications system that employs four transmit antennas can provide a full diversity signal transmission performance of four space-time structures over four time periods. However, typical existing space-time structures are limited to support a signal transmission performance of no better than three space-time structures over four time periods in a four-antenna MIMO system.

Therefore, there is a need for apparatus and methods for providing efficient preamble structures and pilot structures that provide time and frequency synchronization, estimation of noise variance and channel parameters, and low PAPR in their application to MIMO communications systems. Moreover, there is a need for an apparatus and methods for providing space-time structures (i.e., preamble, pilot, or data) that can be applied to MIMO communications systems with any number of transmit and receive antennas and that facilitate full diversity performance of MIMO communications systems.

SUMMARY OF THE INVENTION

The present invention provides an apparatus and methods for providing efficient space-time structures for preambles, pilots and data for multi-input, multi-output (MIMO) communications systems.

Briefly described, one embodiment of the present invention, among others, includes providing a computer program that includes logic configured to provide an initial structure. The computer program further includes logic configured to verify that the rows of the initial structure are linearly independent and logic configured to apply an orthonormalization procedure to the initial structure to obtain a space-time structure.

The present invention can also be viewed as providing methods for providing efficient space-time structures for preambles, pilots and data for MIMO communications systems. In this regard, one embodiment of such a method, among others, can be broadly summarized by the following: providing an initial structure, verifying that the rows of the initial structure are linearly independent, and applying an orthonormalization procedure to the initial structure to obtain a space-time structure.

Another embodiment of a method of the present invention can be broadly described by the following: selecting a data structure, verifying that the data structure is a unitary transmission matrix, and applying the data structure as a space-time preamble structure.

Other apparatus, methods, features and advantages of the present invention will be or become apparent to one with skill in the art upon examination of the following drawings and detailed description. It is intended that all such additional apparatus, methods, features, and advantages be included within this description, be within the scope of the present invention, and be protected by the accompanying claims.

BRIEF DESCRIPTION OF THE DRAWINGS

Many aspects of the invention can be better understood with reference to the following drawings. Moreover, in the drawings, like reference numerals designate corresponding parts throughout the several views.

FIG. **1** is a block diagram of an exemplary Multi-Input, Multi-Output (MIMO) communications system.

FIG. **2** is a block diagram of an exemplary encoder with respect to the communications system depicted in FIG. **1**.

FIG. **3** is a diagram illustrating exemplary signal transmissions and associated signal sample matrices with respect to the communications system depicted in FIG. **1**.

FIG. **4** is a graphical illustration of a version of the receive sample matrix shown in FIG. **3** that is applicable to the MIMO communications system of FIG. **1** when employing Orthogonal Frequency Division Multiplexing (OFDM).

FIG. **5** illustrates an exemplary frame that may be implemented in the MIMO communications system depicted in FIG. **1**.

FIG. **6** is a flow chart illustrating a method for providing efficient space-time structures for preambles, pilots and data that may be implemented in the MIMO communications system depicted in FIG. **1**.

FIG. **7** is a flow chart illustrating an exemplary method to determine an initial structure for use in the method described with respect to FIG. **6**.

FIG. **8** is a flow chart illustrating an alternative method for providing efficient space-time structures for preambles, pilots and data that may be implemented in a MIMO communications system, such as the system depicted in FIG. **1**.

DETAILED DESCRIPTION

The invention now will be described more fully with reference to the accompanying drawings. The invention may, however, be embodied in many different forms and should not be construed as limited to the embodiments set forth herein; rather, these embodiments are intended to convey the scope of the invention to those skilled in the art. Furthermore, all "examples" given herein are intended to be non-limiting.

FIG. **1** shows a block diagram of an exemplary Multi-Input, Multi-Output (MIMO) communications system **6**. The exemplary MIMO communications system **6** and its subcomponents will be described hereinafter to facilitate the description of the present invention. In that regard, the exemplary MIMO communications system **6** may be implemented as a wireless system for the transmission and reception of data across a wireless channel **19**, as depicted in FIG. **1**. For example, the MIMO communications system **6** may be implemented as part of a wireless Local Area Network (LAN) or Metropolitan Area Network (MAN) system, a cellular telephone system, or another type of radio or microwave frequency system incorporating one-way or two-way communications over a range of distances.

The MIMO communications system **6** may transmit and receive signals at various frequencies. For example, the MIMO communications system **6** may transmit and receive signals in a frequency range from 2 to 11 GHz, such as in the unlicensed 5.8 GHz band, using a bandwidth of about 3 to 6 MHz. Further, the MIMO communications system **6** may employ various signal modulation and demodulation techniques, such as Single-Carrier Frequency Domain Equalization (SCFDE) or Orthogonal Frequency Division Multiplexing (OFDM), for example. However, throughout this description, references may be made with respect to a MIMO OFDM communications systems merely to facilitate the description of the invention.

The MIMO communications system **6** may also be implemented as part of a communications system (not shown) that includes an array of sub-channel communications links, which convey one or more signals transmitted by one or more transmitting elements to one or more receiving elements. The sub-channel communications links may include wires (e.g., in a wiring harness) or other forms of tangible transmission medium that span between a data source and a receiver within the communications system.

The MIMO communications system **6** includes a transmitter **8** and a receiver **10**. The transmitter **8** typically transmits signals across a channel **19** to the receiver **10**. As depicted in FIG. **1**, the transmitter **8** typically includes several components. In this regard, the transmitter **8** includes an encoder **14**. The encoder **14** typically encodes data and/or other types of signals received, for example, from a data source **12**. Such signals may alternatively be referred to collectively hereinafter as "data," "signals," or "data signals." The data source **12** may be a device, system, etc. that outputs such signals. The encoder **14** may also perform functions such as employing a channel code on data for transmission and forming sequence structures by space-time processing (STP) techniques. Further, the encoder **14** may separate the received signals onto one or more signal paths **15**, included in the transmitter **8**, which will be referred to hereinafter as transmit diversity branches (TDBs) **15**. Each TDB **15** may correlate to a different sub-channel within the MIMO communications system **6**. The encoder **14** typically facilitates the transmission of signals across the channel **19** by bundling the signals into groups, which are typically referred to as a "frame." Details of a frame, with respect to the present invention, will be discussed further below.

The transmitter **8** also includes one or more modulators **16** that are configured to modulate signals for transmission over the channel **19**. In this regard, the modulators **16** may employ various modulation techniques, such as SCFDE or OFDM. The modulators **16** are typically connected to the encoder **14** by the TDBs **15**. The transmitter also includes one or more transmit antennas **18** connected respectively to the one or more modulators **16**. Thus, each TDB **15** directs signals from the encoder **14** to one or more modulators **16**, and the modulators **16** modulate the signals for transmission by a respective transmit antenna **18**.

As discussed above, the exemplary MIMO communications system **6**, shown in FIG. **1**, also includes a receiver **10**. The receiver **10** also typically includes several components. The receiver includes one or more receive antennas **20** that are connected to one or more demodulators **22**, respectively. The receive antennas **20** typically receive modulated signals that are transmitted across the channel **19** from the transmit antennas **18**. The received signals are typically directed to the demodulators **22** from the respective receive antennas **20**. The demodulators **22** demodulate signals that are received by the respective receive antennas **20**.

The receiver **10** also includes a decoder **24**, which is connected to the demodulators **22**. The decoder **24** typically combines and decodes demodulated signals from the demodulators **22**. In this regard, the decoder **24** typically recovers the original signals that were input to the transmitter **8** from the data source **12** and transmitted across the channel **19**. As depicted in FIG. **1**, the original signals recovered by the decoder **24** may be transmitted to a connected data sink **25**, which may include one or more devices configured to utilize or process the original signals.

As discussed above, the transmitter **8** of the MIMO communications system **6** includes one or more modulators **16** that are connected to one or more transmit antennas **18**, respectively. Further, the receiver **10** of the communications system **6** includes one or more demodulators **22** that are connected to one or more receive antennas **20**, respectively. In this regard, the number of modulators **16** and respective transmit antennas **18** that are implemented in the transmitter **8** may be represented by a first variable, "Q." Similarly, the number of demodulators **22** and respective receive antennas **20** that are implemented in the receiver **10** may be represented by a second variable, "L." In the exemplary MIMO communications system **6**, the number (Q) of modulators **16** and respective transmit antennas **18** may be equivalent or non-equivalent to the number (L) of demodulators **22** and respective receive antennas **20**. In this regard, the communications system **6** may be said to have "Q×L" transmit-receive diversity.

FIG. **2** is a block diagram of an exemplary encoder **14** with respect to the communications system **6** depicted in FIG. **1**. The elements of the encoder **14** shown in FIG. **2** will be described below with respect to several elements that were described above for FIG. **1**. The exemplary encoder **14** includes a channel encoder **26**. The channel encoder **26** typically converts data and/or other types of signals to channel encoded versions of the signals, which may also be referred to collectively as "channel encoded data" or "channel encoded signals." These signals may be received by the channel encoder **26** from a data source **12**, for example. The channel encoder **26** is typically configured to encode signals using an encoding scheme that can be recognized by the decoder **24** of the receiver **10** that is intended to receive the channel encoded signals. In the process of encoding signals, the channel encoder **26** also typically adds parity to the signals so that the receiving decoder **24** can detect errors in the received channel encoded signals, which may occur, for example, due to environmental conditions of the channel **19** or inadvertent noise injection by the transmitter **8** or receiver **10**, for example.

The exemplary encoder **14** depicted in FIG. **2** also includes a symbol mapper **28**, which receives channel encoded data from the channel encoder **26**. The symbol mapper **28** is typically configured to map channel encoded data into data symbols. The symbol mapper **28** typically maps channel encoded data into data symbols by grouping a predetermined number of bits of the data so that each group of bits constitutes a specific symbol that is selected from a pre-determined symbol alphabet. In this regard, a symbol alphabet typically includes a finite set of values. For example, a symbol alphabet of a binary phase shift keying (BPSK) system typically consists of the values +1 and −1, and a symbol alphabet for a quadrature phase shift keying (QPSK) system typically consists of the values 1+j, −1+j, 1−j, and −1−j. The symbol mapper **28** is also typically configured to structure a stream of data symbols into a data section, which will be discussed further below.

The exemplary encoder **14** also includes a space-time processor **30**. The space-time processor **30** is typically configured to encode data symbol streams (i.e., data sections),

received from the symbol mapper **28**, through space-time processing to form space-time structures with properties that enhance the performance of the communication systems **6**. The encoded data sections are output from the space-time processor **30** over Q lines **13**, where Q represents the number of modulators **16** and respective transmit antennas **18** of the transmitter **8**, as discussed above.

As illustrated in FIG. **2**, the Q output lines from the space-time processor **30** input respectively to Q adders **34**. The encoder **14** also includes a pilot/training symbol inserter **32**, which also has Q output lines **17** that input respectively to the Q adders **34**. As depicted in FIG. **2**, the Q adders **34** output to Q transmit diversity branches (TDBs) **15**, which input respectively to Q modulators **16**. The pilot/training symbol inserter **32** typically provides pilot symbols and training symbols that are inserted into (or combined with) data sections by the adders **34**, which then output the modified data sections as space-time structures over the TDBs **15**.

The term pilot symbols, as used in this description, refers to symbols provided by the pilot/training symbol inserter **32**, which are inserted periodically into data sections. Typically, pilot symbols may be inserted at any point in a data section. The term training symbols, as also used in this description, refers to one or more continuous sections of training symbols provided by the pilot/training symbol inserter **32**, which are inserted into data sections. Training symbols are preferably inserted into data sections at the beginning of the section and transmitted once per frame. However, training symbols may also be inserted at other parts of data sections, such as the middle or end of the sections. Preambles (or preamble structures) are symbol structures formed of training symbols. Pilot structures (or pilots) are symbol structures formed of pilot symbols.

Pilot symbols are typically transmitted with data sections to perform minor adjustments to the calibration (i.e., synchronization and channel parameter estimation) of the receiver **10** to the transmitter **8** to accommodate, for example, the time varying nature of the channel **19**. Training symbols, however, are typically used for periodic calibration of the receiver **10** to the transmitter **8**. The training symbols that are transmitted for each sub-channel may be unique. Moreover, different sets of training symbols and/or pilot symbols may be provided by the pilot/training symbol inserter **32**, depending on the operating criteria of the communications system **6**, which may be determined, for example, by the user. However, although pilot symbols and training symbols have different purposes, the structure of preambles and pilot structures are the same. Therefore, all descriptions made hereinafter, in accordance with the present invention, with respect to preambles or preambles structures also apply to pilots or pilot structures unless otherwise specified).

FIG. **3** is a diagram that illustrates exemplary signal transmissions and associated signal sample matrices with respect to the modulator/demodulator configuration of the communications system **6** depicted in FIG. **1**. As shown in FIG. **3**, the configuration includes one or more modulators **16** and one or more demodulators **22**. As discussed above with respect to FIG. **1**, the modulators **16** and the demodulators **22** may be configured to modulate and demodulate signals, respectively, by various techniques, such as SCFDE or OFDM.

Each modulator **16** is connected to one or more respective transmit antennas **18**, and each demodulator **22** is connected to one or more respective receive antennas **20**. As discussed above with respect to FIG. **1**, the transmit antennas **18** are typically configured to transmit modulated signals across a channel **19**, and the receive antennas **20** are typically configured to receive modulated signals via the channel **19**. In this regard, exemplary signal transmissions are depicted in FIG. **3**, which will be discussed further below.

Similar to the above discussion with respect to the MIMO communications system **6** of FIG. **1**, in the modulator/demodulator configuration of FIG. **3**, the number of modulators **16** and respective transmit antennas **18** that are implemented may be represented by the variable, "Q." Accordingly, the number of demodulators **22** and respective receive antennas **20** in the arrangement of FIG. **3** may be represented by the variable, "L." Thus the modulator/demodulator arrangement depicted in FIG. **3** may also be described as having "Q×L" transmit-receive diversity. Moreover, the variables, Q and L, may be equivalent or non-equivalent in various configurations of the modulators **16** and demodulators **22**.

Exemplary signal transmissions from the Q transmit antennas **18** to the L receive antennas **20**, across the channel **19**, are also depicted in FIG. **3**. For example, a first of the L receive antennas **20** may receive each of the Q transmitted signals from the Q transmit antennas **18**. These Q transmitted signals are typically transmitted over channel impulse responses h_{11}, h_{21}, h_{31}, . . . , h_{Q1}, that are transmitted from the 1^{st} to the Q^{th} transmit antennas **18**, respectively, as depicted in FIG. **3**. In this regard, the term h_{ij} (where i=1, 2, 3, . . . , Q and j=1, 2, 3, . . . , L) is used to refer to the channel impulse response, in the time domain, that is transmitted from the i^{th} transmit antenna **18** to the j^{th} receive antenna **20**. Thus, as a further example, the L^{th} receive antenna **20** may receive each of the Q transmitted signals, over the channel impulse responses h_{1L}, h_{2L}, h_{3L}, . . . , h_{QL}, from the 1^{st} to the Q^{th} transmit antennas **18**, respectively, as depicted in FIG. **3**. Although, for simplicity, exemplary signal transmissions are depicted in FIG. **3** from the Q transmit antennas **18** to only the 1^{st} and the L^{th} receive antennas **20**, in a typical MIMO communications system, signals transmissions may occur from any of the Q transmit antennas **18** to any of the L receive antennas **20**.

A transmit sample matrix S is illustrated in FIG. **3**. The matrix S is associated with the signals that are modulated by the Q modulators **16** and transmitted over the channel **19** from the Q transmit antennas **18**. In this regard, the sample matrix S may be associated with signals that are transmitted by a MIMO communications system. Thus, the elements of the transmit sample matrix S may represent Q space-time symbols (i.e., preamble or data), which are simultaneously transmitted from the Q transmit antennas **18** during Q or more symbol periods ("T_S"). For example, the elements of the first row of the transmit sample matrix S may represent the symbols $S_1, S_2, \ldots, S_Q$, which are transmitted from the 1^{st} through the Q^{th} transmit antennas **18**, respectively, at a first time ("t"). Similarly, the elements of the second row of the transmit sample matrix S may represent the symbols $S_{Q+1}, S_{Q+2}, \ldots, S_{2Q}$, which are transmitted from the 1^{st} through the Q^{th} transmit antennas **18**, respectively, at a second time ("$t+T_S$"). The elements of the last row of the transmit sample matrix S may represent the final set of symbols, $S_{(Q-1)Q+1}, S_{(Q-1)Q+2}, \ldots, S_{QQ}$, which are transmitted from the 1^{st} through the Q^{th} transmit antennas **18**, respectively, at a final time ("$t+(Q-1)T_S$").

Also illustrated in FIG. **3** is a receive sample matrix R, which is associated with the signals that are received over the channel **19** by the L receive antennas **20** and demodulated by the L demodulators **22**. Similar to the elements of the transmit sample matrix S, described above, the elements of the receive sample matrix R may represent L space-time symbols, which are simultaneously received by the L receive antennas **20** during Q or more symbol periods ("T_S"). For example, the elements of the first row of the receive sample matrix R may represent the symbols $R_1, R_{Q+1}, \ldots, R_{(L-1)Q+1}$, which are demodulated by the 1^{st} through the L^{th} demodulators **22**,

respectively, at a first time ("t"). Similarly, the elements of the second row of the receive sample matrix R may represent the symbols R_2, R_{Q+2} . . . , $R_{(L-1)Q+2}$, which are demodulated by the 1^{st} through the L^{th} demodulators **22**, respectively, at a second time ("t+T_S"). The elements of the last row of the receive sample matrix R may represent the final set of symbols, R_Q, R_{2Q}, . . . , R_{QL}, which are demodulated by the 1^{st} through the L^{th} demodulators **22**, respectively, at a final time ("t+(Q−1)T_S"). It is noted that although references are made to the same time instances (e.g., t, t+T_S, etc.) in the foregoing descriptions, as well as in FIG. **3**, with respect to the transmit sample matrix S and the receive sample matrix R, there is typically a time delay between the transmission and reception of the signals represented by these matrices.

In addition to the transmit sample matrix S and the receive sample matrix R, there are at least two other matrices that are relevant to represent the transmission and reception of signals in a MIMO communications system, such as the system depicted in FIGS. **1** and **3**. The channel matrix η typically includes elements that represent channel coefficients, which are determined based on characteristics of the channel **19**. The channel matrix η typically has a dimension of Q×L. The noise matrix W typically includes elements that represent additive white Gaussian noise, which typically causes distortion and corruption of received signals that are represented, for example, by the receive sample matrix R. The noise matrix W typically has a dimension of Q×L.

The relationship between the receive sample matrix R, the transmit sample matrix S, the channel matrix η, and the noise matrix W can be expressed by the following equation:

$$R_{k,T\times L}=S_{k,T\times Q}\cdot\eta_{k,Q\times L}+W_{k,T\times L} \quad \text{EQ. 1}$$

With respect to EQ. 1, k represents the sub-carrier or sub-channel of received demodulated signals and T represents a dimension variable that is typically equivalent to Q, although it may have other values. As discussed above, Q and L represent, respectively, the number of modulators **16** and respective transmit antennas **18** and the number of demodulators **22** and respective receive antennas **20** with respect to a typical MIMO communications system **6**.

FIG. **4** is a graphic illustration of a version of the receive sample matrix R' shown in FIG. **3** that is applicable to the MIMO communications system of FIG. **1**, when employing Orthogonal Frequency Division Multiplexing (OFDM). As shown, the x axis represents space, the y axis represents time, and the z axis represents frequency. Each receive sample matrix R_k that is depicted in the space-time dimensions is similar to the receive sample matrix R discussed above with respect to FIG. **3**. However, each element of the receive sample matrix R' illustrated in FIG. **4** also has N frequency components that are each represented by an index, "k". As k varies from 0 to N−1 for the elements of each receive sample matrix R_k in FIG. **4**, the frequency component of the received symbol varies accordingly. Thus, the three-dimensional receive sample matrix R' can be viewed as including N receive sample matrices R_k of dimensions Q×L or Q*L vectors $R_{1,j}$ of length N. For example, with respect to the symbol received by the 1^{st} antenna and demodulated by the 1^{st} demodulator, there is a vector of elements $R_{1,0}$, $R_{1,1}$, . . . , $R_{1,N-1}$, as depicted in FIG. **4**.

FIG. **5** illustrates an exemplary frame **50** that may be implemented in a MIMO communications system that has Q transmit antennas, such as the communications system depicted in FIGS. **1** and **3**. As depicted in FIG. **5**, the frame **50** typically includes Q signal structures **52**, which correspond respectively to the Q antennas. Each signal structure **52** typically includes a preamble **54** and a data section **56**. As discussed above for FIG. **2**, the preamble **54** is typically inserted into the data section **56** by the pilot/training symbol inserter **32**. The preamble **54** typically includes one or more training blocks **58** of length N_I and cyclic prefixes **57** of length G, as depicted in FIG. **5**. The combination of a cyclic prefix **57** and a training block **58** forms a training symbol **53** that has a length of G+N_I samples in the time domain. Thus, as depicted, the preamble **54** typically includes Q training symbols **53** that have an overall length of Q*(G+N_I) samples in the time domain. A cyclic prefix **57** may also be referred to as a guard interval, since the cyclic prefix **57** typically functions to guard the signal structures **52** from inter-symbol interference (ISI) during transmission as a frame **50** across the channel **19**. The time length of the cyclic prefix **57** is typically greater than the maximum length of the channel impulse response h_{ij}, which was discussed above for FIG. **3**.

As also depicted in FIG. **5**, the data section **56** typically includes one or more data blocks **59** of length N and cyclic prefixes **57** of length G. The combination of a cyclic prefix **57** and a data block **59** forms a data symbol **55** that has a length of G+N samples in the time domain. Therefore, the data section **56** of the signal structure **52** typically includes Q or more data symbols **55** that have an overall length of P*Q*(G+N) samples in the time domain, as depicted in FIG. **5**, where P is some positive integer. Although not depicted in FIG. **5**, for simplicity, pilot symbols may also be intermittently inserted into the data symbols **55** by the pilot/training symbol inserter **32**, as discussed above.

The length N_I of a training block **58** may be shorter than the length N of a data block **59** in a signal structure **52**. Typically, the length N_I of a training block **58** in the preamble **54** is established as a fraction of the length N of a data block **59** in the data section **56** to provide the relationship of N_I being equivalent to N/I, where I is some positive integer. For example, N_I may be equivalent to N/4 (i.e., I=4). If the length N_I of a training block **58** is not established, the length N_I may be assumed to be equivalent to N (i.e., I=1). Typically, the length of a training symbol **53** (i.e., G+N_I) is equivalent to the length of a data symbol **55** (i.e., G+N). However, it is feasible for the training symbol **53** to be shorter than the data symbol **55** in the context of the signal structure **52**.

A primary purpose of the preamble **54** is to enable the receiver **10** (FIG. **1**) to identify the arrival of the signal structure **52**. Thus, the preamble **54** may facilitate time synchronization, frequency synchronization, channel parameter estimation, and noise variance estimation. Efficient space-time structures for the preamble **54** ("space-time preamble structures"), in accordance with the present invention, provide time synchronization, frequency synchronization, channel parameter estimation, and noise variance estimation through synchronization signals that have low peak-to-average power ratios (PAPR) (e.g., at or approaching unity).

A space-time preamble structure, which may also be referred to as a space-time training structure, may be represented by a signal transmission matrix S_k. In accordance with an embodiment of the present invention, the signal transmission matrix S_k of an efficient space-time preamble structure should be a unitary transmission matrix in the frequency domain and have a low PAPR in the time domain. In this regard, efficient space-time preamble structures provide enhanced performance in MIMO communications systems.

A unitary transmission matrix contains rows and columns that are orthogonal to each other, and the energy of the signals represented by each row or column is unity. In mathematical

terms, a unitary transmission matrix has the properties represented by the following equations:

$$\sum_{j=1}^{Q} S_{i,j} S_{i',j}^{*} = \begin{cases} 1 & i = i' \\ 0 & i \neq i' \end{cases} \quad \text{EQ. 2A}$$

$$\sum_{i=1}^{Q} S_{i,j} S_{i,j'}^{*} = \begin{cases} 1 & j = j' \\ 0 & j \neq j' \end{cases} \quad \text{EQ. 2B}$$

where $S_{i,j}$ represents the constituent symbols of the unitary transmission matrix.

Providing a space-time preamble structure that is a unitary signal transmission matrix S_k reduces or eliminates noise enhancement during channel estimation of the received signals. Moreover, providing a space-time preamble structure that possesses a low PAPR reduces or eliminates signal nonlinearities and spurious, out-of-band signal transmissions. As will be discussed below, data structures formed by space-time processing (i.e., space-time data structures) to be a unitary transmission matrix also provide enhanced performance in MIMO communications systems.

The following descriptions present several examples of data structures that, in accordance with the present invention, can be applied and/or modified to provide space-time preamble structures that are unitary transmission matrices. As a first example, a diagonal data structure can be applied and/or modified to provide a space-time preamble structure in accordance with the present invention. In this regard, the resulting diagonal space-time preamble structure is a unitary transmission matrix. The following diagonal structure S_{D1} is an example of this unitary transmission matrix that can be applied as a space-time preamble in a MIMO communications system with Q antennas:

$$S_D = \begin{bmatrix} S_1 & 0 & \dots & 0 \\ 0 & S_2 & \dots & \vdots \\ \vdots & 0 & \ddots & 0 \\ 0 & \dots & 0 & S_Q \end{bmatrix} \quad \text{EQ. 3}$$

The foregoing diagonal space-time preamble structure S_{D1} can be simplified so that the same training symbol (e.g., S_1) can be transmitted from each antenna, instead of Q different training symbols (i.e., S_1, S_2, etc.), as shown by the following simplified diagonal structure S_{DS} that can be applied, in accordance with the present invention, as a space-time preamble structure in a MIMO communications system with Q antennas:

$$S_{DS} = \begin{bmatrix} S_1 & 0 & \dots & 0 \\ 0 & S_1 & \dots & \vdots \\ \vdots & 0 & \ddots & 0 \\ 0 & \dots & 0 & S_1 \end{bmatrix} \quad \text{EQ. 4}$$

When the foregoing diagonal structures S_D, S_{DS} are applied as space-time preamble structures in a MIMO communications system, the training symbols are transmitted sequentially in time from each corresponding transmit antenna, and the parameters of the received symbols are estimated by the receivers connected to each receive antenna. Due to their unitary characteristic, the diagonal structures S_D, S_{DS}, provide simplified signal acquisition (i.e., synchronization) and parameter estimation when applied as a space-time preamble structure in a MIMO communications system. These diagonal structures S_D, S_{DS}, are preferably applied as space-time preamble structures, in MIMO communications systems that use two transmit antennas. As the number (Q) of transmit antennas in the MIMO system is increased, the power output from each transmit antenna typically has to be reduced by a factor of Q due to the nature of MIMO systems. As a result, the efficiency of the diagonal space-time preamble structures S_D, S_{DS} may decrease in MIMO systems with more than two transmit antennas, since the diagonal structures S_D, S_{DS} only include symbols on the main diagonal (i.e., spanning from the top-left to the bottom).

A data structure that was introduced by S. Alamouti is another example of a data structure that can be applied and/or modified, in accordance with the present invention, to provide a space-time preamble structure S_A. This data structure is a unitary transmission matrix, and it can be applied as a space-time preamble structure S_A, in MIMO communications systems that employ two transmit antennas. The space-time preamble structure S_A has the following form:

$$S_A = \begin{bmatrix} S_1 & S_2 \\ -S_2^{*} & S_1^{*} \end{bmatrix} \quad \text{EQ. 5}$$

In the above space-time preamble structure S_A, the "*" symbol indicates a complex conjugate operation. The foregoing space-time preamble structure S_A can also be simplified, in accordance with the present invention, so that the same training symbol is transmitted from each of the two antennas of the MIMO system, as shown by the following simplified space-time preamble structure S_{AS}:

$$S_{AS} = \begin{bmatrix} S_1 & S_1 \\ -S_1^{*} & S_1^{*} \end{bmatrix} \quad \text{EQ. 6}$$

Several orthogonal structures that were introduced by V. Tarokh, et al. are examples of data structures that can be applied and/or modified, in accordance with the present invention, to provide space-time preamble structures that are unitary transmission matrices. These data structures can be applied as space-time preamble structures, in accordance with the present invention, in MIMO communications systems that employ four or eight transmit antennas. For a four-antenna MIMO system, the following space-time preamble structure S_{T4} can be applied, in accordance with present invention, when the constituent symbols have real number values:

$$S_{T4} = \begin{bmatrix} S_1 & S_2 & S_3 & S_4 \\ -S_2 & S_1 & -S_4 & S_3 \\ -S_3 & S_4 & S_1 & -S_2 \\ -S_4 & -S_3 & S_2 & S_1 \end{bmatrix} \quad \text{EQ. 7}$$

The foregoing space-time preamble structure S_{T4} can be simplified, in accordance with the present invention, so that the same training symbol is transmitted from each of the four antennas of the MIMO system, as shown by the following simplified space-time preamble structure S_{T4S}. The symbols of this structure S_{T4S} may have complex values (e.g., W+jX):

$$S_{T4S} = \begin{bmatrix} S_1 & S_1 & S_1 & S_1 \\ -S_1 & S_1 & -S_1 & S_1 \\ -S_1 & S_1 & S_1 & -S_1 \\ -S_1 & -S_1 & S_1 & S_1 \end{bmatrix} \quad \text{EQ. 8}$$

The foregoing simplified structures S_{AS}, S_{T4S} (i.e., EQ. 6 and EQ. 8) typically form unitary transmission matrices when applied as space-time preamble structures, without further modification. Furthermore, the PAPR of the simplified space-time preamble structures S_{AS}, S_{T4S} are typically unity when the symbols consist of chirp-type sequences, such as:

$$s_n = \exp\left(\frac{j\pi n^2}{N}\right), \; n = 0, 1, \ldots, N-1).$$

Therefore, these simplified structures S_{AS}, S_{T4S} are typically efficient (i.e., they provide time and frequency synchronization, estimation of noise variance and channel parameters, and low PAPR) when applied, in accordance with the present invention, as space-time preamble structures.

The foregoing structures S_A, S_{T4} (i.e., EQ. 5 and EQ. 7) are also typically efficient when applied as space-time preamble structures, in accordance with the present invention. The structure S_{T4} is typically not efficient when applied as space-time data structures in a MIMO communications system. However, both structures S_A, S_{T4} can be modified and then applied as efficient space-time data structures, in accordance with the present invention. Since the structures S_A, S_{T4} will include symbols with complex values when they are applied as space-time data structures, the resultant data structures will typically not be unitary transmission matrices. Therefore, the structures S_A, S_{T4} can be modified, in accordance with the present invention, to form unitary transmission matrices and, thus, provide efficient space-time data structures. Methods, in accordance with the present invention, to transform these structures S_A, S_{T4} and other structures into efficient space-time data structures will be described below.

The following space-time preamble structure S_{T8} is based on another data structure by Tarokh, et al., and the structure S_{T8} can be applied in eight-antenna MIMO communications systems, in accordance with present invention, when the constituent symbols have real number values:

$$S_{T8} = \begin{bmatrix} S_1 & S_2 & S_3 & S_4 & S_5 & S_6 & S_7 & S_8 \\ -S_2 & S_1 & S_4 & -S_3 & S_6 & -S_5 & -S_8 & S_7 \\ -S_3 & -S_4 & S_1 & S_2 & S_7 & S_8 & -S_5 & -S_6 \\ -S_4 & S_3 & -S_2 & S_1 & S_8 & -S_7 & S_6 & -S_5 \\ -S_5 & -S_6 & -S_7 & -S_8 & S_1 & S_2 & S_3 & S_4 \\ -S_6 & S_5 & -S_8 & S_7 & -S_2 & S_1 & -S_4 & S_3 \\ -S_7 & S_8 & S_5 & -S_6 & -S_3 & S_4 & S_1 & -S_2 \\ -S_8 & -S_7 & S_6 & S_5 & -S_4 & -S_3 & S_2 & S_1 \end{bmatrix} \quad \text{EQ. 10}$$

The foregoing space-time preamble structure S_{T8} can be simplified, in accordance with the present invention, so that the same training symbol is transmitted from each of the eight antennas of the MIMO system, as shown by the following simplified space-time preamble structure S_{T8S}

$$S_{T8S} = \begin{bmatrix} S_1 & S_1 & S_1 & S_1 & S_1 & S_1 & S_1 & S_1 \\ -S_1 & S_1 & S_1 & -S_1 & S_1 & -S_1 & -S_1 & S_1 \\ -S_1 & -S_1 & S_1 & S_1 & S_1 & S_1 & -S_1 & -S_1 \\ -S_1 & S_1 & -S_1 & S_1 & S_1 & -S_1 & S_1 & -S_1 \\ -S_1 & -S_1 & -S_1 & -S_1 & S_1 & S_1 & S_1 & S_1 \\ -S_1 & S_1 & -S_1 & S_1 & -S_1 & S_1 & -S_1 & S_1 \\ -S_1 & S_1 & S_1 & -S_1 & -S_1 & S_1 & S_1 & -S_1 \\ -S_1 & -S_1 & S_1 & S_1 & -S_1 & -S_1 & S_1 & S_1 \end{bmatrix} \quad \text{EQ. 11}$$

The foregoing structures S_{T8}, S_{T8S} (i.e., EQ. 10 and EQ. 11) are typically efficient when applied as space-time preamble structures, in accordance with the present invention. However, these structures S_{T8}, S_{T8S} are typically not efficient when applied as space-time data structures in a MIMO communications system. The structure S_{T8} preferably can be modified and then applied as efficient space-time data structures, in accordance with he present invention. Since the structure S_{T8} will include symbols with complex values when it is applied as a space-time data structure, the resultant data structure will typically not be a unitary transmission matrix. Therefore, the structure S_{T8} can be modified, in accordance with the present invention, to form a unitary transmission matrix and, thus, provide an efficient space-time data structure. Methods, in accordance with the present invention, to transform this structure S_{T8} and other structures into efficient space-time data structures will be described below.

Orthogonal structures, such as those introduced by Tarokh, et al., typically only have applications to MIMO communications systems that employ two, four, or eight transmit antennas. As described above, some of the orthogonal structures can be applied, in accordance with the present invention, in two-antenna MIMO systems as space-time data structures, with complex symbols, that are unitary transmission matrices. However, the application of existing orthogonal structures using complex symbols (e.g., for space-time data structures) in MIMO systems having more than two transmit antennas typically results in a loss of the system diversity gain and/or system bandwidth. For example, the following orthogonal structure S_{T3} was introduced by Tarokh, et al. for use as a data structure with complex symbols in a three-antenna MIMO system:

$$S_{T3} = \begin{bmatrix} S_1 & S_2 & \frac{S_3}{\sqrt{2}} \\ -S_2^* & S_1^* & \frac{S_3}{\sqrt{2}} \\ \frac{S_3^*}{\sqrt{2}} & \frac{S_3^*}{\sqrt{2}} & \frac{-S_1 - S_1^* + S_2 - S_2^*}{2} \\ \frac{S_3^*}{\sqrt{2}} & \frac{S_3^*}{\sqrt{2}} & \frac{S_2 + S_2^* + S_1 - S_1^*}{2} \end{bmatrix} \quad \text{EQ. 12}$$

When the foregoing structure S_{T3} is applied in a three-antenna MIMO system, it does not provide the full diversity performance of the system, which is the capability to transmit three symbols over three symbol periods. Instead, the structure S_{T3} only provides for the transmission of three symbols over four symbol periods, which is apparent since the structure has a four rows instead of three. This lack of full diversity may result in a loss of as much as 25% of system throughput. However, methods, in accordance with the present invention, will be discussed below to transform such inefficient struc-

tures into efficient space-time structures (for preambles or data) that provide full diversity performance in MIMO communications systems.

The foregoing space-time preamble structures, in accordance with the present invention, can be applied in a Q-antenna MIMO communications system, such as the system **6** depicted in FIG. **1**, using any applicable technique. For example, the space-time preamble structure S_{T4} may be stored in a pilot/training symbol inserter **32** of the transmitter **8** of a four-antenna MIMO communications system **6** and combined with one or more data symbols for transmission over a channel **19**, as discussed above.

In general the transmission matrix for Q transmit antennas over Q symbol intervals can be represented by the following matrix $S_Q{}^2$:

$$S_{Q^2} = \begin{bmatrix} S_1 & S_2 & \dots & S_Q \\ S_{Q+1} & S_{Q+2} & \dots & S_{2Q} \\ \vdots & & & \vdots \\ S_{Q(Q-1)+1} & \dots & \dots & S_{Q^2} \end{bmatrix} \quad \text{EQ. 13}$$

This general transmission matrix $S_Q{}^2$ can be composed using Q^2 different symbols (or sequences in the case of OFDM modulation). However, in general, only Q sequences are used to form a structure. As discussed above, the transmission performance of Q symbols over Q symbol periods indicates full diversity performance of the MIMO system and also indicates the utilization of the full bandwidth of the system. Thus, such performance indicates the optimal use of the system resources.

In order to utilize the structure of the foregoing general transmission matrix $S_Q{}^2$ to construct efficient space-time sequence structures for preambles, pilots and data to be applied in MIMO communications systems, the matrix $S_Q{}^2$ is pre-processed and/or pre-conditioned in accordance with the present invention.

FIG. **6** is a flow chart illustrating a method **120** for providing efficient space-time structures for preambles, pilots and data that may be implemented in a MIMO communications system, such as the system **6** depicted in FIG. **1**. The method **120** begins with a step **122** in which one or more initial structures S_{in} are provided for conversion into efficient space-time structures for preambles or data. The structure S_{in} will typically have a form that is applicable to a Q×L MIMO communications system, where Q represents the number of transmit antennas and L represents the number of receive antennas, as discussed above. Thus, if the initial structure S_{in} is to be applied to a MIMO system that has 4 transmit antennas (i.e., Q=4), the structure will typically have 4 columns and 4 rows, similar to the general transmission matrix $S_Q{}^2$ described above. Typically, the initial structure S_{in} is formed of symbols from a known symbol alphabet. As discussed above, a symbol alphabet typically includes a finite set of values. In general, the initial structure S_{in} may be any structure that has a possible application to a MIMO communications system with Q transmit antennas. One method, among others, to determine an initial structure S_{in} will be discussed below with respect to FIG. **7**.

Following step **122**, the method **120** proceeds to step **124** in which the rows of the initial structure S_{in} are verified to be linearly independent. The check for linear independence of the rows of the initial structure S_{in} may be performed by various methods and techniques, which may be known in the art. For example, the rows of the initial structure S_{in} can be tested for linear independence by determining the rank of the initial structure S_{in}. If the rank of the initial structure S_{in} is determined to be Q, the rows of the initial structure S_{in} are linearly independent. If the rows of the initial structure S_{in} are determined to be linearly independent, the method **120** proceeds to the next step **126**. However, if the rows of the initial structure S_{in} are determined not to be linearly independent, the method **120** returns to step **122**, in which one or more different initial structures S_{in} are provided and the method **120** proceeds again to step **124**.

In the step **126**, an orthonormalization (i.e., orthogonalization and normalization) procedure is applied to the initial structure S_{in}. The orthonormalization procedure may be any procedure that transforms the initial structure S_{in} to a space-time structure S_{out} that has the properties of a unitary signal transmission matrix. As discussed above, a unitary transmission matrix has the following mathematical properties:

$$\sum_{j=1}^{Q} S_{i,j} S^*_{i',j} = \begin{cases} 1 & i = i' \\ 0 & i \neq i' \end{cases} \quad \text{EQ. 2A}$$

$$\sum_{i=1}^{Q} S_{i,j} S^*_{i,j'} = \begin{cases} 1 & j = j' \\ 0 & j \neq j' \end{cases} \quad \text{EQ. 2B}$$

where $S_{i,j}$ represents the constituent symbols of the unitary transmission matrix. One example of an orthonormalization procedure that may be applied to the initial structure S_{in} to obtain a space-time structure S_{out} that is a unitary signal transmission matrix is known as a row-wise Gram-Schmidt procedure. An example application of a row-wise Gram-Schmidt procedure will be presented below.

The resultant space-time structure S_{out} that is obtained by the step **126** may be applied as an efficient space-time preamble structure or an efficient space-time data structure, depending on the characteristics of the constituent symbols of the structure. For example, as discussed above, an efficient space-time preamble structure includes symbols that provide time and frequency synchronization and estimation of noise variance and channel parameters. In contrast, an efficient space-time data structure typically includes symbols that have complex values, as also discussed above. Further, if OFDM modulation is employed in the communications system, the constituent symbols will be symbol sequences, as also discussed above.

The resultant space-time structure S_{out} may be applied accordingly as a space-time preamble or data structure in a Q-antenna MIMO communications system, such as the system **6** depicted in FIG. **1**, using any applicable technique, which may be known in the art. For example, a resultant space-time preamble structure S_{out} may be stored in a pilot/training symbol inserter **32** of MIMO communications system transmitter **8** and combined with one or more data symbols for transmission over a channel **19**, as discussed above.

FIG. **7** is a flow chart illustrating an exemplary method **140**, among others, to determine an initial structure S_{in} for use in the step **122** described above for FIG. **6**. The exemplary method **140** begins with a step **142** in which a symbol alphabet is chosen to provide the symbols for the initial structure S_{in}. Preferably, the symbols (or symbol sequences in the case of OFDM modulation) are derived from a complex alphabet on the unit circle, that is, all of the alphabet points have the same energy. The following are exemplary alphabets in this regard:

Binary Phase Shift Keying (BPSK) alphabet: +1, −1

Quadrature Phase Shift Keying (QPSK) alphabet: 1+j, −1+j, −1−j, 1−j

8-Phase Shift Keying (8-PSK) alphabet: exp(j*2πi/8), i=0, 1, 2, . . . , 7

16-Phase Shift Keying (16-PSK) alphabet: exp(j*2πi/16), i=0, 1, 2, . . . , 15

32-Phase Shift Keying (32-PSK) alphabet: exp(j*2πi/32), i=0, 1, 2, . . . , 31

In general, M-Phase Shift Keying (M-PSK) alphabet: exp(j*2πi/M), i=0, 1, 2, . . . , M−1; M=8, 16, 32, . . .

The symbols or symbols sequences may also be derived from polyphase sequences, such as Chirp sequences; Milewski sequences; Frank-Zadoff sequences; Chu sequences; Suehiro polyphase sequences; and Ng et al. sequences, among others known in the art.

Following the step **142**, the method **140** concludes with a step **144** in which the initial configuration of the initial structure S_{in} is chosen. The determination of the initial configuration may add certain specific characteristics to the structure. For example, the initial configuration typically reduces the number of possible symbol combinations from Q^2 to Q. The initial configuration may be chosen from any structure configuration. The following are several examples of a possible initial configuration of the initial structure S_{in}:

Circular configuration, S_C:

$$S_C = \begin{bmatrix} S_1 & S_2 & \dots & S_Q \\ S_Q & S_1 & \dots & S_{Q-1} \\ \vdots & & & \vdots \\ S_2 & \dots & \dots & S_1 \end{bmatrix} \quad \text{EQ. 14}$$

Symmetric configuration, S_S:

$$S_S = \begin{bmatrix} S_1 & S_2 & \dots & S_Q \\ S_2 & S_1 & \dots & S_{Q-1} \\ \vdots & & & \vdots \\ S_Q & \dots & \dots & S_1 \end{bmatrix} \quad \text{EQ. 15}$$

Based on the determination of the symbol alphabet and the initial structure configuration in the step **142** and the step **144**, respectively, an initial structure S_{in} can be determined. This initial structure S_{in} can be used in the method **120**, depicted in FIG. **6**, to obtain an efficient space-time structure, as discussed above.

FIG. **8** is a flow chart illustrating an alternative method **160** for providing efficient space-time structures for preambles, pilots and data that may be implemented in a MIMO communications system, such as the system **6** depicted in FIG. **1**. The method **160** begins with a step **162** in which one or more initial structures S_{in} are provided for conversion into efficient space-time structures for preambles or data. The step **162** is at least substantially similar to the step **122** discussed above with respect to FIG. **6**. Following the step **162**, the method **160** proceeds to a step **164** in which the rows of the initial structure S_{in} are verified to be linearly independent. This step **164** is at least substantially similar to the step **124** discussed above with respect to FIG. **6**.

If the rows of the initial structure S_{in} are determined to be linearly independent, the method **160** proceeds from the step **164** to a step **166** in which an orthonormalization procedure is applied to the initial structure S_{in} to transform the initial structure S_{in} to a space-time structure S_{out} that has the properties of a unitary signal transmission matrix. This step **166** is at least substantially similar to the step **126** discussed above with respect to FIG. **6**. However, if the rows of the initial structure S_{in} are determined not to be linearly independent, the method **160** returns to step **162**.

Following the step **166**, the method **160** proceeds to a step **168** in which the alphabet points of the constituent symbols of the resultant space-time structure S_{out} are checked to be within a tolerable distance of the alphabet points of the constituent symbols of the initial structure S_{in}. The amplitude of the alphabet points may be modified during the orthonormalization procedure in the step **166**. The tolerable distance is typically dependent on the operating capability of components of the MIMO communications system **6**, such as digital-to-analog (D/A) converters. The constituent symbols of the space-time structure S_{out} may be checked to be within a tolerable distance of the original alphabet points by various methods and techniques, which are known in the art. For example, the constituent symbols of the space-time structure S_{out} may be checked to be within a tolerable distance by application of a Euclidean distance metric represented, for example, by the following equation:

$$d_{t,l} = \|S_t - S_l\|^2 \quad \text{EQ. 16}$$

If the constituent symbols of the space-time structure S_{out} are found to be within a tolerable distance from the original alphabet points of the initial structure S_{in}, the space-time structure S_{out} is stored in a memory or other device for application in a MIMO communications system. However, if the constituent symbols of the space-time structure S_{out} are not determined to be within a tolerable distance from the original alphabet points, the method **160** returns to step **162**, in which one or more different initial structures S_{in} are provided and the method **160** proceeds again as described above.

In the case of a MIMO communications system that employs OFDM modulation, the steps **162** through **168** may be repeated until a sufficient number of space-time structures S_{out} that are unitary signal transmission matrices are obtained and stored, as discussed above.

If the symbols are within a tolerable distance, in step **170**, the stored space-time structure S_{out} used to construct space-time sequence structures $S_{out,k}$, where k represents a sub-carrier or sub-channel index of the OFDM setup. The space-time sequence structures $S_{out,k}$ may be constructed by an encoder, as described above with respect to FIGS. **2** and **5**, or other methods, which may be known in the art, may be utilized to construct the space-time sequence structures $S_{out,k}$.

In the final step **172** of the method **160**, the peak-to-average power ratio (PAPR) of the space-time sequence structures $S_{out,k}$ are tested to determine if the PAPR of the structures is low enough to provide efficient signal transmission and reception in a MIMO OFDM communications system. The PAPR of the training sequences may be tested by various methods and techniques, which may be known in the art. For example, the PAPR of the space-time sequence structures $S_{out,k}$ may be tested by converting the structures to the time domain (e.g., by inverse Fourier transform or "IFT") and calculating the PAPR of the resultant signal samples. If the PAPR of the space-time sequence structures $S_{out,k}$ is found to be acceptable (e.g., at or approaching unity), the structures have been determined to be efficient, in accordance with the present invention, and may be used for preambles or data in a MIMO communications system **6** employing OFDM modulation. However, if the PAPR of the space-time sequence structures $S_{out,k}$ are found to be unacceptably high, the method **160** returns to step **162**, in which one or more different initial structures S_{in} are provided and the method **160** proceeds again as described above.

In the case of some orthogonal polyphase sequences, complex coefficients b_i that are used to modulate the sequences

may be useful to form efficient space-time sequence structures $S_{out,k}$. In this regard, modulation of the orthogonal polyphase sequences by the complex coefficients b_i may make the rows of the corresponding space-time structures S_{out} linearly independent. Furthermore, the modulation by the complex coefficients b_i may also reduce the PAPR of the resulting space-time sequence structures $S_{out,k}$ that are formed from the space-time structures S_{out}.

In the step **126** of the method **120** and the step **166** of the method **160**, described above with respect to FIGS. **6** and **8**, respectively, an orthonormalization procedure is applied to the initial structure S_{in} to transform the initial structure S_{in} to a space-time structure S_{out} that has the properties of a unitary signal transmission matrix. As discussed above, one example of such an orthonormalization procedure is a row-wise Gram-Schmidt procedure. In general, when a matrix S_k is subjected to the Gram-Schmidt procedure, the resulting matrix S'_k will be unitary, so long as the rank of S_k is Q or the rows of S_k are linearly independent. In a row-wise application of the Gram-Schmidt procedure to a matrix S_k, the first row of the matrix S_k is unchanged and used as a reference to make the remaining rows orthonormal (i.e., orthogonal and normal). The following matrices illustrate the application of a row-wise Gram-Schmidt procedure to a 4×4 matrix S_k to obtain the orthogonalized unitary matrix S'_k:

$$S_k = \begin{bmatrix} .5e^{-.03j} & .5e^{.00j} & .5e^{.00j} & .5e^{.07j} \\ .5e^{-.89j} & .5e^{-.49j} & .5e^{.17j} & .5e^{-.32j} \\ .5e^{-.69j} & .5e^{-.80j} & .5e^{.20j} & .5e^{-.28j} \\ .5e^{-1.3j} & .5e^{-.72j} & .5e^{-.70j} & .5e^{-.74j} \end{bmatrix} \quad \text{EQ. 17}$$

$$S'_k = \begin{bmatrix} .5e^{-.03j} & .5e^{.00j} & .5e^{.00j} & .5e^{.07j} \\ .62e^{-2.0j} & .16e^{-1.4j} & .76e^{1.3j} & .1e^{-2j} \\ .47e^{-.75j} & .83e^{-2.2j} & .24e^{1.3j} & .14e^{-1.0j} \\ .37e^{-2.6j} & .17e^{-2.4j} & .34e^{-.70j} & .85e^{-.88j} \end{bmatrix} \quad \text{EQ. 18}$$

It is noted that embodiments of the present invention, such as those described above, may be implemented in hardware, software, firmware, or a combination thereof. For example, in some embodiments, the present invention may be implemented as a computer program or application in software or firmware that is stored in a memory and that is executed by a suitable instruction execution system. In other embodiments the present invention may be implemented, for example, with one or a combination of the following technologies, which may be known in the art: one or more discrete logic circuit(s) having logic gates for implementing logic functions upon data signals, an application specific integrated circuit (ASIC) having appropriate combinational logic gates, a programmable gate array(s) (PGA), a field programmable gate array (FPGA), etc.

It is further noted that any process descriptions or blocks in flow charts described above may represent modules, segments, and/or portions of a computer program or application code that includes one or more executable instructions for implementing specific logical functions or steps in the process. Alternate implementations are included within the scope of the present invention in which functions may be executed out of order from that shown in the figures and/or discussed above, including substantially concurrently or in reverse order, depending at least in part on the functionality involved, as will be understood by those skilled in the art.

With regard to any block diagrams described above, although the flow of data or other elements may be depicted as unidirectional or bi-directional, such depictions are merely exemplary and not limiting. Variations of the flows depicted in the block diagrams are included within the scope of the present invention. Furthermore, the functionality of some of the blocks may be implemented by a single combined block within the scope of the present invention.

Moreover, embodiments of the present invention, such as those described above, may comprise an ordered listing of executable instructions for implementing logical functions which can be embodied in any computer-readable medium for use by or in connection with an instruction execution system, apparatus, or device, such as a computer-based system, processor-containing system, or other system that can fetch the instructions from the instruction execution system, apparatus, or device and execute the instructions. In the context of this disclosure, a "computer-readable medium" may be any means that can contain, store, communicate, propagate, or transport the program for use by or in connection with the instruction execution system, apparatus, or device. The computer readable medium may be, for example but not limited to, an electronic, magnetic, optical, electromagnetic, infrared, or semiconductor system, apparatus, device, or propagation medium. More specific examples (i.e., a non-exhaustive list) of the computer-readable medium include the following: an electrical connection (electronic) having one or more wires, a portable computer diskette (magnetic), a random access memory (RAM) (electronic), a read-only memory (ROM) (electronic), an erasable programmable read-only memory (EPROM or Flash memory) (electronic), an optical fiber (optical), and a portable compact disc read-only memory (CDROM) (optical). It is noted that the computer-readable medium may even be paper or another suitable medium upon which the program is printed, as the program can be electronically captured, via for instance optical scanning of the paper or other medium, then compiled, interpreted or otherwise processed in a suitable manner if necessary, and then stored in a computer memory.

Finally, it should be emphasized that the above-described embodiments of the present invention are merely possible examples of implementations set forth for a clear understanding of the principles of the invention. Many variations and modifications may be made to the above-described embodiment(s) of the invention without departing substantially from the spirit and principles of the invention. All such modifications and variations are intended to be included herein within the scope of this disclosure and the invention, and protected by the following claims.

We claim:

1. A [computer program embodied in a] *non-transitory* computer-readable *storage* medium *having a computer program stored thereon* for providing [efficient] *a* space-time [structures] *structure* for preambles, pilots, and data for *a* multi-input, multi-output communications [systems] *system*, the computer program comprising:

logic configured to provide an initial structure;

logic configured to verify that rows of [said] *the* initial structure are linearly independent;

logic configured to apply an orthonormalization procedure to [said] *the* initial structure to obtain a space-time structure for a preamble *structure, a pilot structure,* or [pilot] *a data structure* in a time or frequency domain; and

logic configured to [insert] *apply* the space-time structure as a *space-time* preamble *structure, a space-time pilot structure,* or [pilot] *a space-time data structure* in the time or frequency domain and *combine the space-time*

preamble structure, the space-time pilot structure, or the space-time data structure with one or more data symbols for transmission in the multi-input, multi-output (*MIMO*) communications system.

2. The [computer program] *computer-readable storage medium* of claim **1**, wherein said logic configured to provide an initial structure comprises:

logic configured to choose a symbol alphabet to provide symbols for [said] *the* initial structure; and

logic configured to choose an initial configuration of [said] *the* initial structure.

3. The [computer program] *computer-readable storage medium* of claim **1**, further comprising:

logic configured to confirm that symbols of [said] *the* space-time structure are within a predetermined distance of symbols of [said] *the* initial structure;

logic configured to construct a space-time sequence structure from a plurality of [said] *the* space-time structures; and

logic configured to verify that a peak-to-average power ratio (*PAPR*) of [said] *the* space-time structure is less than a predetermined value.

4. The [computer program] *computer-readable storage medium* of claim **3**, wherein said logic configured to confirm [chat] *that* the symbols of [said] *the* space-time structure are within a predetermined distance of the symbols of [said] *the* initial structure comprises logic configured to apply a Euclidean distance metric to determine the distance between the symbols of [said] *the* space-time structure and the symbols of [said] *the* initial structure.

5. The [computer program] *computer-readable storage medium* of claim **1**, wherein said logic configured to verify that the rows of [said] *the* initial structure are linearly independent comprises logic configured to determine rank of [said] *the* initial structure.

6. The [computer program] *computer-readable storage medium* of claim **1**, wherein said logic configured to apply an orthonormalization procedure to [said] *the* initial structure to obtain a space-time structure comprises logic configured to apply a row-wise Gram-Schmidt procedure to [said] *the* initial structure to obtain [a] *the* space-time structure.

7. The computer-readable storage medium of claim 1, wherein said logic configured to verify comprises logic configured to determine if a rank of the initial structure is equal to a number of associated transmit antennas.

8. The computer-readable storage medium of claim 1, wherein the space-time structure has properties of a unitary signal transmission matrix.

9. The computer-readable storage medium of claim 3, further comprising logic configured to store the space-time structure in a memory of the MIMO communications system if the symbols of the space-time structure are within the predetermined distance of the initial structure.

10. The computer-readable storage medium of claim 3, wherein said logic configured to verify that a PAPR of the space-time structure is less than a predetermined value comprises logic configured to convert the space-time structure to a time domain and calculate the PAPR of resultant signal samples.

11. The computer-readable storage medium of claim 3, further comprising logic configured to store the space-time preamble structure, the space-time pilot structure, or the space-time data structure in an encoder.

12. A method of providing a space-time structure for preambles, pilots, and data for a multi-input, multi-output communications system, the method comprising:

verifying that rows of an initial structure are linearly independent;

applying an orthonormalization procedure to the initial structure at an encoder to obtain the space-time structure for a preamble structure, a pilot structure, or a data structure in a time or frequency domain; and

applying, at the encoder, the space-time structure as a space-time preamble structure, a space-time pilot structure, or a space-time data structure in the time or frequency domain and combining the space-time preamble structure, the space-time pilot structure, or the space-time data structure with one or more data symbols for transmission in the multi-input, multi-output communications system.

13. The method of claim 12, further comprising choosing a symbol alphabet to provide symbols for the initial structure and choosing an initial configuration of the initial structure.

14. The method of claim 12, further comprising:

confirming that symbols of the space-time structure are within a predetermined distance of symbols of the initial structure; and

constructing a space-time sequence structure from a plurality of the space-time structures.

15. The method of claim 14, wherein said confirming comprises applying a Euclidean distance metric to determine the distance between the symbols of the space-time structure and the symbols of the initial structure.

16. The method of claim 14, further comprising storing the space-time structure in a memory of the MIMO communications system if the symbols of the space-time structure are within the predetermined distance of the initial structure.

17. The method of claim 12, further comprising verifying that a peak-to-averagc power ratio (PAPR) of the space-time structure is less than a predetermined value.

18. The method of claim 17, wherein said verifying comprises converting the space-time structure to a time domain and calculating the PAPR of resultant signal samples.

19. The method of claim 12, wherein said verifying that the rows of the initial structure are linearly independent comprises determining rank of the initial structure.

20. The method of claim 12, wherein said applying an orthonormalization procedure comprises applying a row-wise Gram-Schmidt procedure to the initial structure to obtain the space-time structure.

21. The method of claim 12, wherein said verifying comprises determining if a rank of the initial structure is equal to a number of associated transmit antennas.

22. The method of claim 12, wherein the space-time structure has properties of a unitary signal transmission matrix.

23. The method of claim 12, further comprising storing the space-time preamble structure, the space-time pilot structure, or the space-time data structure in an encoder.

24. A communication system comprising:

an encoder having a pilot/training symbol inserter, the pilot/training symbol inserter configured to insert pilot symbols or training symbols into data blocks, wherein the inserted pilot symbols or training symbols include a space-time structure formed using an orthonormalization procedure, wherein the encoder is configured to:

verify that rows of an initial structure are linearly independent; and

apply the orthonormalization procedure to the initial structure to form the space-time structure;

at least one modulator coupled to the encoder, each modulator outputting a frame structure comprising a data structure and at least a preamble structure or a pilot structure; and

at least one transmit antenna, each transmit antenna corresponding to a respective one of the at least one modulator, each transmit antenna transmitting the frame structure output from the corresponding modulator.

25. The communication system of claim 24, wherein the encoder is further configured to choose a symbol alphabet to

provide symbols for the initial structure and choose an initial configuration of the initial structure.

26. The communication system of claim 24, wherein the encoder is further configured to:

confirm that symbols of the space-time structure are within a predetermined distance of symbols of the initial structure; and

construct a space-time sequence structure from a plurality of the space-time structures.

27. The communication system of claim 26, wherein the encoder is further configured to apply a Euclidean distance metric to determine the distance between the symbols of the space-time structure and the symbols of the initial structure.

28. The communication system of claim 26, further comprising a memory in which the space-time structure is stored if the symbols of the space-time structure are within the predetermined distance of the initial structure.

29. The communication system of claim 24, wherein the encoder is further configured to determine a rank of the initial structure.

30. The communication system of claim 24, wherein the encoder is further configured to apply a row-wise Gram-Schmidt procedure to the initial structure to obtain the space-time structure.

31. The communication system of claim 24, wherein the encoder is further configured to determine if a rank of the initial structure is equal to a number of associated transmit antennas.

32. The communication system of claim 24, wherein the encoder is further configured to verify that a peak-to-average power ratio of the space-time structure is less than a predetermined value.

33. The communication system of claim 32, wherein the encoder is further configured to convert the space-time structure to a time domain and calculate the PAPR of resultant signal samples.

34. The communication system of claim 24, wherein the space-time structure has properties of a unitary signal transmission matrix.

35. The communication system of claim 24, wherein the encoder is further configured to store the space-time preamble structure, the space-time pilot structure, or the space-time data structure.

* * * * *

UNITED STATES PATENT AND TRADEMARK OFFICE

CERTIFICATE OF CORRECTION

PATENT NO.	: RE43,294 E
APPLICATION NO.	: 12/555332
DATED	: April 3, 2012
INVENTOR(S)	: Stuber et al.

It is certified that error appears in the above-identified patent and that said Letters Patent is hereby corrected as shown below:

In Column 22, Line 29, in Claim 17, delete "peak-to-averagc" and insert -- peak-to-average --, therefor.

Signed and Sealed this
Twenty-third Day of October, 2012

David J. Kappos
Director of the United States Patent and Trademark Office