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Newman et al.

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(54) **FAULT DETECTION AND CORRECTION BY SUM-SIGNAL MODULATION IN 5G OR 6G**

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H04L 1/00	(2006.01)

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(52) **U.S. Cl.**

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(58) **Field of Classification Search**

None

See application file for complete search history.

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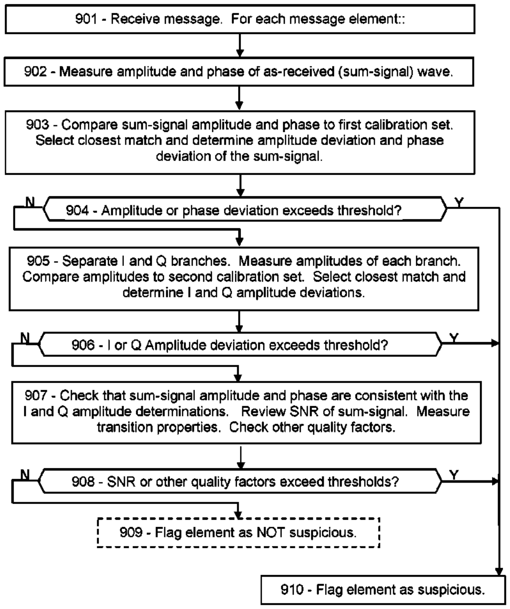
Primary Examiner — Anh Vu H Ly

(57) **ABSTRACT**

A faulted 5G/6G message may be recovered by finding the faulted message elements and altering them until the fault is corrected. Disclosed are methods to evaluate the modulation quality of each message element using multiple criteria. The receiver can determine a first quality by measuring the overall (sum-signal) amplitude and phase of each message element, and comparing to the predetermined amplitude and phase levels. The receiver can determine a second quality by separating the overall wave into orthogonal components (branches) and comparing the branch amplitudes to the predetermined levels. The receiver can determine a third quality according to the SNR of the overall signal and the two branch signals. By combining the first, second, and third quality factors, the receiver can identify the most likely faulted message elements. The receiver can then alter the worst message elements in a nested grid search to find the correct message version.

20 Claims, 9 Drawing Sheets



Related U.S. Application Data

continuation of application No. 17/674,182, filed on Feb. 17, 2022, now Pat. No. 11,398,876.

(60) Provisional application No. 63/310,364, filed on Feb. 15, 2022, provisional application No. 63/310,240, filed on Feb. 15, 2022, provisional application No. 63/309,750, filed on Feb. 14, 2022, provisional application No. 63/309,748, filed on Feb. 14, 2022, provisional application No. 63/282,770, filed on Nov. 24, 2021, provisional application No. 63/281,847, filed on Nov. 22, 2021, provisional application No. 63/281,187, filed on Nov. 19, 2021, provisional application No. 63/280,281, filed on Nov. 17, 2021, provisional application No. 63/230,926, filed on Aug. 9, 2021, provisional application No. 63/159,195, filed on Mar. 10, 2021, provisional application No. 63/159,238, filed on Mar. 10, 2021, provisional application No. 63/157,090, filed on Mar. 5, 2021, provisional application No. 63/151,270, filed on Feb. 19, 2021.

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H04L 27/02	(2006.01)
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H04W 28/04	(2009.01)

(52) **U.S. Cl.**

CPC ***H04L 27/34*** (2013.01); ***H04L 27/364*** (2013.01); ***H04W 28/04*** (2013.01)

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FIG. 1A

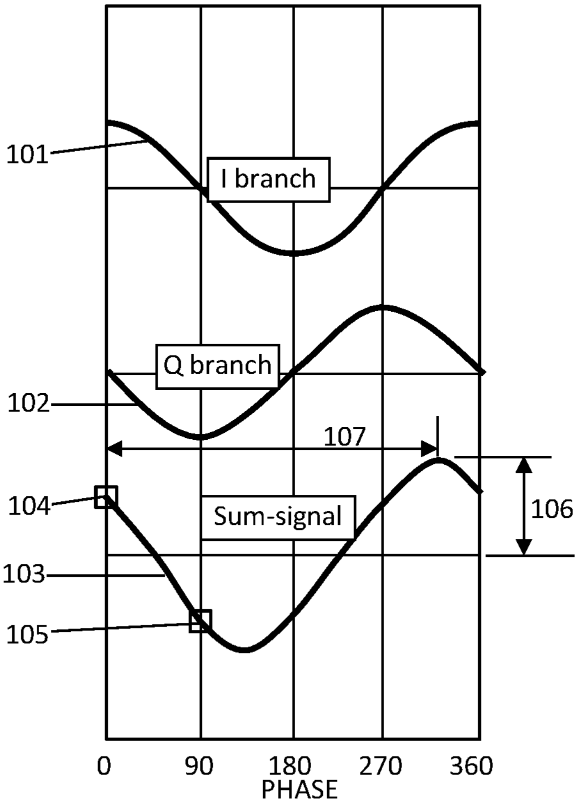


FIG. 1B

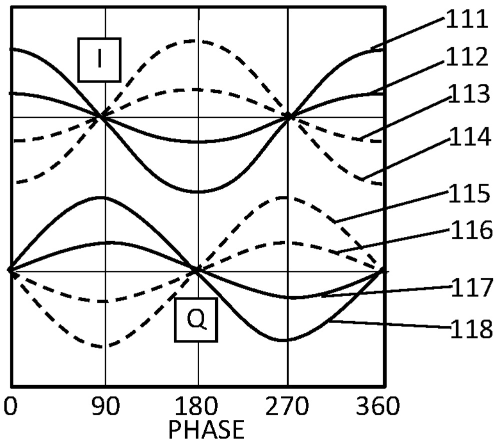


FIG. 1C

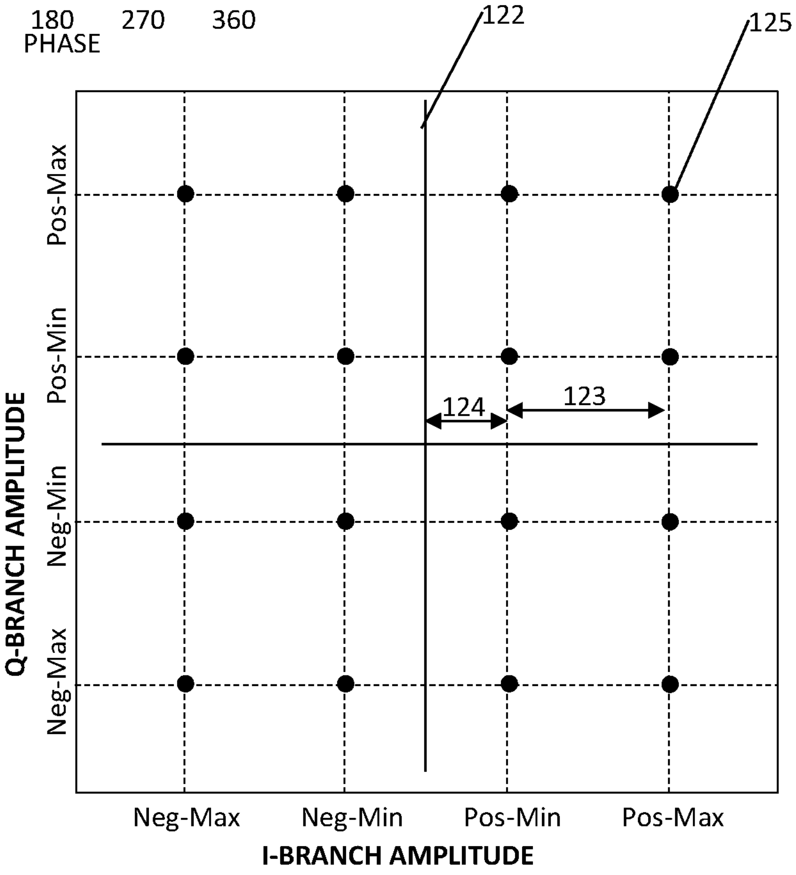


FIG. 2A

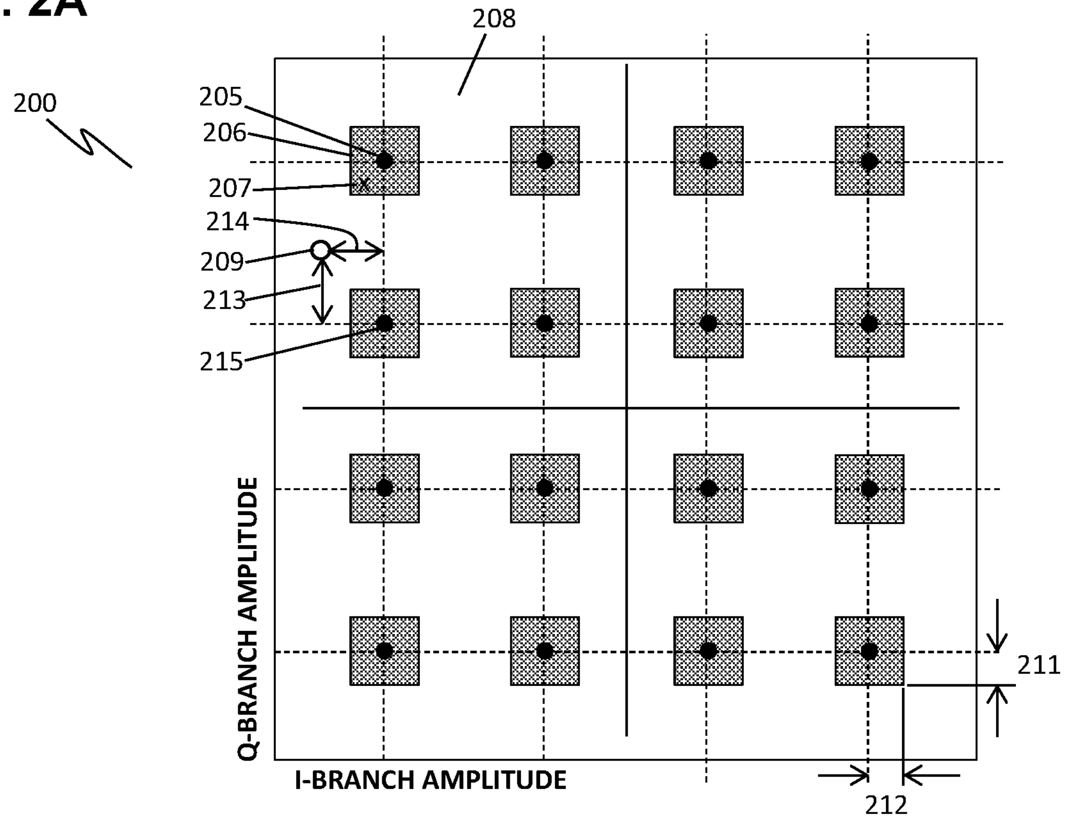

200
208
205
206
207
214
209
213
215
211
212
Q-BRANCH AMPLITUDE
I-BRANCH AMPLITUDE

FIG. 2B

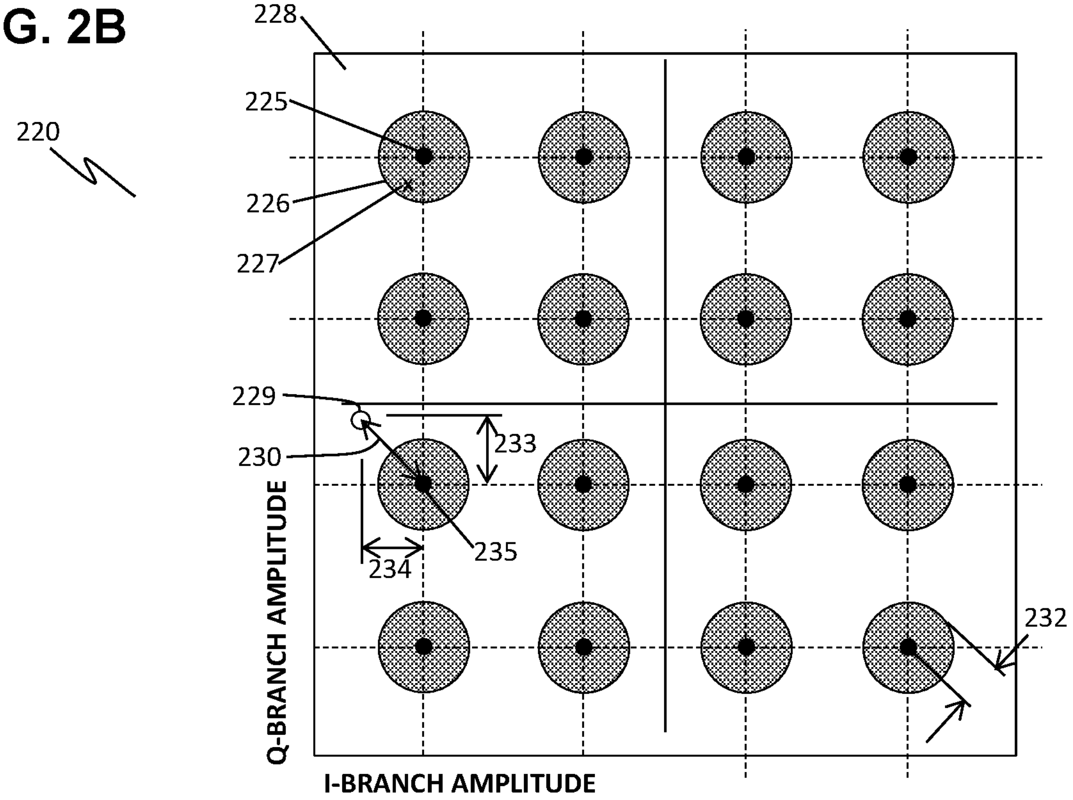

220
228
225
226
227
229
230
233
235
234
232
Q-BRANCH AMPLITUDE
I-BRANCH AMPLITUDE

FIG. 3

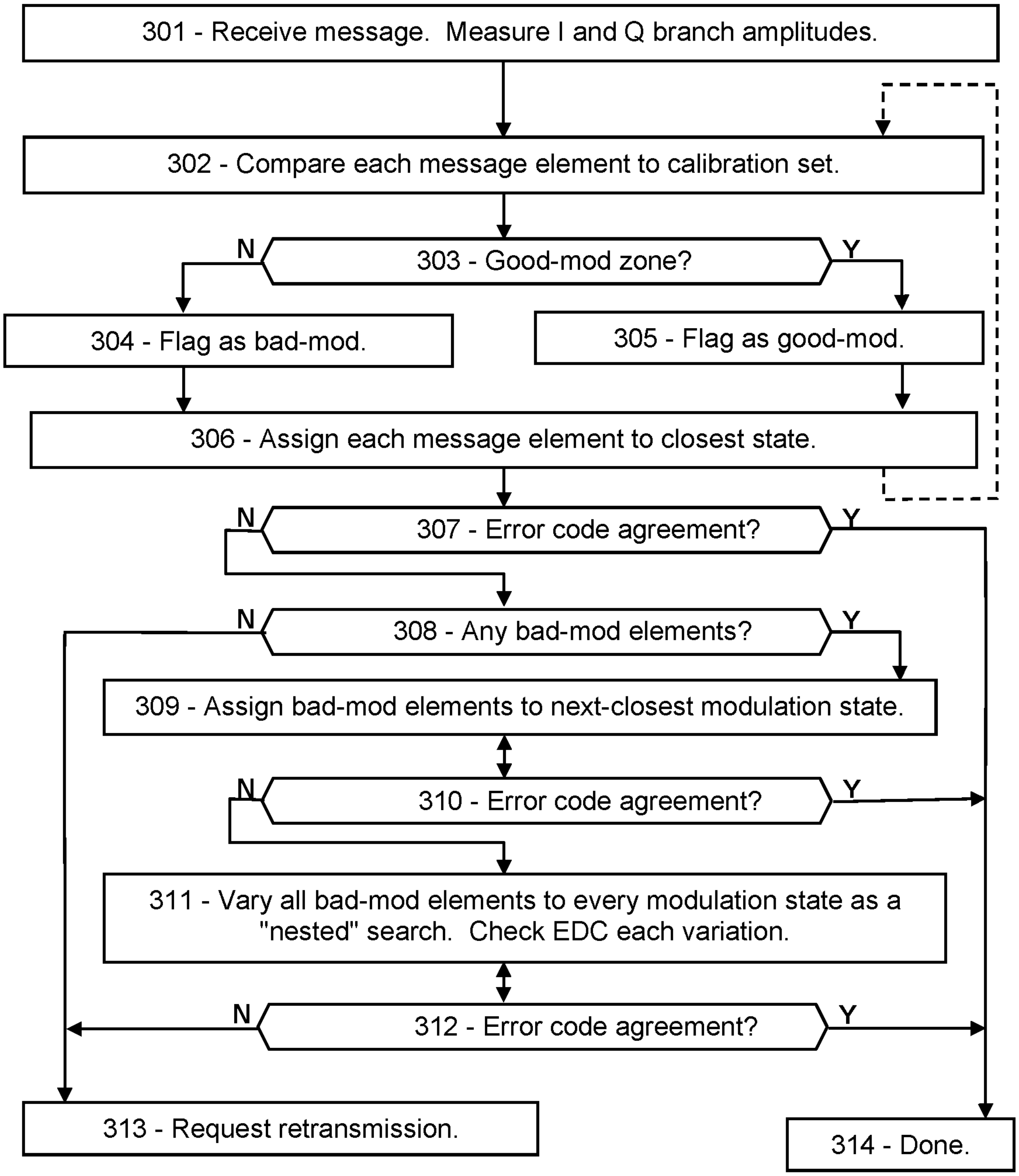

301 - Receive message. Measure I and Q branch amplitudes.
302 - Compare each message element to calibration set.
303 - Good-mod zone?
N
Y
304 - Flag as bad-mod.
305 - Flag as good-mod.
306 - Assign each message element to closest state.
307 - Error code agreement?
N
Y
308 - Any bad-mod elements?
N
Y
309 - Assign bad-mod elements to next-closest modulation state.
310 - Error code agreement?
N
Y
311 - Vary all bad-mod elements to every modulation state as a "nested" search. Check EDC each variation.
312 - Error code agreement?
N
Y
313 - Request retransmission.
314 - Done.

FIG. 4A

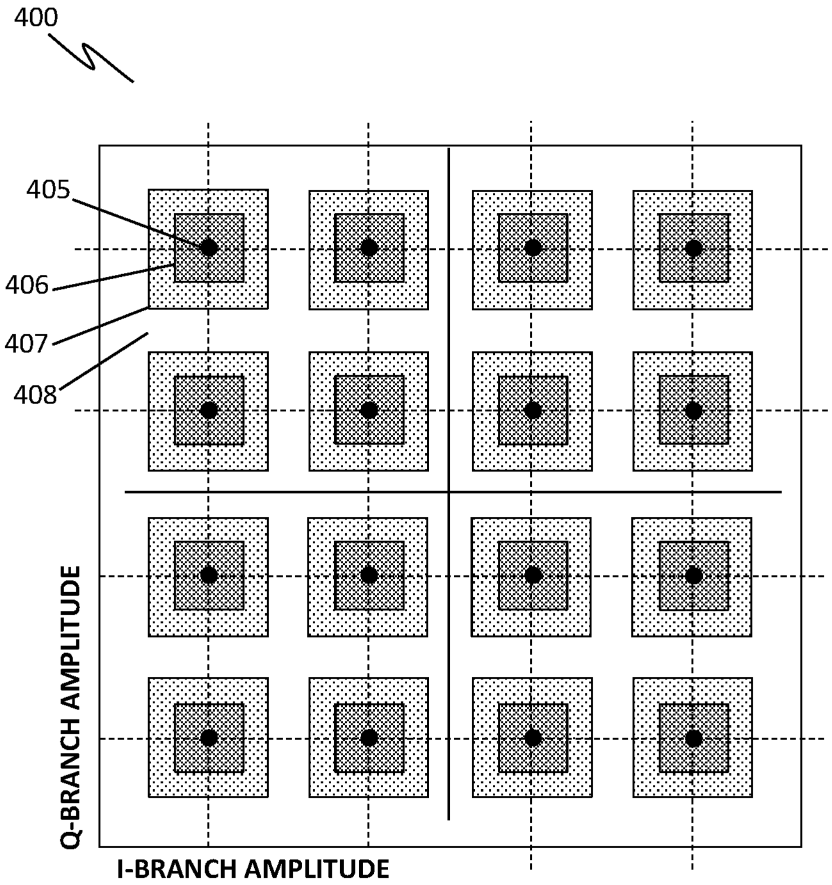


FIG. 4B

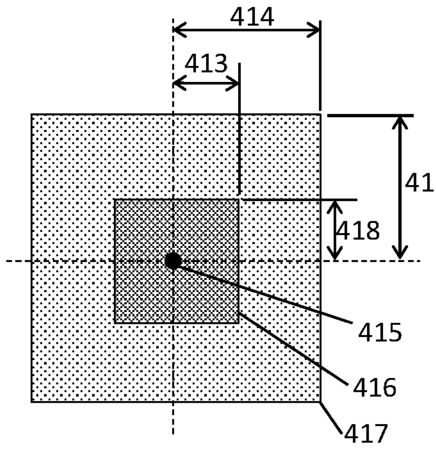


FIG. 4C

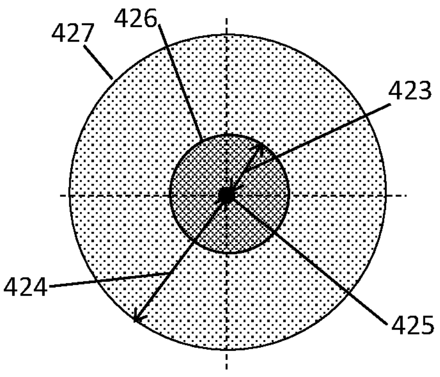


FIG. 5

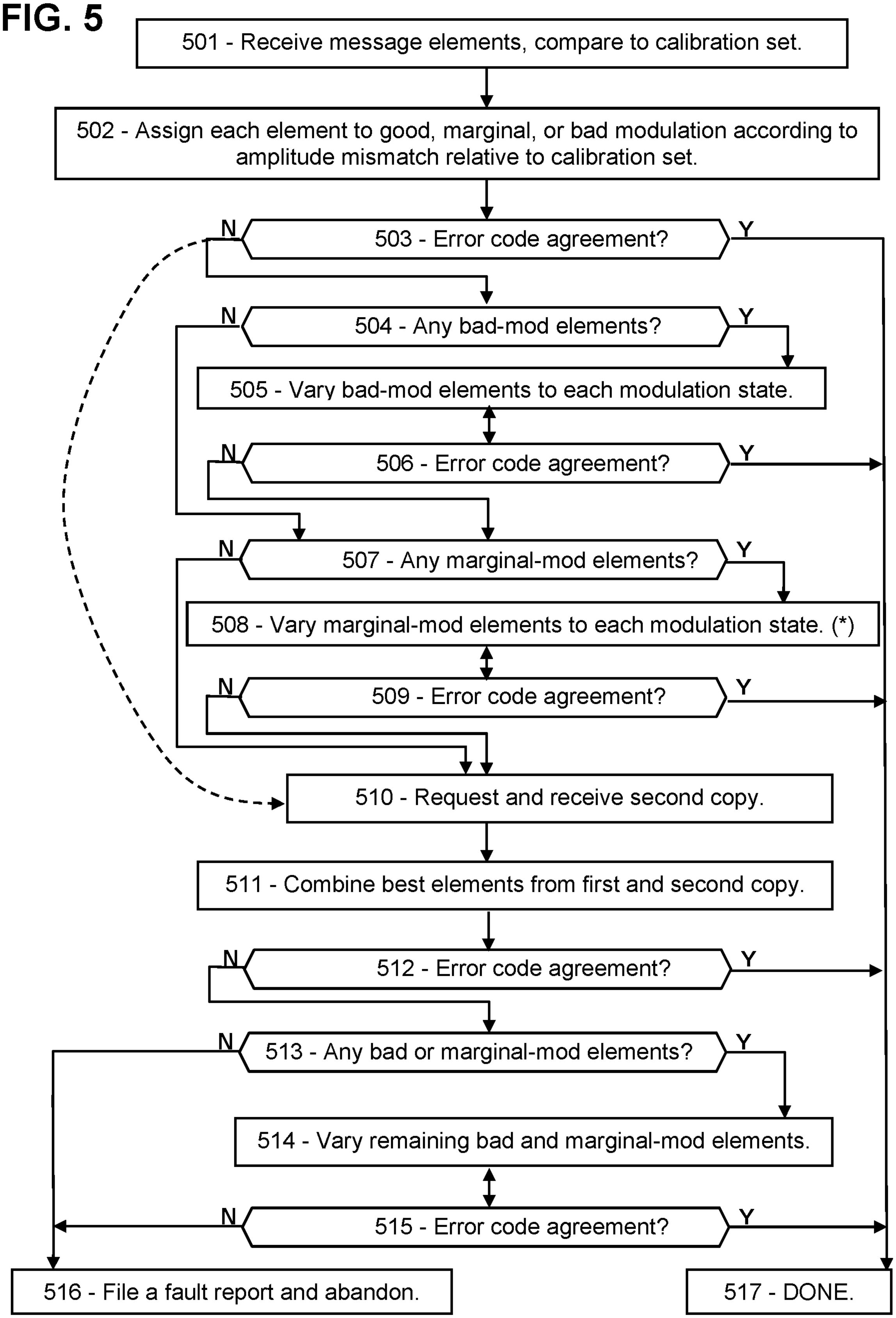

501 - Receive message elements, compare to calibration set.
502 - Assign each element to good, marginal, or bad modulation according to amplitude mismatch relative to calibration set.
N
503 - Error code agreement?
Y
N
504 - Any bad-mod elements?
Y
505 - Vary bad-mod elements to each modulation state.
N
506 - Error code agreement?
Y
N
507 - Any marginal-mod elements?
Y
508 - Vary marginal-mod elements to each modulation state. (*)
N
509 - Error code agreement?
Y
510 - Request and receive second copy.
511 - Combine best elements from first and second copy.
N
512 - Error code agreement?
Y
N
513 - Any bad or marginal-mod elements?
Y
514 - Vary remaining bad and marginal-mod elements.
N
515 - Error code agreement?
Y
516 - File a fault report and abandon.
517 - DONE.

FIG. 6A

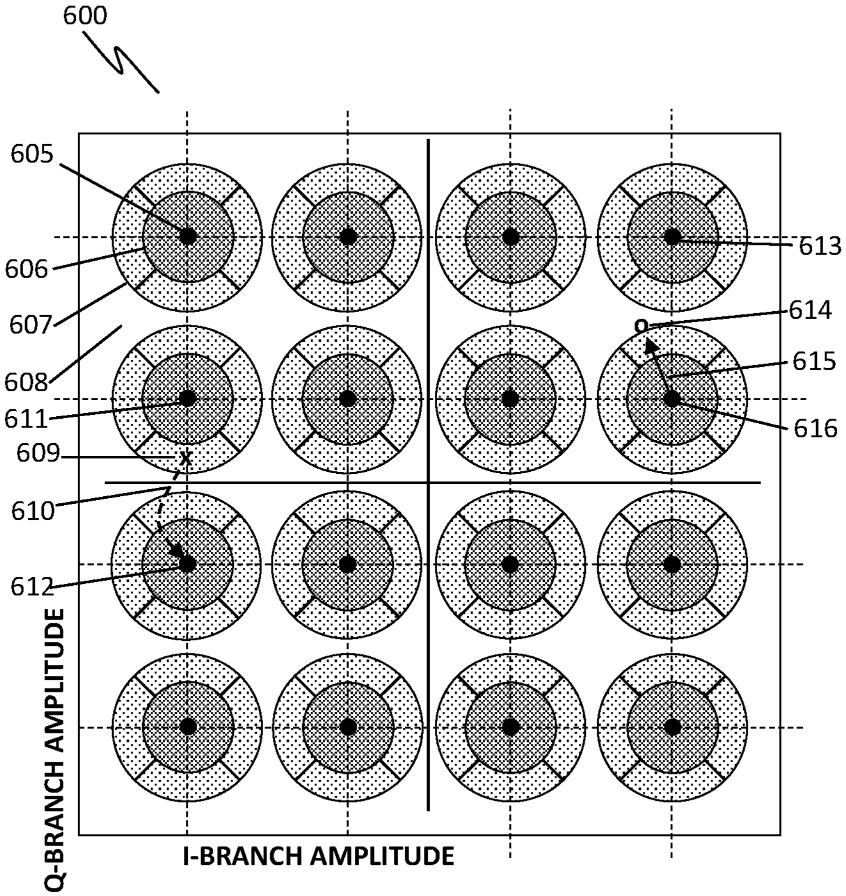


FIG. 6B

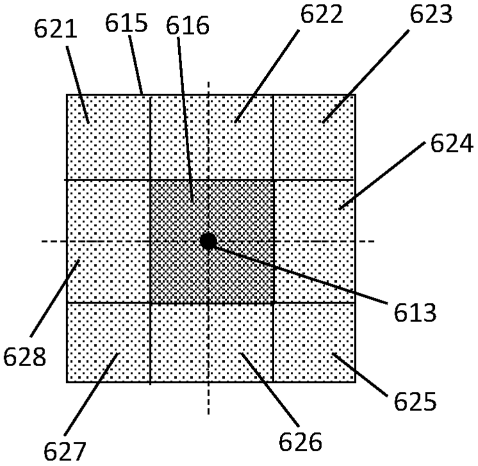


FIG. 6C

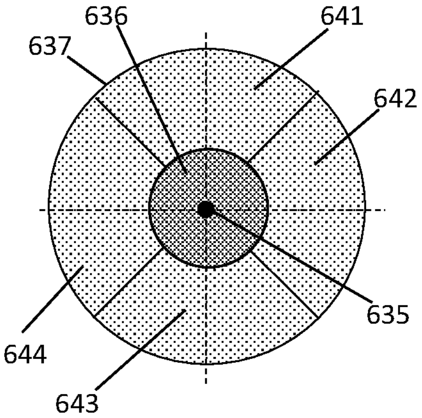


FIG. 7

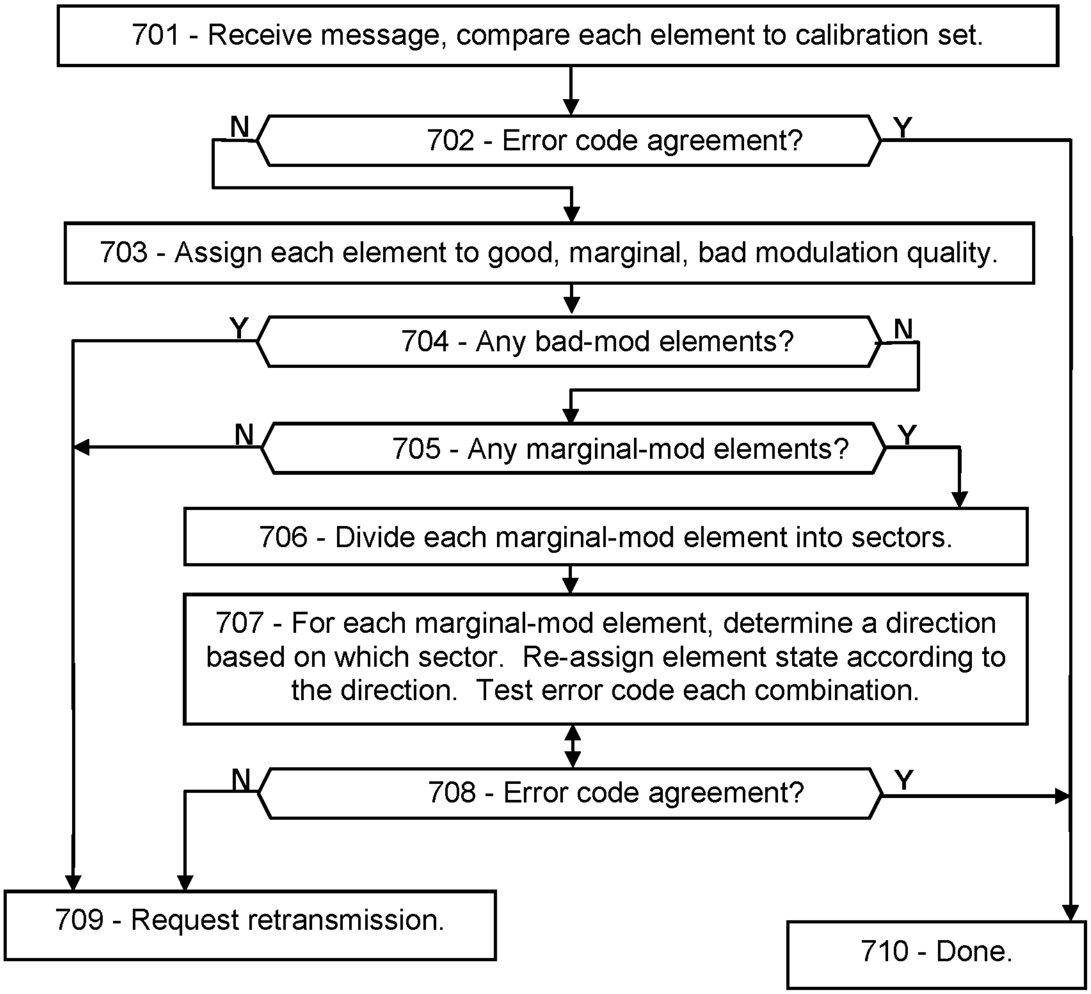

701 - Receive message, compare each element to calibration set.
702 - Error code agreement?
N
Y
703 - Assign each element to good, marginal, bad modulation quality.
704 - Any bad-mod elements?
Y
N
705 - Any marginal-mod elements?
N
Y
706 - Divide each marginal-mod element into sectors.
707 - For each marginal-mod element, determine a direction based on which sector. Re-assign element state according to the direction. Test error code each combination.
708 - Error code agreement?
N
Y
709 - Request retransmission.
710 - Done.

FIG. 8

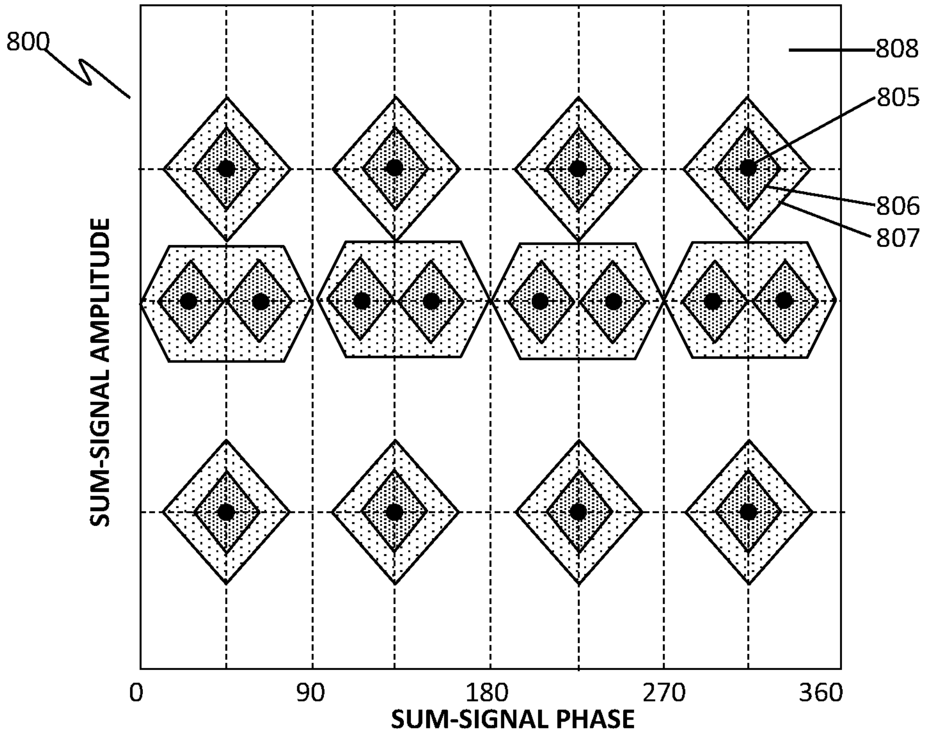
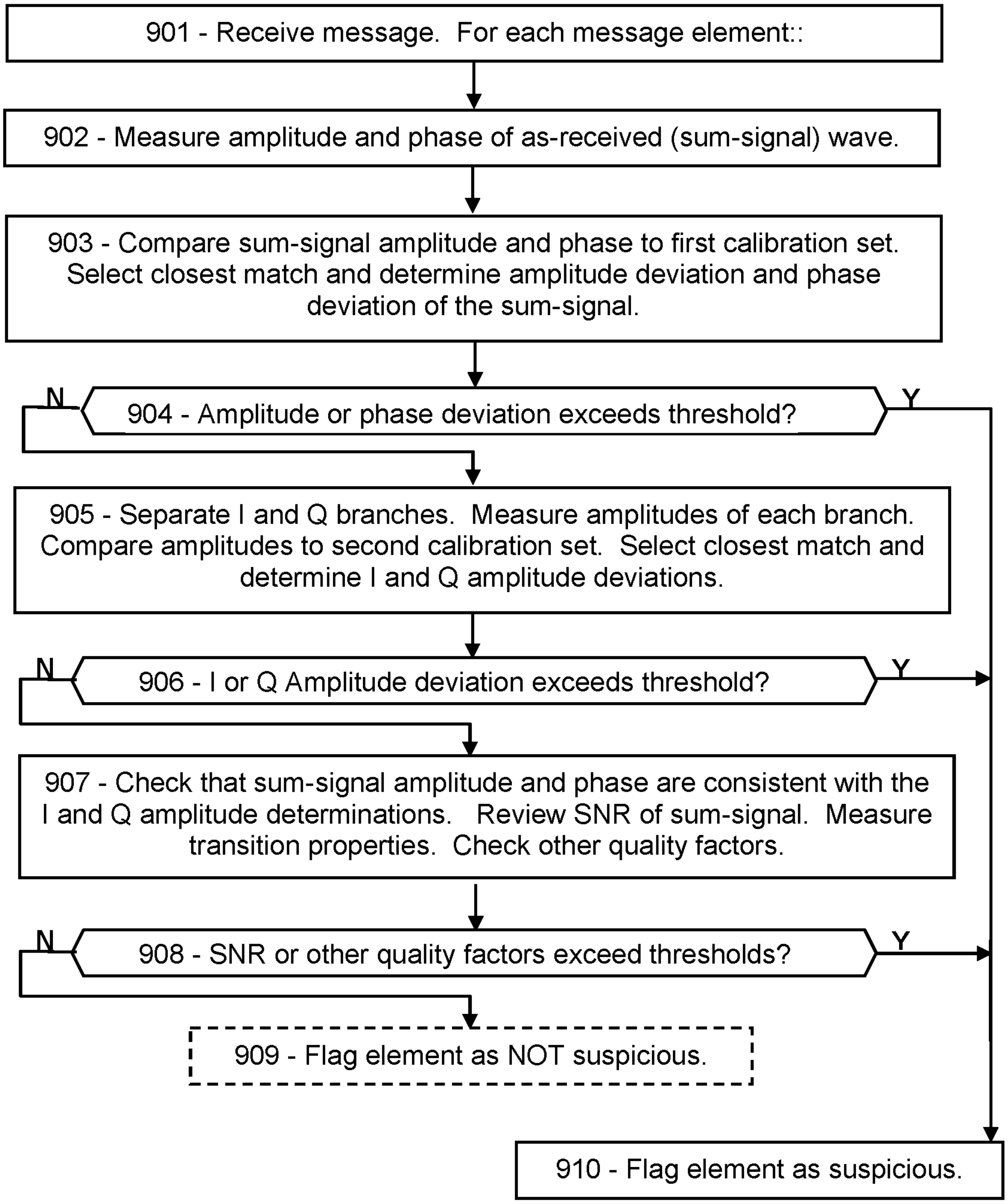

800
808
805
806
807
SUM-SIGNAL AMPLITUDE
0
90
180
270
360
SUM-SIGNAL PHASE

FIG. 9


901 - Receive message. For each message element::
902 - Measure amplitude and phase of as-received (sum-signal) wave.
903 - Compare sum-signal amplitude and phase to first calibration set. Select closest match and determine amplitude deviation and phase deviation of the sum-signal.
N
904 - Amplitude or phase deviation exceeds threshold?
Y
905 - Separate I and Q branches. Measure amplitudes of each branch. Compare amplitudes to second calibration set. Select closest match and determine I and Q amplitude deviations.
N
906 - I or Q Amplitude deviation exceeds threshold?
Y
907 - Check that sum-signal amplitude and phase are consistent with the I and Q amplitude determinations. Review SNR of sum-signal. Measure transition properties. Check other quality factors.
N
908 - SNR or other quality factors exceed thresholds?
Y
909 - Flag element as NOT suspicious.
910 - Flag element as suspicious.

FAULT DETECTION AND CORRECTION BY SUM-SIGNAL MODULATION IN 5G OR 6G

PRIORITY CLAIMS AND RELATED APPLICATIONS

This application is a continuation of U.S. patent application Ser. No. 17/862,555, entitled "Identifying Specific Faults in 5G/6G Messages by Modulation Quality", filed Jul. 12, 2022, which is a continuation of U.S. patent application Ser. No. 17/674,182, entitled "Error Detection and Correction in 5G/6G Pulse-Amplitude Modulation", filed Feb. 17, 2022, which claims the benefit of U.S. Provisional Patent Application Ser. No. 63/151,270, entitled "Wireless Modulation for Mitigation of Noise and Interference", filed Feb. 19, 2021, and U.S. Provisional Patent Application Ser. No. 63/157,090, entitled "Asymmetric Modulation for High-Reliability 5G Communications", filed Mar. 5, 2021, and U.S. Provisional Patent Application Ser. No. 63/159,195, entitled "Asymmetric Modulation for High-Reliability 5G Communications", filed Mar. 10, 2021, and U.S. Provisional Patent Application Ser. No. 63/159,238, entitled "Selecting a Modulation Table to Mitigate 5G Message Faults", filed Mar. 10, 2021, and U.S. Provisional Patent Application Ser. No. 63/230,926, entitled "Error Detection and Correction in 5G by Modulation Quality", filed Aug. 9, 2021, and U.S. Provisional Patent Application Ser. No. 63/280,281, entitled "Error Detection and Correction in 5G by Modulation Quality in 5G/6G", filed Nov. 17, 2021, and U.S. Provisional Patent Application Ser. No. 63/281,187, entitled "Error Correction by Merging Copies of 5G/6G Messages", filed Nov. 19, 2021, and U.S. Provisional Patent Application Ser. No. 63/281,847, entitled "Retransmission of Selected Message Portions in 5G/6G", filed Nov. 22, 2021, and U.S. Provisional Patent Application Ser. No. 63/282,770, entitled "AI-Based Error Detection and Correction in 5G/6G Messaging", filed Nov. 24, 2021, and U.S. Provisional Patent Application Ser. No. 63/309,748, entitled "Error Detection and Correction in 5G/6G Pulse-Amplitude Modulation", filed Feb. 14, 2022, and U.S. Provisional Patent Application Ser. No. 63/309,750, entitled "Error Correction by Merging Copies of PAM-Modulated 5G/6G Messages", filed Feb. 14, 2022, and U.S. Provisional Patent Application Ser. No. 63/310,240, entitled "Retransmission of Selected PAM-Modulated Message Portions in 5G/6G", filed Feb. 15, 2022, and U.S. Provisional Patent Application Ser. No. 63/310,364, entitled "Artificial-Intelligence Error Mitigation in 5G/6G Messaging", filed Feb. 15, 2022, all of which are hereby incorporated by reference in their entireties.

FIELD OF THE INVENTION

The disclosure includes means for detecting and correcting wireless message errors.

BACKGROUND OF THE INVENTION

Transmission faults are inevitable in wireless communication, due to noise, interference, attenuation, and other distortions. In 5G and 6G, faulted messages are detected according to an error-detection code embedded in the message, and corrupted messages are generally discarded or ignored. The message may then be retransmitted and checked again, leading to further delays. What is needed is means for determining which resource elements of a message are faulted, and means for repairing those faults.

This Background is provided to introduce a brief context for the Summary and Detailed Description that follow. This Background is not intended to be an aid in determining the scope of the claimed subject matter nor be viewed as limiting the claimed subject matter to implementations that solve any or all of the disadvantages or problems presented above.

SUMMARY OF THE INVENTION

In a first aspect, there is a method for a wireless receiver to demodulate a wireless message, the method comprising: receiving a message comprising message elements, each message element comprising an I branch signal multiplexed with an orthogonal Q branch signal, wherein each signal, of the I branch signal and the Q branch signal, is modulated according to a first plurality of predetermined branch amplitude levels; determining, according to an error-correction code associated with the message, that the message is corrupted; for each message element, determining a sum-signal comprising the I branch signal added to the Q branch signal, and determining a sum-signal amplitude and a sum-signal phase of the sum-signal; and for each message element, determining a modulation quality by: comparing the sum-signal amplitude to a second plurality of predetermined sum-signal amplitude levels; and comparing the sum-signal phase to a third plurality of predetermined sum-signal phase levels.

In another aspect, there is non-transitory computer-readable media in a wireless receiver, the media containing instructions that when implemented in a computing environment cause a method to be performed, the method comprising: receiving a message comprising message elements, each message element modulated according to a modulation scheme, the modulation scheme comprising a sum-signal amplitude and a sum-signal phase, wherein each sum-signal amplitude is modulated, by a transmitter, according to integer Namp predetermined amplitude levels, and each sum-signal phase is modulated, by the transmitter, according to integer Nphase predetermined phase levels; determining, according to an error-detection code associated with the message, that the message as received is corrupted; for each message element of the message as received, determining a modulation quality according to a combination of an amplitude displacement and a phase displacement, wherein the amplitude displacement comprises a difference between the sum-signal amplitude and a closest predetermined amplitude level of the Namp predetermined amplitude levels, and the phase displacement comprises a difference between the sum-signal phase and a closest predetermined phase level of the Nphase predetermined phase levels.

In another aspect, there is a wireless receiver configured to: determine, according to a demodulation reference, a first plurality of predetermined sum-signal amplitude modulation levels and a second plurality of predetermined sum-signal phase modulation levels; receive a message comprising message elements, each message element modulated according to a modulation scheme, the modulation scheme comprising, for each message element of the message, an I branch signal multiplexed with an orthogonal Q branch signal; for each message element, measure an I branch amplitude of the I branch signal and a Q branch amplitude of the Q branch signal; for each message element, determine a sum-signal comprising a sum of the I branch signal plus the Q branch signal, and determine a sum-signal amplitude and a sum-signal phase of the sum-signal; for each message element, determine a sum-signal amplitude deviation comprising a difference between the sum-signal amplitude of the message element and a closest sum-signal amplitude level of the first plurality, and determine a sum-signal phase deviation comprising a difference between the sum-signal phase of the message element and a closest sum-signal phase level of the second plurality; and for each message element, determine a sum-signal modulation quality according to a combination of the sum-signal amplitude deviation and the sum-signal phase deviation.

This Summary is provided to introduce a selection of concepts in a simplified form. The concepts are further described in the Detailed Description section. Elements or steps other than those described in this Summary are possible, and no element or step is necessarily required. This Summary is not intended to identify key features or essential features of the claimed subject matter, nor is it intended for use as an aid in determining the scope of the claimed subject matter. The claimed subject matter is not limited to implementations that solve any or all disadvantages noted in any part of this disclosure.

These and other embodiments are described in further detail with reference to the figures and accompanying detailed description as provided below.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. **1**A is a chart showing exemplary embodiments of components of a PAM signal, according to some embodiments.

FIG. **1**B is a chart showing exemplary embodiments of further components of a PAM signal, according to some embodiments.

FIG. **1**C is a "constellation" table showing an exemplary embodiment of states of a PAM modulation scheme, according to some embodiments.

FIG. **2**A is a schematic showing an exemplary embodiment of a constellation table for 16QAM, according to some embodiments.

FIG. **2**B is a schematic showing another exemplary embodiment of a constellation table for 16QAM, according to some embodiments.

FIG. **3** is a flowchart showing an exemplary embodiment of a process for detecting and correcting message errors, according to some embodiments.

FIG. **4**A is a schematic sketch showing an exemplary embodiment of a constellation table with multiple levels of modulation quality, according to some embodiments.

FIG. **4**B is a schematic sketch showing an exemplary embodiment of a single modulation state with multiple levels of modulation quality, according to some embodiments.

FIG. **4**C is a schematic sketch showing another exemplary embodiment of a single modulation state with multiple levels of modulation quality, according to some embodiments.

FIG. **5** is a flowchart showing an exemplary embodiment of a process for detecting and correcting message errors using multiple levels of modulation quality, according to some embodiments.

FIG. **6**A is a schematic sketch showing an exemplary embodiment of a constellation table for 16QAM with directional deviation sectors, according to some embodiments.

FIG. **6**B is a schematic sketch showing an exemplary embodiment of a single modulation state with directional deviation sectors, according to some embodiments.

FIG. **6**C is a schematic sketch showing another exemplary embodiment of a single modulation state with directional deviation sectors, according to some embodiments.

FIG. **7** is a flowchart showing an exemplary embodiment of a process for detecting and correcting message errors according to directional deviation sectors, according to some embodiments.

FIG. **8** is a modulation table showing an exemplary embodiment of modulation states and error zones, according to some embodiments.

FIG. **9** is a flowchart showing an exemplary embodiment of a procedure for detecting message faults by measuring sum-signal properties, according to some embodiments.

Like reference numerals refer to like elements throughout.

DETAILED DESCRIPTION

Disclosed herein are procedures enabling a wireless receiver to detect, localize, and correct individual errors in a received message, thereby enhancing reliability and avoiding retransmission delays, according to some embodiments. Systems and methods disclosed herein (the "systems" and "methods", also occasionally termed "embodiments" or "arrangements", generally according to present principles) can provide urgently needed wireless communication protocols to reduce retransmission burdens, improve reliability, and reduce overall delays in networks such as 5G and 6G networks, according to some embodiments. Commonly in wireless communication, interference or noise may distort one or more message elements, resulting in a faulted message reception. Such a message is generally rejected by the receiving entity because the message disagrees with its error-detection code (EDC), such as a CRC (cyclic redundancy code) or a parity construct. However, the faulted message still contains a great deal of information, especially if the fault is restricted to one or a few message resource elements. For example, a message modulated according to PAM (pulse-amplitude modulation) may include one or more message elements with improper amplitude modulation, which may reveal the locations of message faults. Systems and methods disclosed herein can provide means for detecting one or more faulted resource elements in a PAM-modulated message, and efficient procedures for determining the correct value of those resource elements, thereby providing a low-latency high-reliability solution to message fault problems, according to some embodiments.

Terms used herein generally follow 3GPP (Third Generation Partnership Project) usage, but with clarification where needed to resolve ambiguities. As used herein, "5G" represents fifth-generation and "6G" sixth-generation wireless technology. A network (or cell or LAN or local area network or the like) may include a base station (or gNB or generation-node-B or eNB or evolution-node-B or access point) in signal communication with a plurality of user devices (or UE or user equipment or nodes or terminals) and operationally connected to a core network (CN) which handles non-radio tasks, such as administration, and is usually connected to a larger network such as the Internet. "Receiver" is to be construed broadly, including processors accessible by the recipient of a message, and configured to perform calculations on received signals or messages. Embodiments may include direct user-to-user ("sidelink") communication such as V2V (vehicle-to-vehicle) communication, V2X (vehicle-to-anything), X2X (anything-to-anything, also called D2D or device-to-device) and base station communications or V2N (vehicle-to-network). "Vehicle" is to be construed broadly, including any mobile wireless communication device. The time-frequency space is generally configured as a "resource grid" including a number of "resource elements", each resource element being a specific unit of time termed a "symbol time", and a specific frequency and bandwidth termed a "subcarrier" (or "subchannel" in some references). Each subcarrier can be independently modulated to convey message information. Thus a resource element, spanning a single symbol in time and a single subcarrier in frequency, is the smallest unit of a message. "RNTI" (radio network temporary identity) or "C-RNTI" (cell radio network temporary identification) is a network-assigned user code. "QoS" is quality of service, or priority. "QCI" (QoS class identifier) defines various performance levels. "QPSK" (quad phase-shift keying) is a modulation scheme with two bits per message element, and "16QAM" (quadrature amplitude modulation with 16 states) is a modulation scheme with 4 bits per message element. "SNR" (signal-to-noise ratio) and "SINR" (signal-to-interference-and-noise ratio) are treated equivalently herein.

"PAM" (pulse-amplitude modulation, not to be confused with signal generation by rapid pulsatile energy bursts) is a message modulation technology in which bits of a message are allocated to two sinusoidal "branch" signals, which are then amplitude-modulated to encode the message bits, and then summed with a 90-degree phase offset, and transmitted. The receiver can then receive the transmitted signal, separate the two branch signals, and measure their amplitudes. The receiver can demodulate the message elements by separating the two branch signals, measuring their amplitudes, and comparing to a set of predetermined amplitude levels of the PAM modulation scheme. The branches may be termed the "real" and "imaginary" branches, or the "I and Q" (in-phase and quadrature-phase) branches. A "constellation table" is a chart showing the I and Q modulation states of a PAM modulation scheme.

The "sum-signal" is the as-received waveform before separating the branches, or equivalently, the sum of the two branches. Each of the I-branch and Q-branch signals may be amplitude modulated according to one of the predetermined amplitude levels. For example, 16QAM has two predetermined amplitude levels, such as +1 and +3 in some units, and their negatives. Each branch can then be amplitude modulated as −3, −1, +1, or +3, thereby representing four possible "branch amplitudes". Each message element includes two branches, each of which has four branch amplitude possibilities, thereby providing 4×4=16 total modulation states, as expected for 16QAM.

In addition to the 3 GPP terms, the following terms are defined herein. Although in references a modulated resource element of a message may be referred to as a "symbol", this may be confused with the same term for a time interval, among other things. Therefore, each modulated resource element of a message is referred to as a "modulated message resource element", or more simply as a "message element", in examples below. A "demodulation reference" is a set of modulated resource elements that exhibit levels of a modulation scheme (as opposed to conveying data). A "calibration set" is one or more amplitude values, which have been determined according to a demodulation reference, representing the predetermined amplitude levels of a modulation scheme, or the negative of those levels. A "sum-signal" is a signal produced by adding (or summing) the I-branch and Q-branch signals. A receiver, upon receiving the sum-signal, can separate the two branches therein, and measure the amplitude of each branch. A "branch amplitude" is the amplitude of an I or Q branch signal, as determined by a receiver. The receiver can demodulate a message element by extracting its I and Q branch signals, measuring their branch amplitudes, and comparing to the levels of a calibration set according to a preceding demodulation reference. An "amplitude deviation" of a message element is the difference between its I or Q branch amplitude and the closest predetermined amplitude level in the calibration set. Accordingly, the "modulation quality" of a message element is a measure of how close the I and Q branch amplitudes are to the closest predetermined amplitude level of the modulation scheme, or equivalently how close the modulation of the message element is to the closest state of the modulation scheme, as indicated by amplitude levels in the calibration set. Thus the "closest state" of the modulation scheme to a particular message element is the state that has the closest amplitude levels to the I-branch and Q-branch amplitudes. Each state corresponds to a first predetermined amplitude level and a second predetermined amplitude level, corresponding to the I-branch and Q-branch amplitudes of a demodulation reference, for example. The closest state to a particular message element is the state in which the difference between the first predetermined amplitude is closest to the message element's I-branch amplitude and the second predetermined amplitude is closest to the message element's Q-branch amplitude. The modulation quality may be calculated by adding those differences in magnitude, or the square root of the sum of the squares of the differences, or other formula relating the deviation of the message element's amplitudes from the modulation state's amplitudes.

A message may be configured "time-spanning" by occupying sequential symbol-times at a single frequency, or "frequency-spanning" on multiple subcarriers at a single symbol-time. An "EDC" (error-detecting code) is a field in a message configured to detect faults, such as a "CRC" (cyclic redundancy code) or a parity construct or the like. A message is "unicast" if it is addressed to a specific recipient, and "broadcast" if it includes no recipient address. Transmissions are "isotropic" if they provide roughly the same wave energy in all horizontal directions. A device "knows" something if it has the relevant information. A device "listens" or "monitors" a channel or frequency if the device receives, or attempts to receive, signals on the channel or frequency. A message is "faulted" or "corrupted" if one or more bits of the message are changed relative to the original message. "Receptivity" is the quality of reception of a message. If one or more elements of a "subject" message have been changed when received, the message "fails the EDC test", that is, the embedded error-detection code disagrees with the bit-level content of the message. The fault may have occurred during the modulation step in the transmitter, or in propagation through the air, or at the receive side, and may be due to electronic noise or external interference or atmospheric absorption or scattering or reflection of the electromagnetic wave, to name just a few possible sources of message faults. Distortion of the I and Q branch amplitudes can cause the receiver to incorrectly demodulate the message elements, in which case the message fails the EDC test.

Upon detecting a faulted message, the recipient in 5G/6G can do one of several things. If the recipient knows that the faulted message is intended for that recipient, such as a base station that has scheduled an uplink message at a particular time or a user device receiving a scheduled downlink message, the recipient can request a retransmission after detecting the fault. For most downlink control messages, however, the user device does not know the time or frequency or length of the message, or even if the message is intended for that user device, because in 5G and 6G the downlink control messages are generally scrambled by the recipient's identification code. User devices then perform a "blind search" by attempting to unscramble candidate downlink control messages to locate their messages. However, a faulted message will disagree with its error-detection code, causing the message to appear as intended for some other user device, and would be ignored by the intended recipient. Then the user device, upon failing to receive the message within a predetermined interval, can request a retransmission, if it is expecting a message. Alternatively, the base station can retransmit the message after failing to receive an expected acknowledgement, among other options. In each case, substantial time is lost, and substantial extra transmission power is wasted, responding to a faulted message. Such delays may be especially critical for low-latency applications such as remote surgery and traffic safety.

In contrast, the methods and systems disclosed herein may enable a user device to recover the faulted message in a fraction of the retransmission time, thereby saving the message, avoiding the retransmission delays, enhancing network reliability, and avoiding adding to the electromagnetic background by avoiding the retransmission, according to some embodiments. As a first example, the systems and methods disclosed herein include a method for mitigating a message fault by determining a modulation quality of each message element. If the message is determined to be faulted, the receiver can alter the "suspicious" message elements (or, more specifically, alter the modulation state that the message element is assigned to) based on modulation quality, and compare the altered message to the error-detection code, as a way of seeking the correct message demodulation.

Following are examples of PAM modulation schemes, according to which a faulted message element may be revealed and possibly repaired.

FIG. **1**A is a chart showing exemplary embodiments of components of a PAM signal, according to some embodiments. As depicted in this non-limiting example, a PAM-modulated message element includes two "branches" labeled I and Q, each branch being a sinusoidal signal which is amplitude modulated at one of the predetermined amplitude levels (or its negative) of the modulation scheme. The branch amplitudes thereby encode the bits of the message element. The I branch **101** is depicted here as a cosine curve, while the Q branch **102** is a sine curve. The two branches **101**, **102** are summed and transmitted as the sum-signal **103**. The Q branch has zero signal at a zero-degree phase where the I branch is maximum, and the I branch is zero at the 90-degree phase at which the Q branch is maximum. The receiver, by selecting each branch separately (using RF mixers, for example), can measure the amplitude of each branch, and thereby identify the message bits encoded in those amplitude levels. For example, the receiver may determine that the "branch amplitude" of the I branch **101** is as indicated by a square **104**, and the amplitude of the Q branch **102** is as indicated by another square **105**.

Generally, the transmitter sets each of the branch amplitudes **104** and **105** to equal one of the predetermined amplitude levels of the modulation scheme, or its negative. For example, in 16QAM with PAM modulation, there are two predetermined amplitude levels (such as +1 and +3 in some units), and their negatives. Each branch can then be amplitude modulated according to one of the predetermined amplitude levels or its negative, such as +3, +1, −1, −3). In this context, the "predetermined amplitude levels of the modulation scheme" can include both positive and negative values, thereby including all four predetermined values in the calibration set by which the received message elements are then demodulated. The values are generally arranged to be uniformly separated. The sum-signal **103** is the sum of the two branches **101** and **102**, each with a branch amplitude set equal to one of those four values, thereby constructing 16 possible states. Higher-order modulation include more predetermined levels (three in 64QAM, in for 256QAM, and so forth). QPSK, with 4 states, has only a single predetermined amplitude level, which can be positive or negative for each of the two branches, thereby forming 4 states as expected. As mentioned, in PAM the number of states in the modulation scheme is then $(2L)^2$, accounting for both positive and negative values of the L predetermined amplitude levels of the modulation scheme.

In some embodiments, the receiver can also analyze the sum-signal itself **103** to extract further information about the modulation quality, or to reveal modulation information more readily measured than the branch amplitudes. For example, the figure further indicates as **106** the amplitude of the sum-signal, and its peak phase as **107**. As described below, the receiver may extract fault information by testing the sum-signal properties, and/or by comparing the sum-signal properties to the expected PAM levels.

FIG. **1**B is a chart showing exemplary embodiments of further components of a PAM signal, according to some embodiments. As depicted in this non-limiting example, eight waves are shown depicting I branches and Q branches for various modulation states. In PAM, a small number (such as two) positive amplitude levels may be predetermined. In modulating the branches of a message element, the amplitude levels may be provided as either positive or negative values, and the phase may be provided as zero or 90 degrees, thereby composing the eight curves depicted. The message element is then transmitted with one of the four I waves added to one of the four Q waves, thereby generating 16 states of a modulation scheme such as 16QAM. In higher order modulation, more amplitude levels are provided, but the procedure is the same.

More specifically, wave **111** represents the maximally positive I branch signal, **112** the minimally positive I signal, and **113** and **114** the minimally and maximally negative I signals, respectively. On the Q branch, **118** and **117** are the maximally and minimally positive levels, while **115** and **116** are the maximally and minimally negative signals, respectively. The receiver, by determining which of the predetermined amplitude levels most closely matches the detected I or Q branch amplitude, can thereby demodulate the message element.

FIG. **1**C is a constellation chart showing an exemplary embodiment of states of a PAM modulation scheme, according to some embodiments. As depicted in this non-limiting example, 16 states are indicated as dots **125** in an array with the predetermined I-branch amplitude levels shown horizontally and the Q-branch amplitude levels vertically. The branch levels are labeled as "Pos-Max" for the maximally positive amplitude value, "Pos-Min" for the minimally positive amplitude level, then "Neg-Min and Neg-Max" for the maximally and minimally negative amplitude states. The transmitted message element is composed of one I-branch amplitude signal plus one Q-branch amplitude signal, transmitted together as a sum-signal.

The central cross shape **122** indicates zero amplitude. In PAM generally, zero amplitude is not used for messaging, and the branch phases are offset from the carrier by 45 degrees for carrier suppression. In the chart, the minimally positive amplitude is each displaced from zero by the value **124**, and the maximally positive level is an additional amount **123**. For example, the value **124** could represent one unit and the value **123** could represent two units, thereby providing that the various states are all separated from their adjacent neighbors by the same amount, namely two units. The receiver, by measuring the I and Q branch amplitudes and comparing to a previously-determined set of amplitude levels (from a demodulation reference, for example), can select the modulation state with the closest match to the measured amplitudes and thereby demodulate the message element.

The following examples indicate how faulted message elements in a PAM-modulated message may be detected.

FIG. **2**A is a schematic showing an exemplary embodiment of a PAM constellation table, according to some embodiments. As depicted in this non-limiting example, a constellation table **200** includes 16 states **205** of 16QAM, each state **205** including one of the four I-branch amplitudes summed with one of the four Q-branch amplitudes. Around each modulation state **205** is a rectangular form in dark stipple representing a "good-modulation zone" **206** (or "good-mod" in figures). The size of the good-modulation zone **206** is shown as the dimensions **211** and **212**. Usually, the good modulation zone **206** is square. If the receiver measures the message element's branch amplitudes to be within one of the good-modulation zones **206**, the message element is assigned to the associated modulation state **205**. For example, the small "x" **207** indicates a measured as-received message element, having an I-branch amplitude and a Q-branch amplitude accordingly, thereby falling within the good-modulation zone **206** of the associated state **205**.

The exterior white space **208** is a "bad-modulation zone" (or "bad-mod") in which the modulation of the message element falls outside all of the good-modulation zones, and therefore is invalid or illegal and not used for modulation. For example, a particular message element is received with modulation in I and Q amplitudes as depicted by an "o" **209**, which is in the bad-modulation zone **208**. The received message element may exhibit an I-branch amplitude deviation **214** and a Q-branch amplitude deviation **213** relative to the closest modulation state, which in this case is **215**. If the I-branch amplitude deviation **214** is greater than the good modulation zone width **212**, or the Q-branch amplitude deviation **213** is greater than the good modulation zone height **211** (relative to the nearest state **215**), then that message element is flagged as bad-modulation. In some embodiments, the bad-modulation message elements may be assigned to the nearest modulation state **215** initially, although this assumption may be revised later if the message fails its error-detection test.

After all of the message elements have been assigned to the closest states of the modulation scheme, the message may be checked against an error-detection code which is normally embedded in the message. If the message agrees with the error-detection code, the tentative assignment of the bad-modulation message elements is confirmed, and the message has been successfully demodulated. If not, the receiver may attempt to recover the message by altering the bad-modulation message elements. As used herein, "altering" a message element means changing which state of the modulation scheme is assigned to the message element. After changing the assigned state of the suspicious message element, the altered message may be tested again with the error-detection code to see if the altered message is the correct version.

FIG. **2**B is a schematic showing another exemplary embodiment of a PAM constellation table for 16QAM, according to some embodiments. As depicted in this non-limiting example, the constellation table **220** may include four I-branch amplitude levels and four Q-branch amplitude levels, for sixteen states **225**. Each state **225** is surrounded in this case by a circular good-modulation zone **226**, each with a radius **232** as indicated. The exterior white space **228** represents bad-modulation.

A particular message element "x" **227** is shown in a good-modulation zone **226** associated with the state **225**. The radial distance (not labeled) between the message element's modulation and the closest state is less than the radius **232** of the good-modulation zones.

Another message element "o" **229** has an I-branch amplitude deviation **234** and a Q-branch amplitude deviation **233**, and is at a distance **230** from the nearest state **235**. If that distance **230** is less than the radius **232** of the good-modulation zone, the message element is allocated to "good-modulation". However, in this case the distance **230** is greater than the radius **232**, and therefore the message element is flagged as "suspicious" or "bad-modulation" and may be altered later for fault mitigation, if needed. Initially, however, the message element may be assigned to the nearest state **235** for purposes of demodulating the message.

While the figure shows the 16QAM modulation scheme, many other modulation schemes are possible. For example, 64QAM and 256QAM involve additional I and Q amplitude levels, whereas QPSK has only a single amplitude level (repeated positive and negative, I and Q, thereby making four QPSK states). The methods described herein for 16QAM can be applied straightforwardly to QPSK and higher QAM modulation schemes, according to some embodiments.

The figure, and the other examples to follow, are presented according to a standard pulse-amplitude modulation scheme. In other embodiments, however, the message may employ classical amplitude and phase modulation, in which each message element is amplitude modulated according to one of Namp amplitude levels and phase-modulated according to one of Nphase phase levels. The multiplexed amplitude and phase modulations thereby generate Namp×Nphase distinct states. For example, with classical amplitude-phase modulation, 16QAM has four amplitude and four phase levels, resulting in 16 combinations. Upon receipt, the receiver measures the amplitude and phase of the signal, then selects whichever predetermined state most closely matches those values. The systems and methods described herein are straightforwardly applicable to classical amplitude and phase modulation as well as other modulation technologies. As long as the modulation scheme involves modulating the phase and/or the amplitude of an electromagnetic wave, it is immaterial which modulation technology is employed. For consistency and clarity, most of the examples refer to PAM, however the principles disclosed herein may apply to each of these modulation technologies, as will be apparent to artisans with ordinary skill in the art after reading the present disclosure.

FIG. **3** is a flowchart showing an exemplary embodiment of a process for detecting and correcting message errors, according to some embodiments. As depicted in this non-limiting example, a receiver may receive a message at **301**, and may measure the amplitude of each I and Q branch of each message element at **302**, and compare each message element's amplitude values to the amplitude levels of a calibration set, which represents the states of the modulation scheme. At **303**, the receiver determines whether each message element's amplitude values fall within a predetermined range of one of the states of the modulation scheme. If so, at **305** the message element is flagged as good-modulation. If the message element's amplitudes are outside the range of the states of the modulation scheme (or if the distance to the nearest state is greater than the good-modulation radius), then the message element is flagged as bad-modulation at **304**. In either case, at **306** the message element is assigned the nearest modulation state initially. The state determinations, allocations, and assignments are repeated for each message element, as suggested by a dashed arrow.

At **307**, after assigning each message element to the closest state, the receiver can compare the message to an error-detection code. If there is agreement, the message is assumed to be correctly demodulated, and the task is done at **314**. If the message fails the error-detection code, then at **308** the receiver can determine whether the message includes any message elements flagged as bad-modulation. If not, then the receiver may request a retransmission at **313**, or other action depending on reception rules and other conditions. If at **308** there is at least one message element flagged as bad-modulation, then at **309**, the receiver may alter the assigned state of each bad-modulation element to the next-closest modulation state instead of the closest one. The "next-closest" state is the closest state to the message element's modulation, except the closest one. Some types of noise and interference cause mainly small changes in the branch amplitudes of the message elements, and therefore an economical strategy for recovering the message may be to alter each bad-modulation element by a small amount, testing each such alteration against the error-detection code.

At **310**, the message with the altered assignment is tested against the error-detection code, and if there is agreement, the task is done at **314**. If not, the receiver may continue altering any remaining bad-mod element assignments to their next-closest state, one at time, and test each alteration. After testing each one of the bad-mod elements individually in this way, the receiver can then alter the bad-mod elements two at a time, testing each alteration for agreement with the error-detection code. If not successful, the receiver can alter the assignments in combinations of three, and other numbers of bad-mod elements, altering each one to the nearest and next-nearest states of the modulation scheme. The receiver can continue varying the bad-mod elements until all possible combinations of the bad-mod elements have been altered to their next-closest state of the modulation scheme, and can test each altered message against the error-detection code. This process is a loop, cycling through steps **309** and **310** repeatedly until all combinations have been tested. However, for clarity in the figure, the steps are shown simply as a command **309** and an interrogator **310**, with a double-ended arrow between them. The double-ended arrow indicates that the two steps are to be performed repeatedly and cyclically until all the associated variations have all been tested, and aborting the loop if any of the variations passes the EDC test.

If the message fails the error-detection test for all of the alterations of the bad-mod elements to their closest and next-closest states, the flow proceeds to **311** for a more exhaustive search. Here each of the bad-mod message elements is again altered sequentially, but now they are varied to all of the states of the modulation scheme, instead of being restricted to just the closest and the next-closest states, and each such alteration is tested (skipping the already-tested alterations, however). Each of the bad-mod message elements can be tested sequentially at each of the states, while all of the other bad-mod message elements are also altered in turn. Such a grid search, in which two or more items are independently varied among multiple settings, and all possible combinations are tested, may be termed a "nested" search. For example, if there are B bad-mod message elements and the modulation scheme has S states, the number of combinations is S^B separate tests. If any of those tests results in agreement with the error-detection code at **312**, the task is done at **314**. If none of the tests is in agreement, at **313** a retransmission is requested. The current message is then abandoned, or, in another embodiment, the message may be retained for analysis when the retransmitted version is received.

In most cases, the time required for a retransmission may be much longer than the time required to alter an assigned modulation state of a message element and compare to the error-detection code, and therefore it may be economical to attempt to repair the faulted message in this way, by altering the state assignments of the message elements having the worst modulation quality, as measured by how far the branch amplitude values fail to match the levels of the calibration set. However, there is a limit to how many alterations the receiver can test in a given time. If the number of bad-modulation message elements exceeds a threshold number, the receiver may request a retransmission immediately instead of embarking on a probably futile effort to repair the message.

FIG. **4A** is a schematic sketch showing an exemplary embodiment of a constellation table with multiple levels of modulation quality, according to some embodiments. As depicted in this non-limiting example, a constellation table **400** (for 16QAM in this case) includes four I-branch amplitude levels, four Q-branch levels, and sixteen states **405**. Around each state **405** is a good-modulation zone **406** in dark stipple, surrounded by a marginal (that is, marginal quality) modulation zone **407** in light stipple, and the remaining white space **408** is a bad-modulation zone. A message element with modulation falling in (or occupying) one of the good-modulation zones **406** may be assigned to the associated state **405** of the modulation scheme. A message element with modulation falling in the marginal-modulation zone **407** may also be assigned to the associated state **405**, but with a flag indicating that it is suspicious due to its lower quality of fit to the predetermined amplitude levels. A message element with modulation falling in the bad-modulation zone **408** may be assigned to the nearest state **405**, but with a flag indicating that it is bad-modulation or very suspicious. If the message is subsequently determined to be faulted, the bad-modulation elements may be altered first, to determine whether any alterations may satisfy the EDC test. If none of those variations succeeds in agreeing with the error-detection code, then the bad-modulation elements and the marginal-modulation elements may be varied together in a nested grid search. The lowest-quality, bad-modulation elements may be varied first because they are the most likely sources of the message failure. If those variations fail to agree with the error-detection code, or if there are no bad-modulation elements, then the message elements with marginal quality modulation may be varied. However, if the number of bad-modulation and marginal-modulation elements exceeds a maximum value, the receiver may request a retransmission instead of performing a grid search, due to the time and calculational effort required to perform large numbers of variations.

FIG. **4B** is a schematic sketch showing an exemplary embodiment of a single modulation state with multiple levels of modulation quality, according to some embodiments. As depicted in this non-limiting example, a modulation state **415** (such as one of the modulation states of the previous figure) may be configured as the multiplexed I and

Q amplitude modulations of the modulation scheme. The modulation state **415** may be surrounded by a good-modulation zone **416**, and further surrounded by a marginal-modulation zone **417**. The good-modulation zone **416** may be a rectangular region with a half-width **413** in the I-branch and **418** in the Q-branch as shown. The marginal-modulation zone **417** may be a rectangular region with half-dimensions **414** and **419**. Message elements modulated in the good-modulation zone **416** may be assigned the associated state **415** with high probability. Message elements modulated in the marginal-modulation zone **417** may also be assigned the state **415** too, but flagged as suspicious. Message elements modulated exterior to the marginal-modulation zone **417** may also be assigned the state **415** if that is the closest one, but may be flagged as likely bad-modulation for the purposes of mitigating faults.

FIG. **4C** is a schematic sketch showing another exemplary embodiment of a single modulation state with multiple levels of modulation quality, according to some embodiments. As depicted in this non-limiting example, a single modulation state **425** may be surrounded by a round region of good modulation **426** which may be surrounded by an annular region of marginal quality modulation **427**. The radius **423** of the good-modulation region **426** is shown, and the outer radius **424** of the marginal-modulation region **427** is shown. Thus a message element may be allocated to the good-modulation category if the I and Q branch amplitudes are such that the modulation falls in the good-modulation zone **426**, and likewise for the marginal-modulation zone **427**. For example, the "distance" of the message element from the state **425** may be calculated as the square root of the I-branch amplitude deviation squared plus the Q-branch amplitude deviation squared. If this distance is less than the good-modulation radius **423** the message element, is allocated good modulation quality. If the distance is greater than the good-modulation radius **423** but less than the marginal-modulation radius **424**, the message element may be allocated marginal modulation quality. If the distance is greater than the marginal-modulation radius **424**, the message element may be allocated bad modulation quality. The foregoing examples involved categorizing message elements into two or three categories according to modulation quality, and altering the message elements in each category. In some embodiments, the receiver may use any number of such categories, not restricted to two or three. In some embodiments, the receiver may eschew categories and may instead select which message elements to alter based on the calculated distance, in phase-amplitude space, of each message element from the closest state.

FIG. **5** is a flowchart showing an exemplary embodiment of a process for detecting and correcting message errors using multiple levels of modulation quality, according to some embodiments. As depicted in this non-limiting example, at **501** a receiver receives a message and compares each message element to the amplitude levels previously provided in a calibration set. The calibration set includes the I-branch and Q-branch amplitude levels of the modulation scheme, as provided by a demodulation reference, for example. At **502**, the receiver assigns each message element to the closest state of the modulation scheme, and also categorizes the modulation quality of each message element as good, marginal, or bad-modulation depending on the distance of the message modulation to the nearest state of the modulation scheme. After attempting to demodulate the message elements, the receiver compares the message to an error-detection code at **503**. If the message agrees with the error-detection code, the task is done at **517**. If not, the receiver checks, at **504**, whether the message contains any bad-modulation elements, and drops to **507** if not. If the message has one or more bad-modulation elements, at **505** the receiver varies the bad-modulation elements among all of the states of the modulation scheme in a nested grid search, as indicated by a double arrow. For example, the receiver may alter the first bad-modulation element successively to each state, while keeping the other bad-modulation elements assigned to their closest states, and may test each variation against the error-detection code. The receiver may perform a similar scan using the second bad-modulation element while keeping all the others at their closest state values, and may continue such a single-element variation until all of the bad-modulation elements have been explored individually. Then, if no match has been found, the receiver may vary combinations of the bad-modulation elements across all of the states, testing all combinations of the bad-modulation elements at all states of the modulation scheme. If any one of those variations satisfies the error-detection code, the message is correctly demodulated and the task is done at **517**. If not, the flow proceeds to **507**.

At **507**, the receiver determines whether the message has any marginal-modulation elements, and if so, it varies the marginal-modulation elements and the bad-modulation elements together in a nested search at **508**, as indicated by a double arrow. (The asterisk is explained later.) The receiver can vary the bad and marginal-modulation elements in an exhaustive grid search by setting each of the suspicious elements to each of the states of the modulation scheme, and test the error-detection code for each variation at **509**. If any of those variations agrees with the error-detection code, the task is done. If not, or if there are no marginal-modulation elements, the receiver may request and receive a second copy of the message at **510**, and may merge the first and second copies by selecting the message elements with the best quality modulation at **511**, and then may test the merged version against the error-detection code at **512**. If successful, it is done. If not, the flow proceeds to **513**.

At **513**, the receiver may determine whether the merged message still includes any bad or marginal-modulation elements. The receiver may also note any message elements that differ in the originally received version and the retransmitted version, yet occupy good-modulation zones in each version. Such message elements are termed "paradoxical", and may be flagged as suspicious since the two message copies contradict each other. If the merged message has all good-modulation message elements and no suspicious (bad or marginal or paradoxical) message elements, yet still fails the EDC test, then there is some kind of problem, in which case the receiver may abandon the message at **516** and optionally file a fault report. However, if the merged message has one or more suspicious message elements at **514**, the receiver may vary those in another nested search such as described above, testing each variation at **515**. If one of those variations agrees with the error-detection code, the task is finally done. If not, the receiver may abandon at **516**.

In some embodiments, the receiver may determine the modulation quality as a calculated value, instead of the good-marginal-bad categories. The receiver can then vary the remaining suspicious elements according to the modulation quality value, starting with the message element that has the lowest modulation quality. The receiver can then proceed to vary and test the second-lowest modulation quality message element, and so forth until the error-detection code matches.

In some embodiments, the amount of time required to perform the searches of **506** and **509** may exceed the amount of time to request and receive a second copy of the message, in which case the receiver may request the second copy as soon as the initial version fails the error-detection code, as indicated by a dashed arrow. The receiver may already know how much time it takes to test all combinations given the number of bad and marginal-modulation elements, using an algorithm for example. While waiting for a retransmission, the receiver may continue to test variations, since the receiver might succeed in demodulating the message before the retransmitted message arrives.

In some embodiments, the variations of the marginal-modulation message elements at **508** may be done in two stages for improved efficiency, as indicated by an asterisk (*). Many types of noise cause only small changes in the modulation of message elements, whereas interference from a nearby transmission can cause a large change in the message element. If the background is due mainly to noise or to low-amplitude interference, the amount of distortion produced upon each message element may be small. In that case, the message elements with marginal quality modulation are likely to belong to the associated state or to one of the adjacent states of the modulation scheme, as opposed to a more distant state that differs by a large amount in amplitude and phase. Therefore, the distortion is more likely to move the I-branch or Q-branch amplitude (or both) by one amplitude step than a larger number of amplitude steps. The receiver may exploit this by altering each of the marginal-modulation message elements to its nearest neighbors and testing those small-step alterations first, before attempting larger jumps. For example, a particular state of the modulation scheme has eight adjacent states if the particular state is in the middle of the constellation table, or five adjacent states if at one edge, or three adjacent states if at a corner. The receiver may save time and enhance the likelihood of finding a solution by testing those eight (or five or three) nearest-neighbor alterations first, before testing the larger variations across the entire constellation table. If the message has more than one marginal-modulation element, the receiver may perform a nested grid search by altering the assigned state of each of the marginal-modulation message elements to each of their adjacent states, exploring all combinations of all marginal-modulation elements in their adjacent states. If none of those adjacent-neighbor alterations passes the EDC test, then the receiver may proceed to vary the marginal-modulation message elements across the entire set of states of the modulation scheme (preferably skipping the alterations that have already been checked). By testing the most likely combinations of message alterations first, the receiver may avoid a large number of unlikely variations, and may thereby resolve the fault and recover the correct message quickly, according to some embodiments.

The systems and methods disclosed herein further include "directional sectors" defined around each state of the modulation scheme. The directional sectors may indicate how a faulted message may be recovered, according to some embodiments.

FIG. **6**A is a schematic sketch showing an exemplary embodiment of a constellation table for 16QAM with directional deviation sectors, according to some embodiments. As depicted in this non-limiting example, a constellation table **600** includes states **605**, each state surrounded by a good (quality) modulation zone **606** and a marginal (quality) modulation zone **607** within white space bad (quality) modulation area **608**. The marginal-modulation zones **607** are divided into multiple sectors, as explained in more detail in the next figure.

The sectors may assist the receiver in recovering a faulted message. For example, if a message fails the EDC test, the receiver may look for a particular message element modulated in a marginal-modulation zone **607**, such as the "x" **609**. The message element represented by the "x" **609** is initially assigned to the nearest state which is **611**. However, since the message fails the error-detection test with that assignment, and since the "x" message element's modulation quality is only marginal, the receiver may attempt to correct the message by altering the assignment to a different state. For example, the receiver may alter the assignment to the adjacent state in a direction indicated by the sector that the "x" **609** occupies, that is, altering the assignment to the state **612**. In the depicted case, the "x" **609** is in a sector directed toward a lower Q-branch amplitude state with the same I-branch amplitude, and therefore the receiver may attempt altering the message element to the next-lower Q-branch amplitude **612**, as indicated by a dashed arrow **610**, and may test that message alteration against the EDC code. Direction-assisted alteration may be an economical strategy for mitigating a message fault first in a direction as indicated by the occupied sector, before embarking on a wider search. The receiver may thereby enhance the probability that the correct state assignment may be determined without having to vary multiple message element assignments across the entire modulation table.

The figure further depicts another message element "o" **614** which lies in the bad-modulation zone **608** but has been assigned to the nearest state **616** of the modulation scheme. Also shown is an arrow **615** indicating a direction of the message element's modulation relative to the nearest state **616**. If the message is found to be faulted, then the bad-modulation message element **614** may be re-assigned to the closest neighboring state in the direction of the arrow **615**, which in this case is the state **613**, and that alteration may be tested against the error-detection code. Instead of using sectors to define a direction, and instead of restricting the directionality to just the marginal-modulation elements, the arrow **615** pointing toward the message element's location on the constellation table may be used to guide the first and most likely alteration, which is to state **613** in this case.

In some embodiments, the receiver may determine which message elements are most likely faulted, and in which direction to alter the state assignment, according to calculations instead of zones and sectors. For example, the receiver can determine a modulation quality according to a distance from the message element's modulation to the nearest state of the modulation scheme, and can calculate a direction according to the position of the message element's modulation relative to the nearest state. If the distance is larger than the distances of any of the other message elements of the message, then the receiver may alter the state assignment of that lowest-quality message element to the adjacent state in the direction calculated, and thereby test the most likely version of the message before embarking on a long and tedious nested search.

FIG. **6**B is a schematic sketch showing an exemplary embodiment of a single modulation state with directional deviation sectors, according to some embodiments. As depicted in this non-limiting example, a modulation state may include a state **613** with a good-modulation zone **616** surrounded by a marginal-modulation zone **615**. The marginal-modulation zone **615** is divided into eight sectors in this case, **621**, **622**, **623**, **624**, **625**, **626**, **627**, and **628**. The sectors **621**-**628** may assist the receiver in determining how to modify and recover a faulted message. For example, if the message as-received fails the error-detection code and one of the message elements is modulated according to, say, sector **624**, then the receiver may alter that message element to the adjacent state in the indicated direction, and may test that variation.

It may be noted that a state may not have an adjacent state in a specified direction. If the current modulation state **613** is already at the edge of the constellation table, then the receiver cannot increase the state assignment further, and therefore may ignore the sector information if the occupied sector points in an illegal direction

FIG. **6**C is a schematic sketch showing another exemplary embodiment of a single modulation state with directional deviation sectors, according to some embodiments. As depicted in this non-limiting example, a single modulation state of a modulation scheme is indicated as **635**, surrounded by a good modulation zone **636** and a marginal modulation zone **637** which is divided into four sectors **641**, **642**, **643**, **644**. As in the previous example, the receiver may receive a faulted message containing at least one marginal-modulation element, and may attempt to recover the message by altering the state assignment of that marginal-modulation element. Initially, the assignment may be altered to an adjacent state in the direction of the sector in which the message element occurs. By making the most likely alterations first, the receiver may thereby find the correct message quickly, saving time and reducing the calculation burden. The receiver may thereby use the sector information present in the marginal-modulation elements of a faulted message as a guide for varying the state assignments of those message elements. If those initial small steps fail to agree with the error-check code, then larger variations may be tested before abandoning the message.

In another embodiment, instead of using categories of modulation quality and sectors in the marginal-modulation zone, the receiver may calculate a direction based on the I and Q amplitude deviations, and may alter a message element with low modulation quality to an adjacent state according to the calculated direction. Basing the initial alteration on the direction of a message element with low modulation quality, relative to the closest state of the modulation scheme, may thereby test the most likely version of the message before attempting a wider search.

FIG. **7** is a flowchart showing an exemplary embodiment of a process for detecting and correcting message errors according to directional deviation sectors, according to some embodiments. As depicted in this non-limiting example, a receiver may receive a message at **701**, and demodulate each message element using a previously determined calibration set including the branch amplitude levels of the modulation scheme, At **702**, the receiver can compare the message to an embedded error-detection code. If the message passes the EDC test, the task is done at **710**. If not, at **703** the receiver may allocate each message element to good, marginal, or bad-modulation zones according to the distance from the modulation of the message element to the nearest state, or according to the nearest I and Q amplitude levels. At **704**, the receiver determines whether any of the message elements occupies the bad-modulation zone, and if so, the receiver may alter the bad-modulation elements or request a retransmission at **709**. If there are no bad-modulation elements, the receiver may determine at **705** whether there are any marginal-modulation elements, in which case the receiver may attempt to recover the message using the sector information. At **706**, if not sooner, the receiver may divide each marginal-modulation zone into sectors according to position, and at **707** may determine a direction based on the amplitude deviations of the message element relative to the amplitude levels of the modulation scheme, and may allocate each marginal-modulation message element to one of the sectors. The receiver may then alter each marginal-modulation message element to the adjacent modulation state in the direction indicated by the occupied sector, and may test that variation against the error-detection code. If the altered message passes the error-detection test at **708**, the receiver has succeeded in recovering a faulted message and is done. If not, the receiver may request a retransmission and may merge the message with the retransmitted copy, in some embodiments.

In another embodiment, upon receiving a corrupted message, the receiver can calculate a distance value and a direction value according to the modulation of each message element relative to the nearest state of the modulation scheme. To attempt to recover the corrupted message, the receiver can select the message element with the largest distance value, and can alter that message element's state assignment to an adjacent state according to the direction value, and test that altered version against the error-detection code. The receiver can then alter other message element assignments according to their distance values, starting with the largest distance values, and altering each of the message elements to adjacent states according to the direction value. The receiver can perform a nested search among the message elements with distance values exceeding a threshold, for example, testing each such combination. The receiver can begin by altering the message element with the lowest modulation quality, and then proceed to test message elements with successively higher modulation quality. If not successful, the receiver can then alter the message element with the largest distance across all of the states of the modulation scheme, testing each. The receiver can then select further message elements according to distance and vary each according to their direction values or alternatively across the entire modulation scheme, testing each combination. Thus the receiver can select which message elements to alter, and in what order, based on their distance values instead of the good-marginal-bad categories, and the receiver can alter each message element according to the direction value instead of the deviation sectors. In addition, the receiver can calculate how long it will take to perform the alterations, given the number and size of the distance values of the message elements, and can determine whether the amount of time will likely exceed the time required for a retransmission, in which case the receiver may request the retransmission before or concurrently with performing the alterations and tests just described.

FIG. **8** is a modulation table showing an exemplary embodiment of modulation states and error zones, according to some embodiments. As depicted in this non-limiting example, a modulation table **800** is an array of modulation states of a modulation scheme, arranged according to a phase and an amplitude of the as-received signal. In the case of a PAM-modulated message, the as-received signal may be the sum-signal, which is equal to the I-branch wave added to the Q-branch wave. In this case, the receiver analyzes the sum-signal without separating the I and Q components. For example, the receiver can analyze the sum-signal for its overall amplitude and phase. Such an analysis corresponds to classical amplitude and phase demodulation. The amplitude and phase of the sum-signal may provide information about noise and interference more readily and/or more precisely than amplitude analysis of the I and Q branches of PAM, in some embodiments.

The depicted modulation scheme in this case is 16QAM, transmitted according to PAM and analyzed according to the amplitude and phase of the sum-signal. Each state is depicted as a dot **805**. The non-uniform distribution of states **805** is due to the effects of trigonometrically adding two sinusoidal waves at different phases and amplitudes. Although the position of each state on the modulation table **800** is deterministically determined by the amplitude modulations of the I and Q branches in the ideal case, in practical systems the demodulation results are subject to noise and interference as well as measurement uncertainties. Hence, the sum-signal wave properties, including its amplitude and phase, may provide distinct or at least improved information about which message elements are likely faulted. In some embodiments, each message element may be analyzed by both methods, including amplitude analysis of the separate I and Q branches, and amplitude-phase analysis of the sum-signal before branch separation. Those results may be combined by, for example, allocating a message element to a "suspicious" category if the message element fails a modulation-quality test by either PAM analysis or sum-signal amplitude-phase determination.

In some embodiments, a good-modulation zone **806** and a larger marginal modulation zone **807** may be defined around each state **805** in the modulation table **800**, with a bad-modulation zone **808** exterior to the other zones. Message elements in which the sum-signal amplitude and phase occur in the marginal **807** or bad modulation **808** zones may thereby reveal faults that may not be exposed in PAM analysis due to their different sensitivities to interference-induced phase errors, among other differences. In some embodiments, the receiver may test each message element according to the amplitude and phase properties of the sum-signal, then separate the I and Q branches and test each of them for agreement with one of the predetermined branch amplitude levels, and thereby flag a message element as suspicious if the message element appears in the bad or marginal modulation zone according to either the PAM analysis or the amplitude-phase analysis. The receiver may also check that the sum-signal amplitude and phase values are consistent with the PAM state determined from the I and Q branches, and thereby apply yet another independent fault detection test. The receiver may thereby reveal suspicious message elements that may be missed if tested using only a single analysis type.

The examples provided above disclosed methods for evaluating message elements based on the modulation quality. But in real communications, many factors may affect the fault rate and the types of faults likely to occur, and many other types of information may be gleaned from the message elements. For example, the likelihood that a particular message element is at fault may be determined, in part, by the SNR of the signal received because interference or noise is likely to cause the received signal to exhibit variations that can be measured by the receiver. In addition, interference from transmissions in other cells is often time-shifted due to differences in cell time-bases, signal propagation time, etc. In that case, the effects of interference may show up in the modulated signal of each message element in various ways, such as a stepped transition between modulations of adjacent resource elements instead of a sharp transition. Detection of time dispersion may further indicate which message elements are faulted. In addition, if a message is transmitted with a phase-only modulation scheme such as QPSK, then a message symbol with an amplitude different from the other message elements may be suspicious. The receiver may therefore calculate an overall quality factor for each message element, the overall quality factor including some combination of the modulation distance from the nearest state, the SNR, amplitude anomalies, and other measures of message element quality, for example.

FIG. **9** is a flowchart showing an exemplary embodiment of a procedure for detecting message faults by measuring sum-signal properties, according to some embodiments. As depicted in this non-limiting example, at message faults may be detected by analyzing each received message element from multiple viewpoints including PAM analysis of the I and Q branches, classic amplitude and phase measurements of the sum-signal, measurement of the SNR or transition properties between message elements, and other measures of message quality as may be devised.

At **901**, a message comprising message elements is received. For each message element, the rest of the flowchart is then implemented. At **902**, the amplitude and phase of the as-received sum-signal are measured and, at **903**, compared to a first calibration set that includes the expected amplitude and phase levels of the modulation scheme according to a PAM modulation technology. The receiver may further determine an amplitude deviation and a phase deviation of the message element's sum-signal relative to the closest amplitude-phase match in the first calibration set. Then at **904**, the receiver can determine whether the amplitude and/or phase deviation of the sum-signal exceeds a predetermined threshold (including optionally separate thresholds for amplitude and phase). In addition, or alternatively, the amplitude and phase deviations may be combined (and optionally normalized) to determine a distance or a modulation quality of the sum-signal relative to the closest state, and thereby determine whether the distance exceeds a threshold. At **904**, if the amplitude deviation or phase deviation of the sum-signal, or other combination, exceeds a predetermined threshold, then at **910** the message element is flagged as "suspicious", although it may be assigned to the nearest state of the modulation scheme anyway.

At **905**, the receiver may separate the I and Q branches, then measure the branch amplitudes and compare to a second calibration set that includes the amplitude levels of PAM, including positive and negative levels, as determined from a prior demodulation reference, for example. The receiver may then select the closest match in the second calibration set, and thereby measure the I and Q amplitude deviations of the message element relative to that closest state. At **906**, the receiver may determine whether the I or Q amplitude deviations, or both, exceed a threshold, and if so, flag the message element as suspicious at **910**.

At **907**, the receiver may check whether the amplitude and phase values determined for the sum-signal are in fact consistent with the PAM state implied by the branch-amplitude values for the I and Q branches. The receiver may also measure the SNR of the sum-signal during the symbol-time of the message element. The receiver may measure the transition properties of the sum-signal in switching between the preceding and/or the succeeding message element. The receiver may further determine other parameters related to the modulation quality or likely fault status of the message element. At **908**, the receiver may determine whether the SNR or transition properties or other factors exceed their relevant thresholds, and if so, flag the message element as suspicious.

At **909**, if the message element passes all of the above tests, the receiver may optionally (in dash) flag the message element as not suspicious. Alternatively, the receiver may simply move on to the next message element without recording anything about the successful message element, since non-faulted may be the default status of most message elements, absent evidence to the contrary.

By performing quality tests on message elements based on PAM amplitudes as well as sum-signal amplitude and phase properties, the receiver may thereby reveal likely faulted message elements that may be difficult to detect using just one of the demodulation technologies. By further including other quality factors such as SNR and transition parameters in the analysis, an improved determination of which message elements are likely faulted and which are likely non-faulted may become feasible. Then, if the number of suspicious message elements is within a practical limit, the receiver may alter each of the suspicious message elements according to their nearest neighbors, optionally with directional assistance, and test each such alteration against the error-detection code, and thereby rescue a faulted message while avoiding the delays and costs involved in seeking a retransmission.

Systems and methods disclosed herein are aimed at improving the error detection capability of receivers in 5G and 6G communications, and to recover faulted messages. The receiver may allocate each message element to a good, marginal, or bad quality of modulation based on how far the element's modulation differs from the amplitude levels of the closest modulation state. The receiver may also divide each marginal-modulation zone into sectors and may vary each marginal-modulation element to an adjacent state in the direction indicated by the occupied sector, to search for the correct modulation state of each message element. Alternatively, the receiver may select which message elements to alter, and how to alter them, according to a distance and a direction of the message element's modulation relative to the closest state of the modulation scheme. The receiver may thereby recover faulted messages that would otherwise be discarded, reducing delays and improving reliability under adverse noise or interference conditions, while avoiding unnecessary requests and retransmissions. As a result, network efficiency may be improved and user satisfaction may be provided with little or no additional cost.

The wireless embodiments of this disclosure may be aptly suited for cloud backup protection, according to some embodiments. Furthermore, the cloud backup can be provided cyber-security, such as blockchain, to lock or protect data, thereby preventing malevolent actors from making changes. The cyber-security may thereby avoid changes that, in some applications, could result in hazards including lethal hazards, such as in applications related to traffic safety, electric grid management, law enforcement, or national security.

In some embodiments, non-transitory computer-readable media may include instructions that, when executed by a computing environment, cause a method to be performed, the method according to the principles disclosed herein. In some embodiments, the instructions (such as software or firmware) may be upgradable or updatable, to provide additional capabilities and/or to fix errors and/or to remove security vulnerabilities, among many other reasons for updating software. In some embodiments, the updates may be provided monthly, quarterly, annually, every 2 or 3 or 4 years, or upon other interval, or at the convenience of the owner, for example. In some embodiments, the updates (especially updates providing added capabilities) may be provided on a fee basis. The intent of the updates may be to cause the updated software to perform better than previously, and to thereby provide additional user satisfaction.

The systems and methods may be fully implemented in any number of computing devices. Typically, instructions are laid out on computer readable media, generally non-transitory, and these instructions are sufficient to allow a processor in the computing device to implement the method of the invention. The computer readable marginal may be a hard drive or solid state storage having instructions that, when run, or sooner, are loaded into random access memory. Inputs to the application, e.g., from the plurality of users or from any one user, may be by any number of appropriate computer input devices. For example, users may employ vehicular controls, as well as a keyboard, mouse, touchscreen, joystick, trackpad, other pointing device, or any other such computer input device to input data relevant to the calculations. Data may also be input by way of one or more sensors on the robot, an inserted memory chip, hard drive, flash drives, flash memory, optical media, magnetic media, or any other type of file-storing marginal. The outputs may be delivered to a user by way of signals transmitted to robot steering and throttle controls, a video graphics card or integrated graphics chipset coupled to a display that may be seen by a user. Given this teaching, any number of other tangible outputs will also be understood to be contemplated by the invention. For example, outputs may be stored on a memory chip, hard drive, flash drives, flash memory, optical media, magnetic media, or any other type of output. It should also be noted that the invention may be implemented on any number of different types of computing devices, e.g., embedded systems and processors, personal computers, laptop computers, notebook computers, net book computers, handheld computers, personal digital assistants, mobile phones, smart phones, tablet computers, and also on devices specifically designed for these purpose. In one implementation, a user of a smart phone or Wi-Fi-connected device downloads a copy of the application to their device from a server using a wireless Internet connection. An appropriate authentication procedure and secure transaction process may provide for payment to be made to the seller. The application may download over the mobile connection, or over the Wi-Fi or other wireless network connection. The application may then be run by the user. Such a networked system may provide a suitable computing environment for an implementation in which a plurality of users provide separate inputs to the system and method.

It is to be understood that the foregoing description is not a definition of the invention but is a description of one or more preferred exemplary embodiments of the invention. The invention is not limited to the particular embodiments(s) disclosed herein, but rather is defined solely by the claims below. Furthermore, the statements contained in the foregoing description relate to particular embodiments and are not to be construed as limitations on the scope of the invention or on the definition of terms used in the claims, except where a term or phrase is expressly defined above. Various other embodiments and various changes and modifications to the disclosed embodiment(s) will become apparent to those skilled in the art. For example, the specific combination and order of steps is just one possibility, as the present method may include a combination of steps that has fewer, greater, or different steps than that shown here. All such other embodiments, changes, and modifications are intended to come within the scope of the appended claims.

As used in this specification and claims, the terms "for example", "e.g.", "for instance", "such as", and "like" and the terms "comprising", "having", "including", and their other verb forms, when used in conjunction with a listing of one or more components or other items, are each to be construed as open-ended, meaning that the listing is not to be considered as excluding other additional components or items. Other terms are to be construed using their broadest reasonable meaning unless they are used in a context that requires a different interpretation.

The invention claimed is:

1. A method for a wireless receiver to demodulate a wireless message, the method comprising:

a) receiving a message comprising message elements, each message element comprising an I branch signal multiplexed with an orthogonal Q branch signal, wherein each signal, of the I branch signal and the Q branch signal, is modulated according to a first plurality of predetermined branch amplitude levels;

b) determining, according to an error-correction code associated with the message, that the message is corrupted;

c) for each message element, determining a sum-signal comprising the I branch signal added to the Q branch signal, and determining a sum-signal amplitude and a sum-signal phase of the sum-signal; and

d) for each message element, determining a modulation quality by:

i) comparing the sum-signal amplitude to a second plurality of predetermined sum-signal amplitude levels; and

ii) comparing the sum-signal phase to a third plurality of predetermined sum-signal phase levels.

2. The method of claim **1**, wherein the message is received according to 5G or 6G technology.

3. The method of claim **1**, further comprising, for each message element:

a) determining a sum-signal amplitude deviation comprising the sum-signal amplitude minus a closest sum-signal amplitude level of the second plurality;

b) determining a sum-signal phase deviation comprising the sum-signal phase minus a closest sum-signal phase level of the third plurality; and

c) calculating a sum-signal modulation quality according to a combination of the sum-signal amplitude deviation and the sum-signal phase deviation.

4. The method of claim **3**, wherein, for each message element:

a) the sum-signal modulation quality is inversely related to a square root of a sum of the sum-signal amplitude deviation squared plus the sum-signal phase deviation squared.

5. The method of claim **3**, wherein, for each message element:

a) the sum-signal modulation quality is inversely related to a sum of a magnitude of the sum-signal amplitude deviation plus a magnitude of the sum-signal phase deviation.

6. The method of claim **3**, the method further comprising, for each message element:

a) determining an I branch amplitude according to the I branch signal, and determining a Q branch amplitude according to the Q branch signal;

b) determining an I branch deviation comprising a difference between the I branch amplitude and a closest predetermined branch amplitude level of the first plurality;

c) determining a Q branch deviation comprising a difference between the Q branch amplitude and a closest predetermined branch amplitude level of the first plurality; and

d) determining a branch modulation quality according to a combination of the I branch deviation and the Q branch deviation.

7. The method of claim **6**, wherein, for each message element:

a) the branch modulation quality is inversely related to a square root of a sum of the I branch deviation squared plus the Q branch deviation squared.

8. The method of claim **6**, wherein, for each message element:

a) the branch modulation quality is inversely related to a sum of a magnitude of the I branch deviation plus a magnitude of the Q branch deviation.

9. The method of claim **6**, further comprising, for each message element:

a) determining a first signal-to-noise ratio (SNR) value of the sum-signal, a second SNR value of the I branch signal, and a third SNR value of the Q branch signal; and

b) determining a SNR modulation quality inversely related to a combination of the first, second, and third SNR values.

10. The method of claim **9**, wherein, for each message element:

a) the modulation quality of the message element is inversely related to a combination of the sum-signal modulation quality, the branch modulation quality, and the SNR modulation quality.

11. Non-transitory computer-readable media in a wireless receiver, the media containing instructions that when implemented in a computing environment cause a method to be performed, the method comprising:

a) receiving a message comprising message elements, each message element modulated according to a modulation scheme, the modulation scheme comprising a sum-signal amplitude and a sum-signal phase, wherein each sum-signal amplitude is modulated, by a transmitter, according to integer Namp predetermined amplitude levels, and each sum-signal phase is modulated, by the transmitter, according to integer Nphase predetermined phase levels;

b) determining, according to an error-detection code associated with the message, that the message as received is corrupted;

c) for each message element of the message as received, determining a modulation quality according to a combination of an amplitude displacement and a phase displacement, wherein the amplitude displacement comprises a difference between the sum-signal amplitude and a closest predetermined amplitude level of the Namp predetermined amplitude levels, and the phase displacement comprises a difference between the sum-signal phase and a closest predetermined phase level of the Nphase predetermined phase levels.

12. The non-transitory computer-readable media of claim **11**, the method further comprising:

a) selecting a particular message element having a lowest modulation quality;

b) altering the sum-signal amplitude or the sum-signal phase, or both, of the particular message element; and

c) determining whether the message, including the alteration, is corrupted.

13. The non-transitory computer-readable media of claim **12**, wherein:

a) the altering the sum-signal amplitude comprises assigning one of the predetermined amplitude levels, other than the closest predetermined amplitude level, to the particular message element; and

b) the altering the sum-signal phase comprises assigning one of the predetermined phase levels, other than the closest predetermined phase level, to the particular message element.

14. The non-transitory computer-readable media of claim **11**, wherein:

a) for each message element, the modulation quality is inversely related to a square root of a sum of the amplitude displacement squared plus the phase displacement squared.

15. The non-transitory computer-readable media of claim **11**, wherein:

a) for each message element, the modulation quality is inversely related to a sum of a magnitude of the amplitude displacement plus a magnitude of the phase displacement.

16. A wireless receiver comprising signal processing electronics and a processor, the wireless receiver configured to:

a) determine, according to a demodulation reference, using the signal processing electronics, a first plurality of predetermined sum-signal amplitude modulation levels and a second plurality of predetermined sum-signal phase modulation levels;

b) receive, using the signal processing electronics, a message comprising message elements, each message element modulated according to a modulation scheme, the modulation scheme comprising, for each message element of the message, an I branch signal multiplexed with an orthogonal Q branch signal;

c) for each message element, using the signal processing electronics, measure an I branch amplitude of the I branch signal and a Q branch amplitude of the Q branch signal;

d) for each message element, using the processor, determine a sum-signal comprising a sum of the I branch signal plus the Q branch signal, and determine a sum-signal amplitude and a sum-signal phase of the sum-signal;

e) for each message element, using the processor, determine a sum-signal amplitude deviation comprising a difference between the sum-signal amplitude of the message element and a closest sum-signal amplitude level of the first plurality, and determine a sum-signal phase deviation comprising a difference between the sum-signal phase of the message element and a closest sum-signal phase level of the second plurality; and

f) for each message element, using the processor, determine a sum-signal modulation quality according to a combination of the sum-signal amplitude deviation and the sum-signal phase deviation.

17. The wireless receiver of claim **16**, further configured to:

a) determine, according to the demodulation reference, using the signal processing electronics, a third plurality of branch amplitude levels of the modulation scheme;

b) for each message element, determine an I branch deviation comprising a difference between the I branch amplitude and a closest branch amplitude level of the third plurality, and determine a Q branch deviation comprising a difference between the Q branch amplitude and a closest branch amplitude level of the third plurality; and

c) for each message element, determine a branch modulation quality inversely related to a combination of the I branch deviation and the Q branch deviation.

18. The wireless receiver of claim **17**, further configured to:

a) for each message element, using the processor, determine a first signal-to-noise ratio of the sum-signal, a second signal-to-noise ratio of the I branch signal, and a third signal-to-noise ratio of the Q branch signal.

19. The wireless receiver of claim **18**, further configured to:

a) for each message element, using the processor, determine an overall modulation quality comprising a combination of the sum-signal modulation quality, the branch modulation quality, and the first, second, and third signal-to-noise ratios.

20. The wireless receiver of claim **19**, further configured to:

a) select, using the processor, a particular message element having a lowest overall modulation quality;

b) in a nested grid search, successively replace the particular message element with a substitute message element, wherein the substitute message element comprises one of the predetermined sum-signal amplitude levels multiplexed with one of the predetermined sum-signal phase levels, wherein the nested grid search comprises all combinations of the predetermined sum-signal amplitude levels and the predetermined sum-signal phase levels; and

c) for each of the substitutions, determine whether the message, including the substituted message element, is corrupted.

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