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(54) **WIRELESS SENSORS AND CORRESPONDING SYSTEMS AND METHODS FOR INTRA-OPERATIVE NERVE ROOT DECOMPRESSION MONITORING**

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A61B 5/01	(2006.01)
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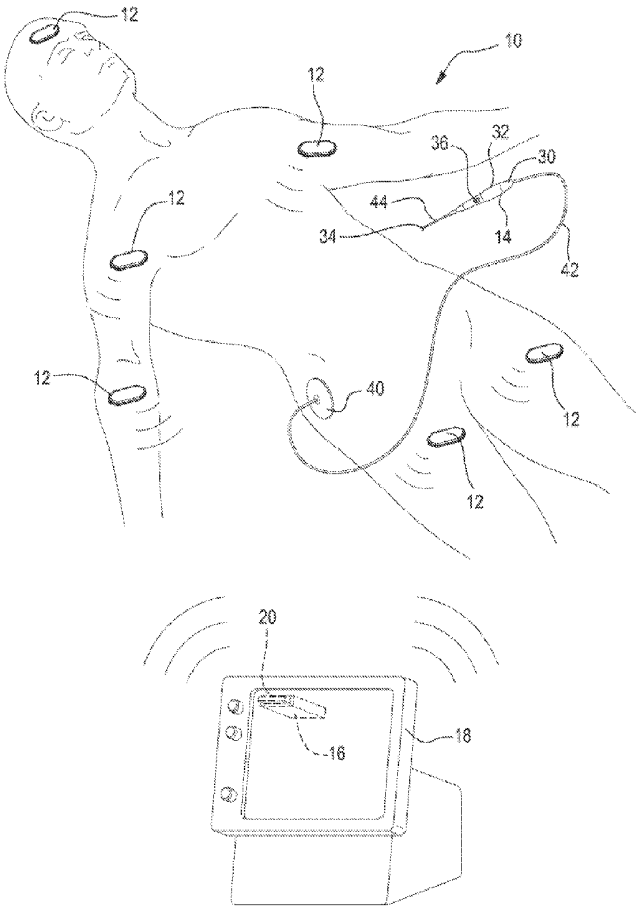
(57) **ABSTRACT**

A sensor including an array of pins, a sensing element, a control module, and a physical layer module. The array of pins or needles is configured to be inserted in tissue of a patient. The sensing element is separate from the array of pins or needles and is configured to (i) detect a first parameter of the tissue, and (ii) generate a first signal indicative of the first parameter. The control module is configured to (i) receive the first signal, (ii) monitor a second parameter of the tissue based on a second signal received from the array of pins or needles, and (ii) generate a third signal based on the first signal and the second parameter, where the third signal is indicative of a level of decompression of a nerve of the patient. The physical layer module is configured to wirelessly transmit the third signal from the sensor to a console interface module or a nerve integrity monitoring device.



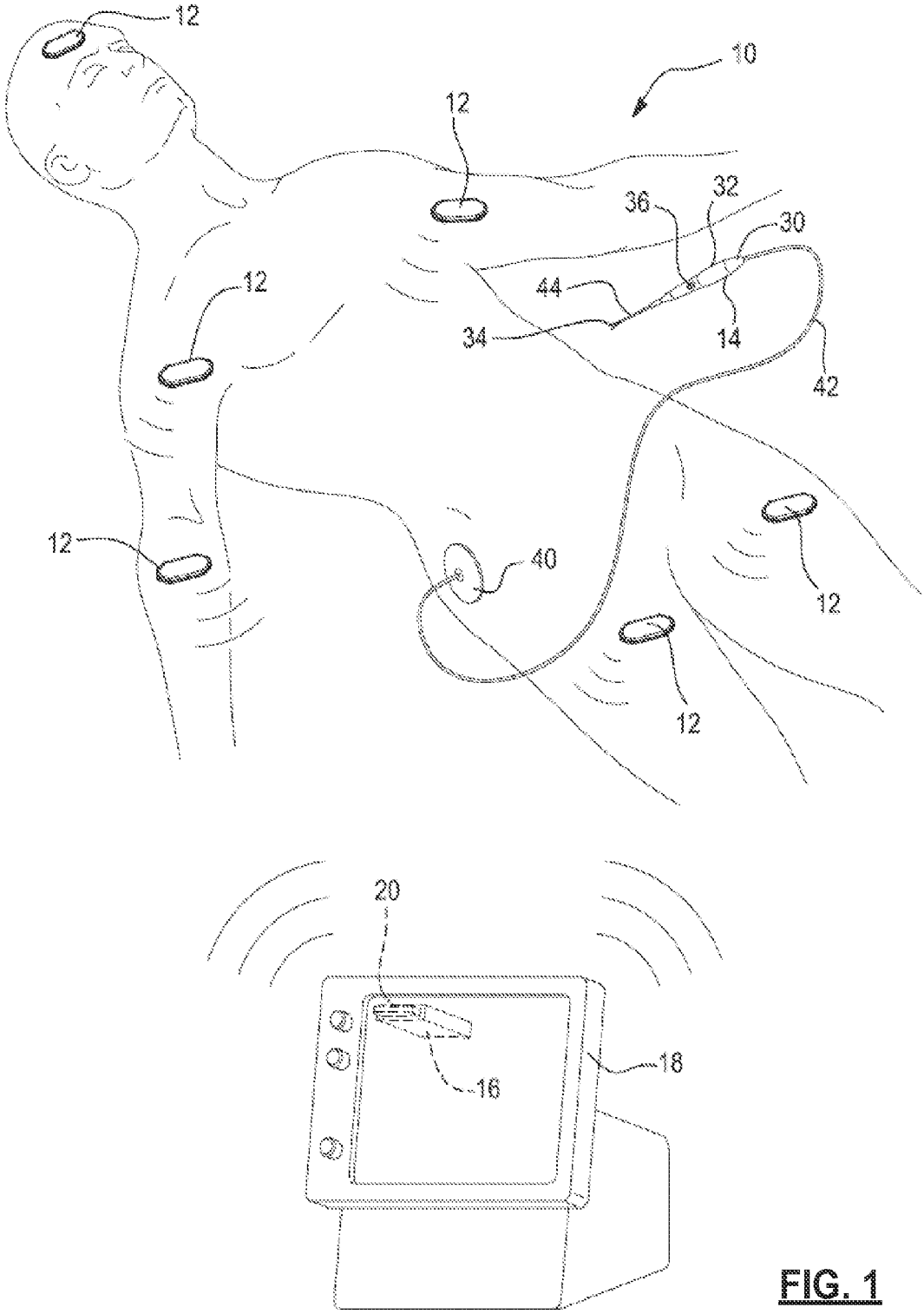


FIG. 1

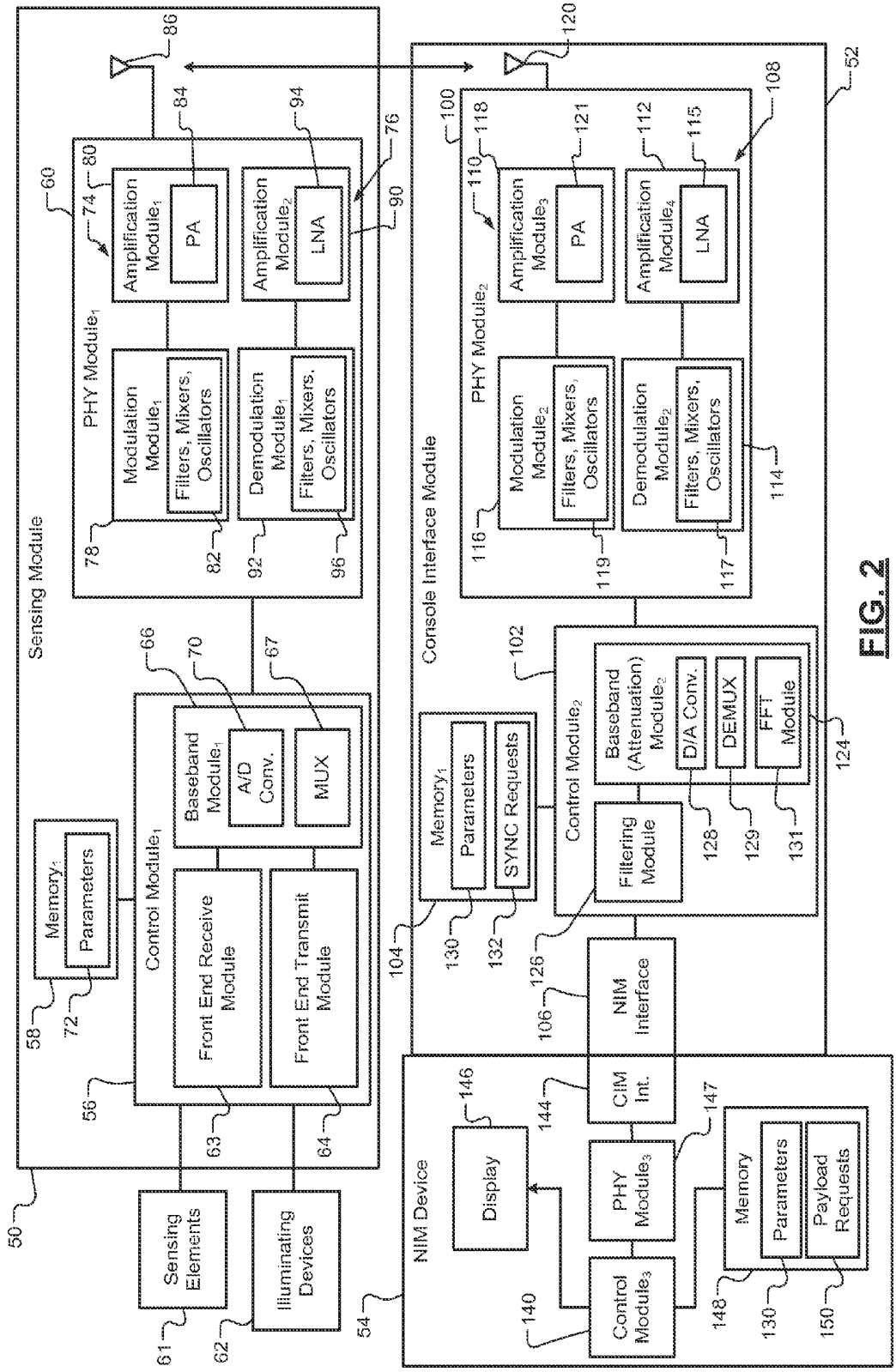

Sensing Module
Console Interface Module
NIM Device
PHY Module1
PHY Module2
PHY Module3
Amplification Module1
Amplification Module2
Amplification Module3
Amplification Module4
Modulation Module1
Demodulation Module1
Modulation Module2
Demodulation Module2
Filters, Mixers, Oscillators
PA
LNA
Control Module1
Control Module2
Control Module3
Baseband Module1
A/D Conv.
MUX
Front End Receive Module
Front End Transmit Module
Memory1
Parameters
Memory2
SYNC Requests
Baseband (Attenuation) Module2
D/A Conv.
DEMUX
FFT Module
Filtering Module
NIM Interface
CIM Int.
Display
Memory
Payload Requests
Sensing Elements
Illuminating Devices
50
52
54
56
58
60
61
62
63
64
66
67
70
72
74
76
78
80
82
84
86
90
92
94
96
100
102
104
106
108
110
112
114
115
116
117
118
119
120
121
124
126
128
129
130
131
132
140
144
146
147
148
150

FIG. 2

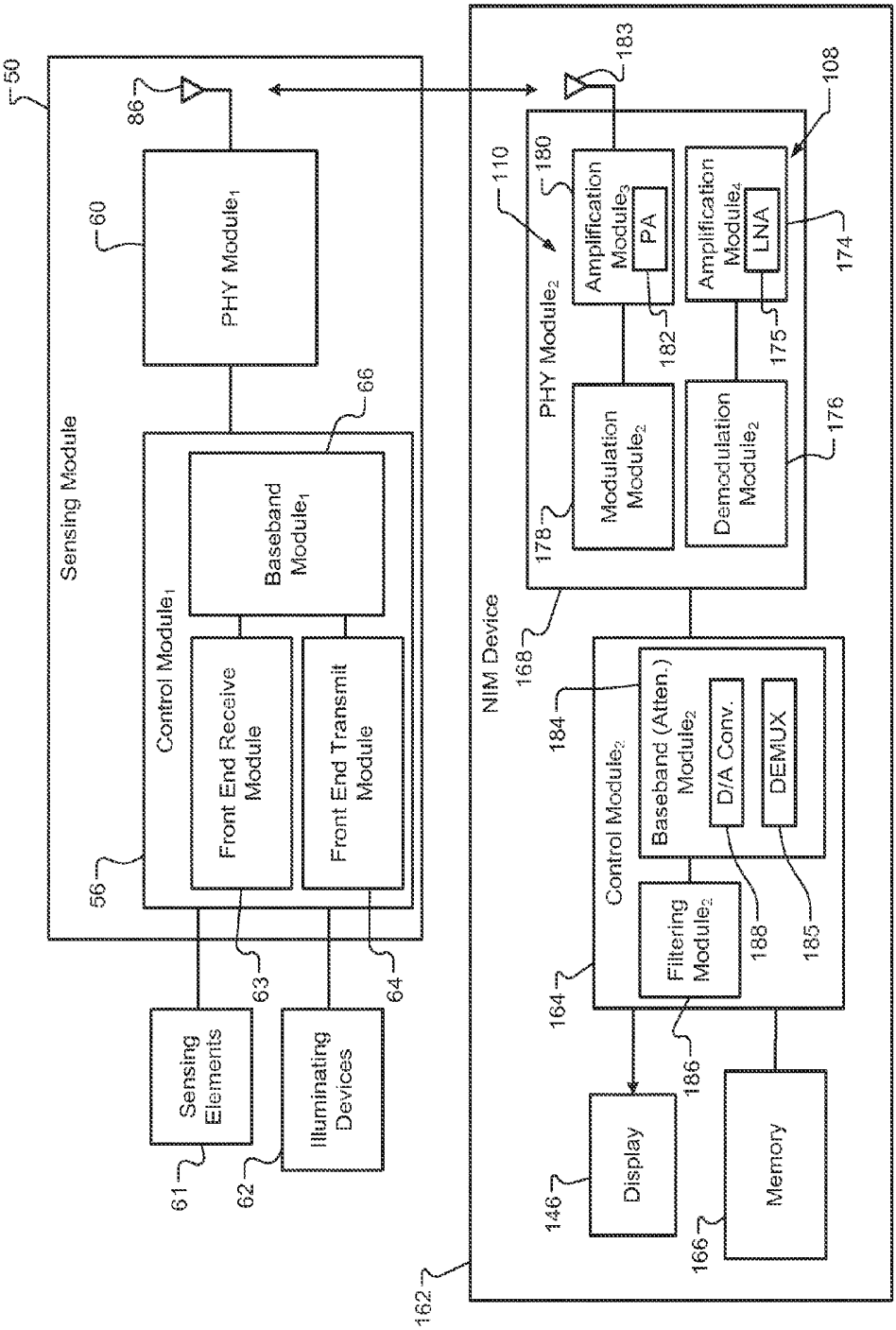

50
Sensing Module
86
60
PHY Module1
66
Baseband Module1
Control Module1
Front End Receive Module
Front End Transmit Module
56
63
64
Sensing Elements
Illuminating Devices
61
62
162
NIM Device
183
108
110
180
PHY Module2
Amplification Module3
PA
Amplification Module4
LNA
174
182
175
Modulation Module2
Demodulation Module2
176
178
168
184
Control Module2
Baseband (Atten.) Module2
D/A Conv.
DEMUX
Filtering Module2
188
185
164
186
146
Display
166
Memory

FIG. 3

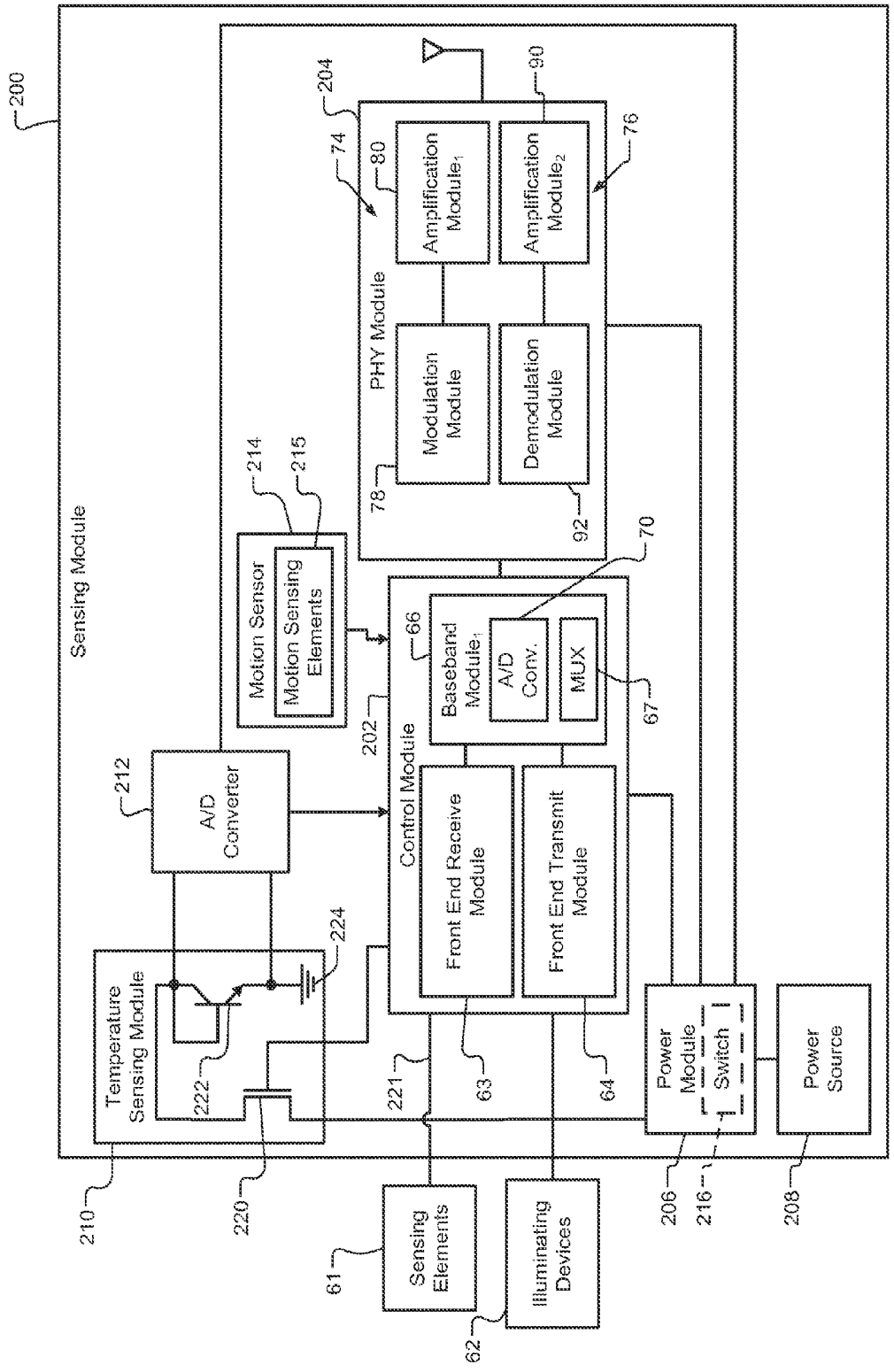

200
Sensing Module
204
74
80
Amplification Module1
90
Amplification Module2
76
PHY Module
Modulation Module
78
Demodulation Module
92
214
215
Motion Sensor
Motion Sensing Elements
70
66
Baseband Module1
A/D Conv.
MUX
67
202
Control Module
212
A/D Converter
Front End Receive Module
Front End Transmit Module
224
Temperature Sensing Module
222
221
63
64
Power Module
Switch
Power Source
210
220
206
216
208
61
Sensing Elements
62
Illuminating Devices

FIG. 4

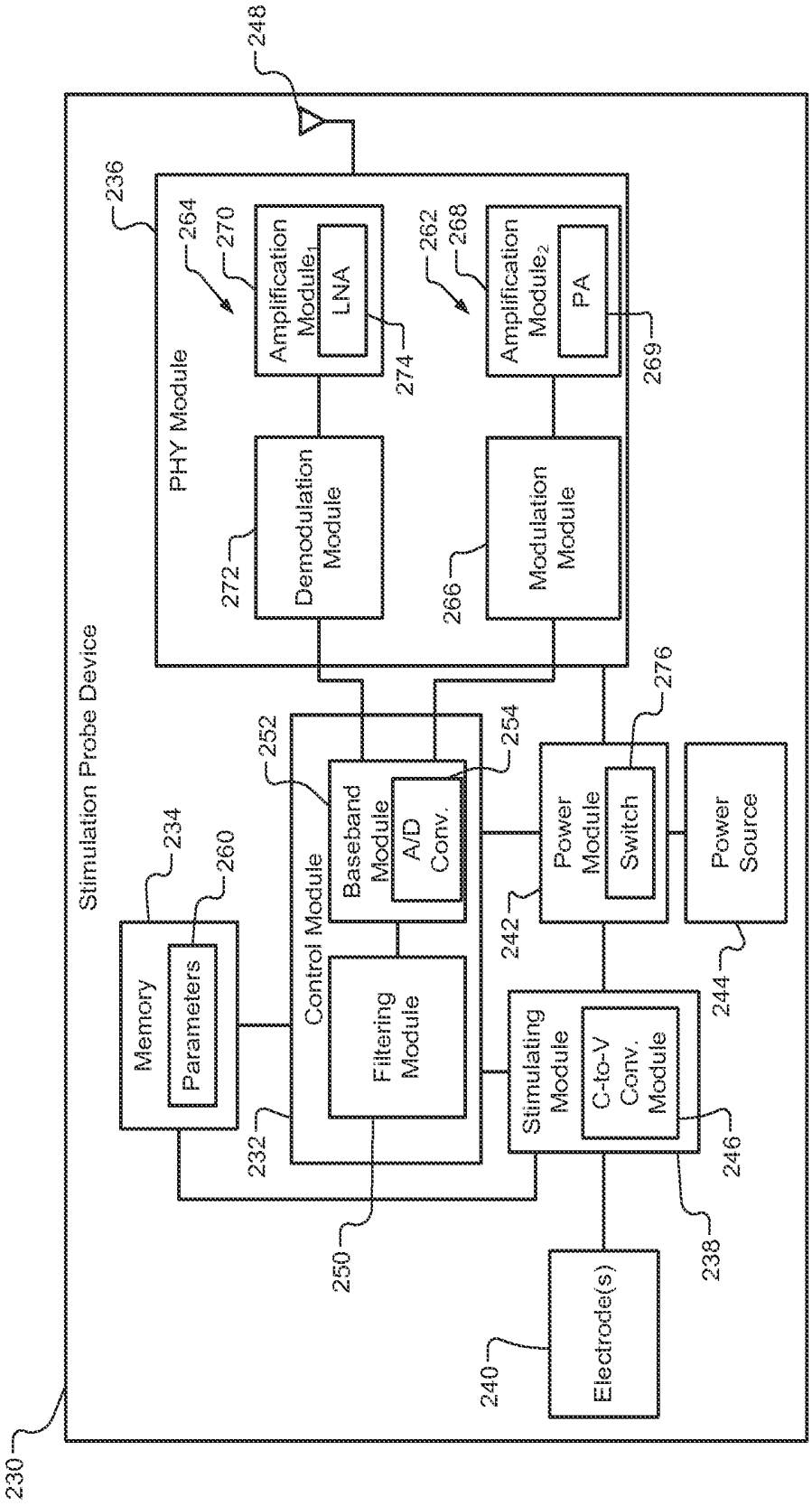

Stimulation Probe Device
230
248
236
PHY Module
264
270
Amplification Module1
LNA
274
262
268
Amplification Module2
PA
269
272
Demodulation Module
266
Modulation Module
276
252
254
Control Module
Baseband Module
A/D Conv.
234
260
Memory
Parameters
232
Filtering Module
250
242
Power Module
Switch
Power Source
244
Stimulating Module
C-to-V Conv. Module
246
238
240
Electrode(s)

FIG. 5

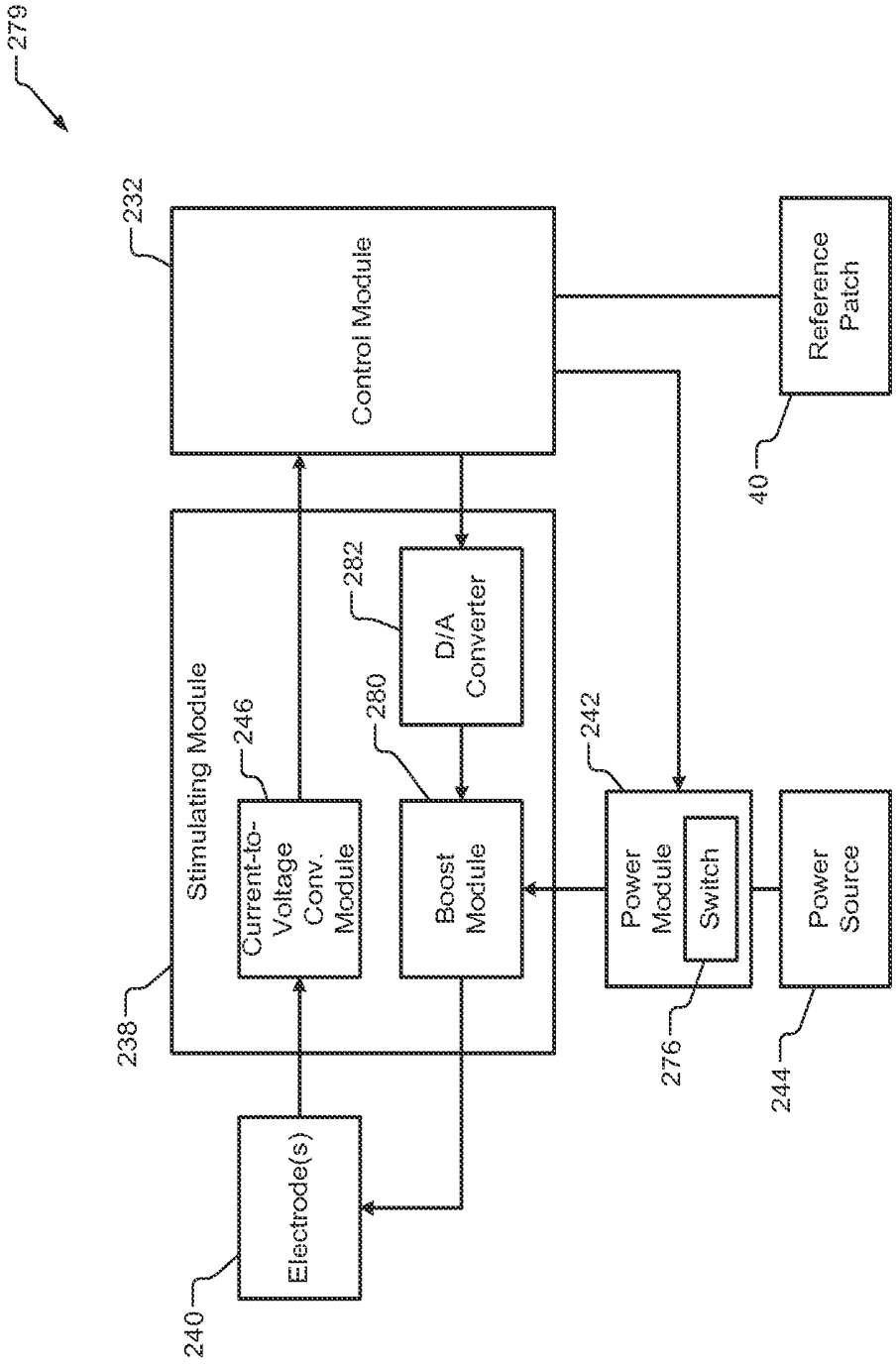

279
232
Control Module
Reference Patch
40
Stimulating Module
282
D/A Converter
280
246
Current-to-Voltage Conv. Module
Boost Module
242
Power Module
Switch
Power Source
238
276
244
Electrode(s)
240

FIG. 6

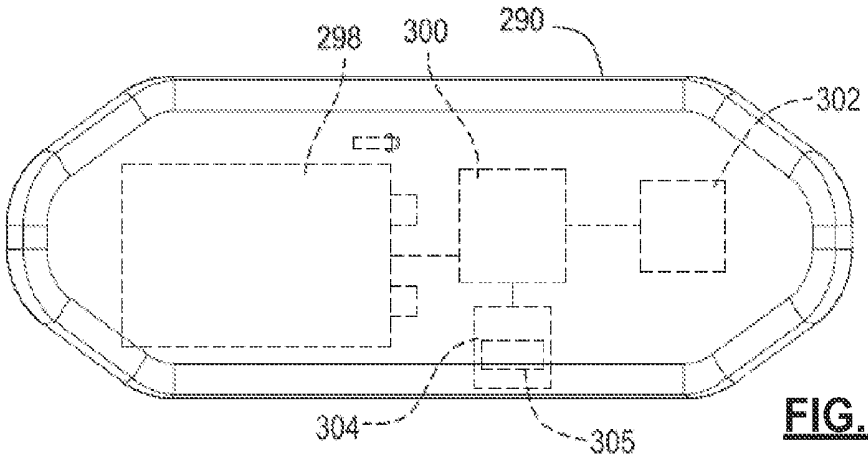


FIG. 7

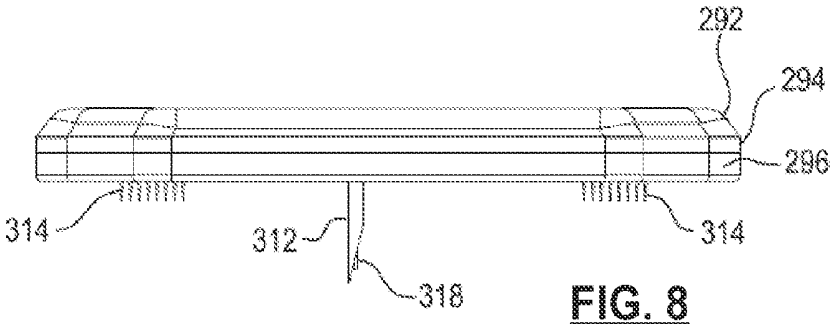


FIG. 8

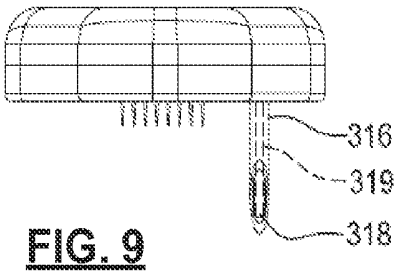


FIG. 9

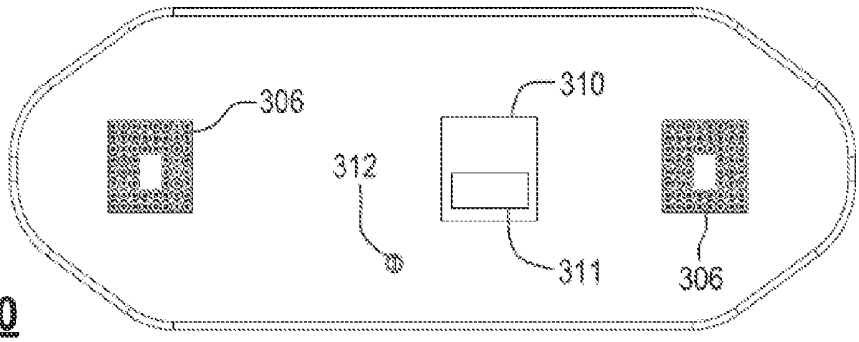


FIG. 10

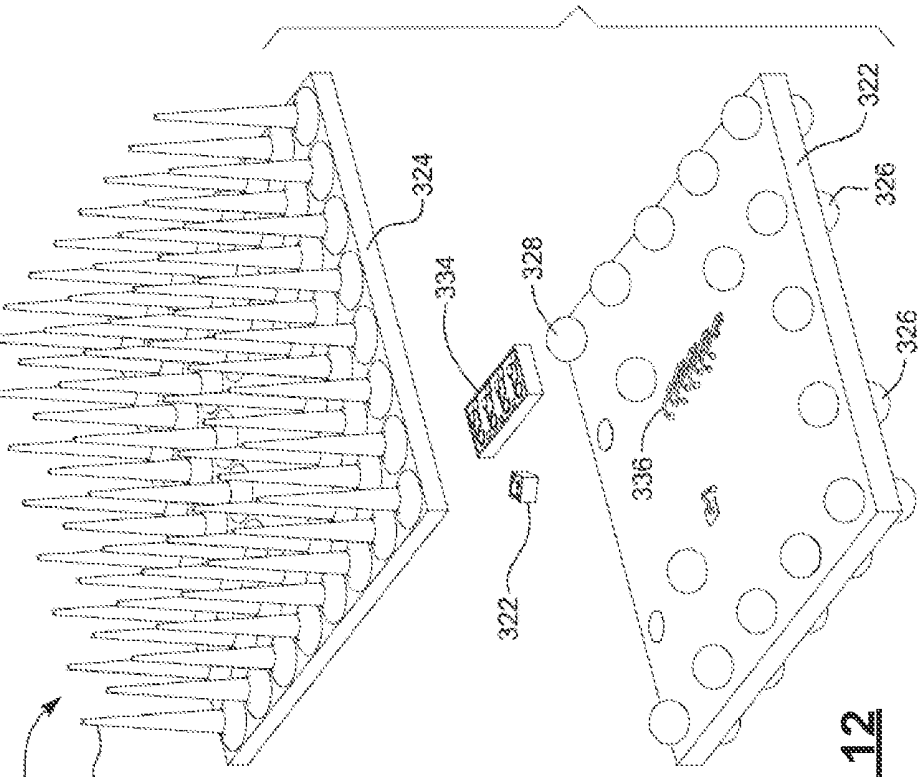


FIG. 12

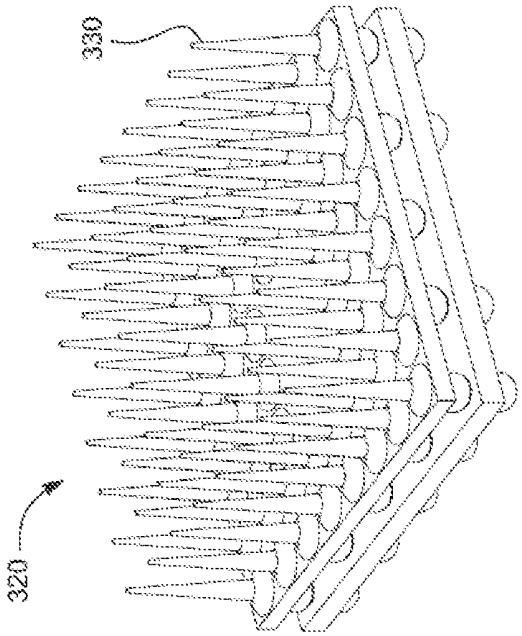


FIG. 11

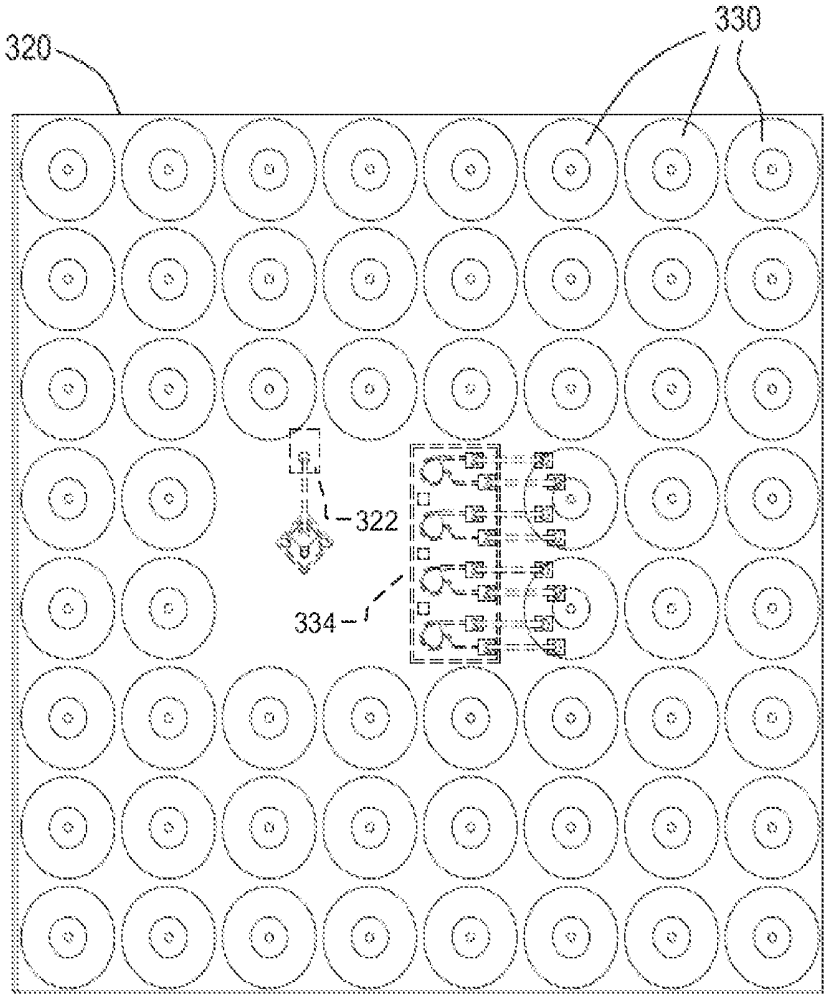


FIG. 13

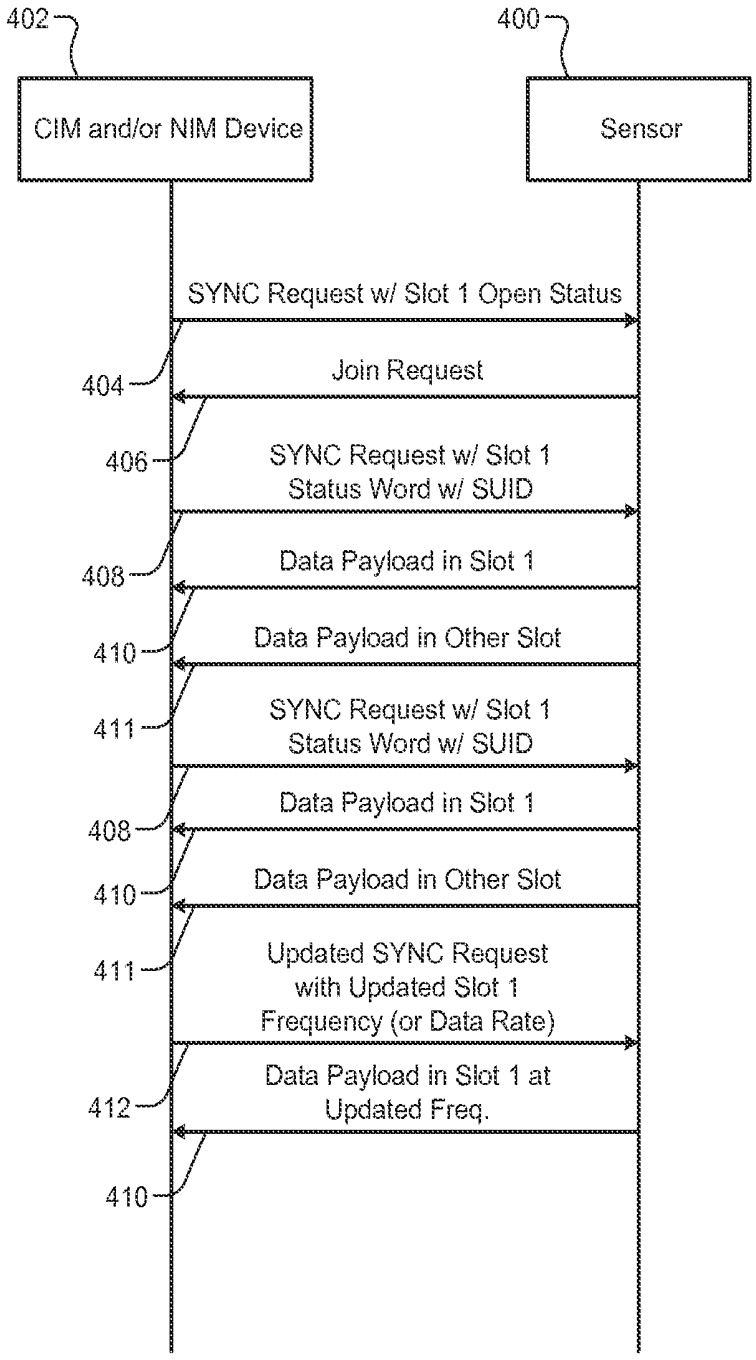

402
400
CIM and/or NIM Device
Sensor
SYNC Request w/ Slot 1 Open Status
404
Join Request
406
SYNC Request w/ Slot 1 Status Word w/ SUID
408
Data Payload in Slot 1
410
Data Payload in Other Slot
411
SYNC Request w/ Slot 1 Status Word w/ SUID
408
Data Payload in Slot 1
410
Data Payload in Other Slot
411
Updated SYNC Request with Updated Slot 1 Frequency (or Data Rate)
412
Data Payload in Slot 1 at Updated Freq.
410

FIG. 14

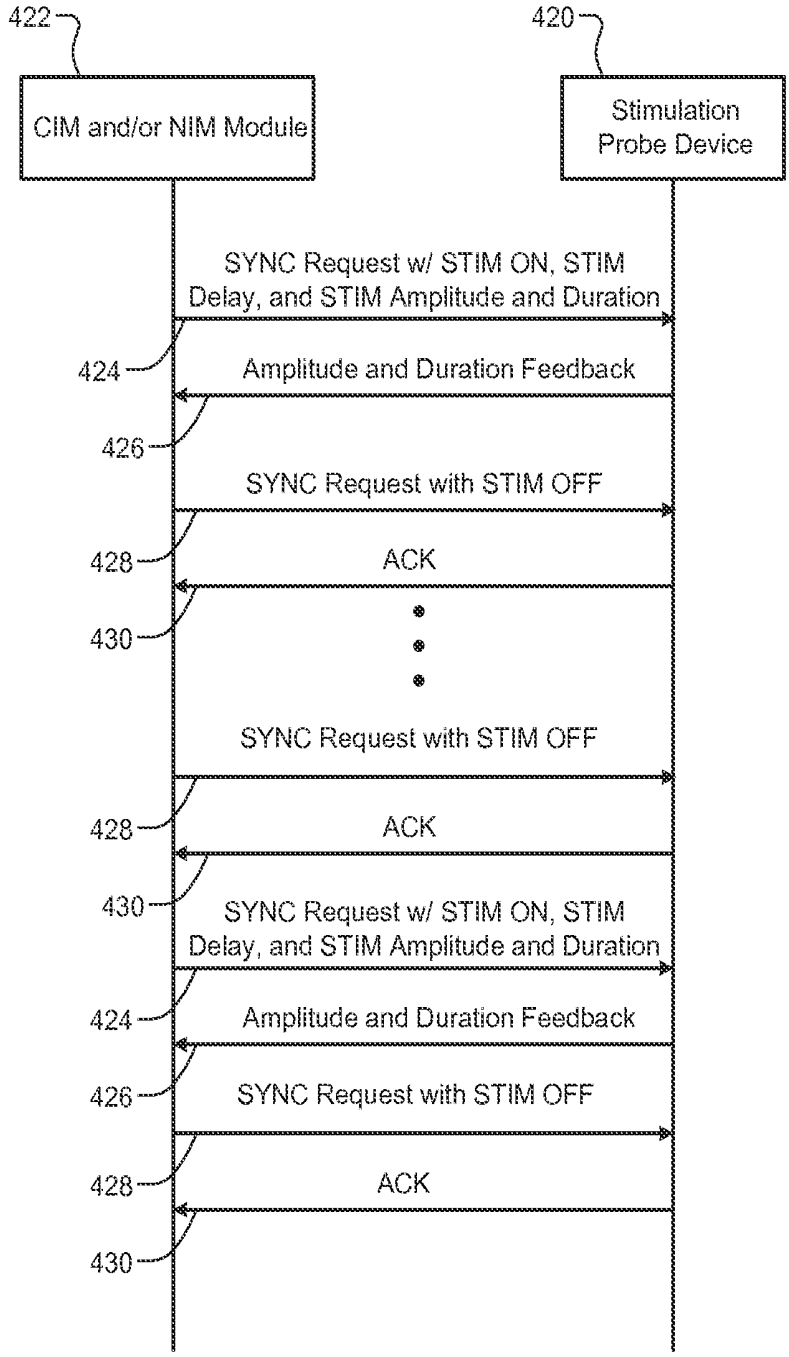

422
420
CIM and/or NIM Module
Stimulation Probe Device
SYNC Request w/ STIM ON, STIM Delay, and STIM Amplitude and Duration
424
Amplitude and Duration Feedback
426
SYNC Request with STIM OFF
428
ACK
430
SYNC Request with STIM OFF
428
ACK
430
SYNC Request w/ STIM ON, STIM Delay, and STIM Amplitude and Duration
424
Amplitude and Duration Feedback
426
SYNC Request with STIM OFF
428
ACK
430

FIG. 15

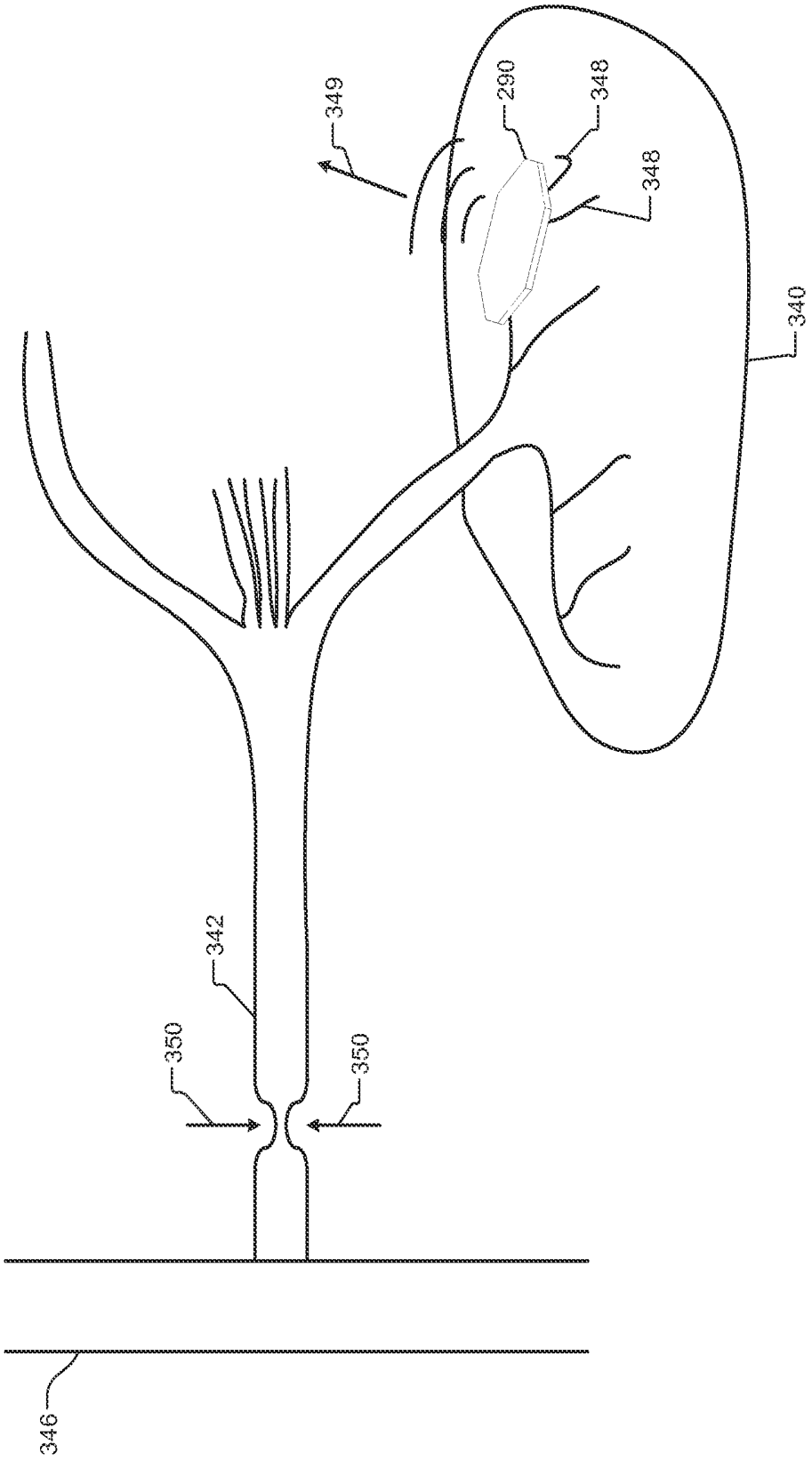


FIG. 16

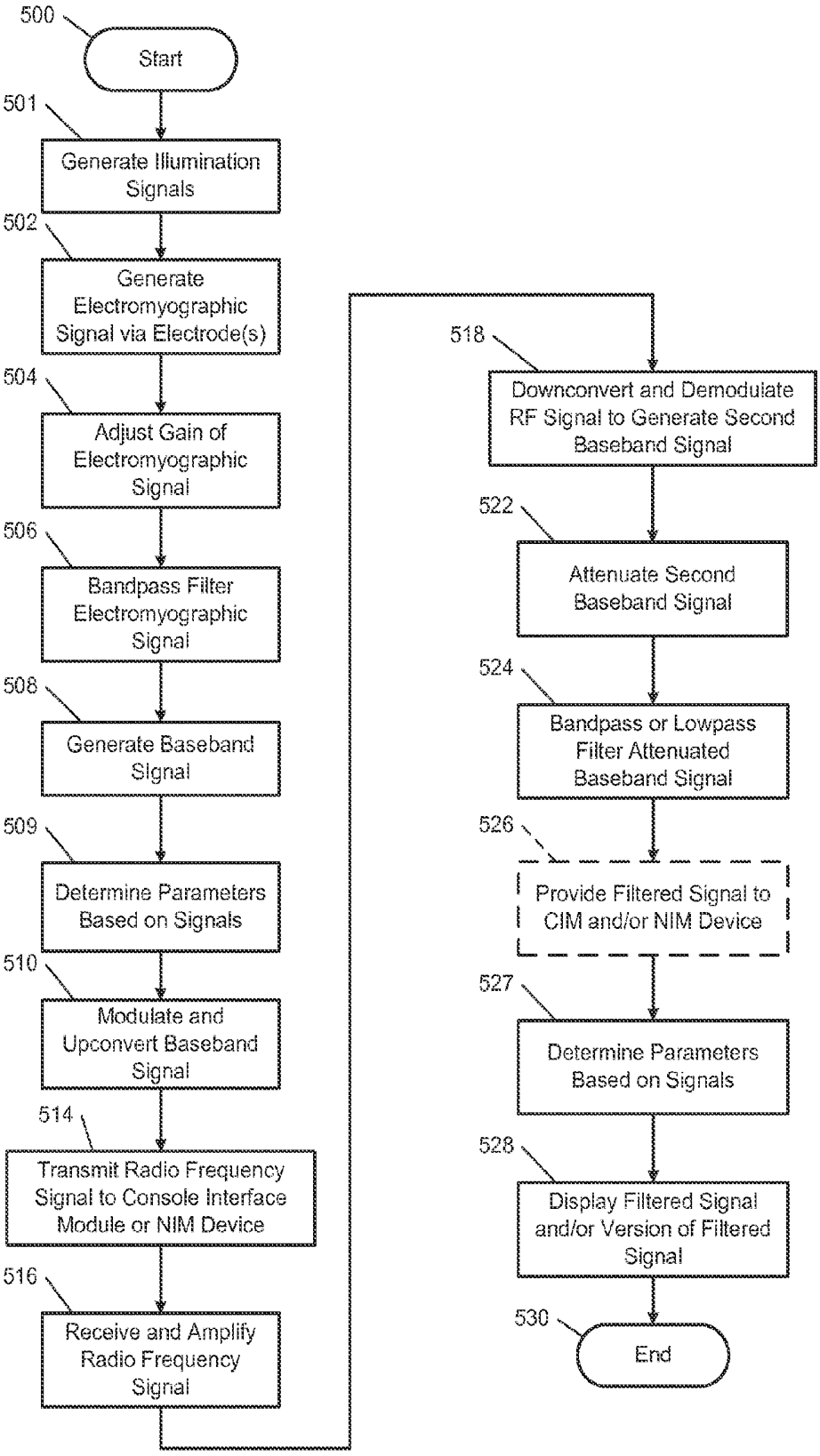

500
Start
501
Generate Illumination Signals
502
Generate Electromyographic Signal via Electrode(s)
504
Adjust Gain of Electromyographic Signal
506
Bandpass Filter Electromyographic Signal
508
Generate Baseband Signal
509
Determine Parameters Based on Signals
510
Modulate and Upconvert Baseband Signal
514
Transmit Radio Frequency Signal to Console Interface Module or NIM Device
516
Receive and Amplify Radio Frequency Signal
518
Downconvert and Demodulate RF Signal to Generate Second Baseband Signal
522
Attenuate Second Baseband Signal
524
Bandpass or Lowpass Filter Attenuated Baseband Signal
526
Provide Filtered Signal to CIM and/or NIM Device
527
Determine Parameters Based on Signals
528
Display Filtered Signal and/or Version of Filtered Signal
530
End

FIG. 17

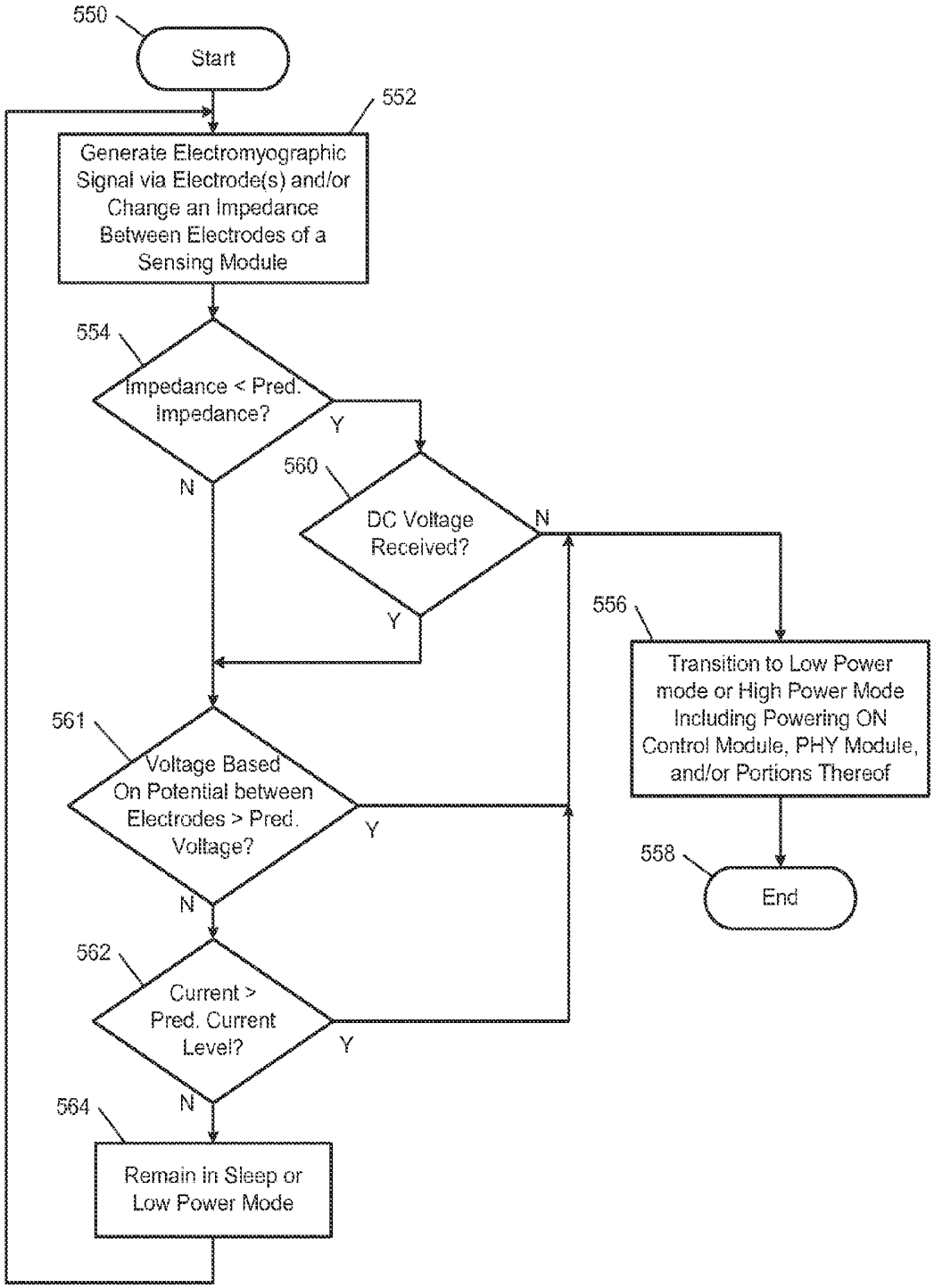

550
Start
552
Generate Electromyographic Signal via Electrode(s) and/or Change an Impedance Between Electrodes of a Sensing Module
554
Impedance < Pred. Impedance?
Y
N
560
DC Voltage Received?
N
Y
556
Transition to Low Power mode or High Power Mode Including Powering ON Control Module, PHY Module, and/or Portions Thereof
558
End
561
Voltage Based On Potential between Electrodes > Pred. Voltage?
Y
N
562
Current > Pred. Current Level?
Y
N
564
Remain in Sleep or Low Power Mode

FIG. 18

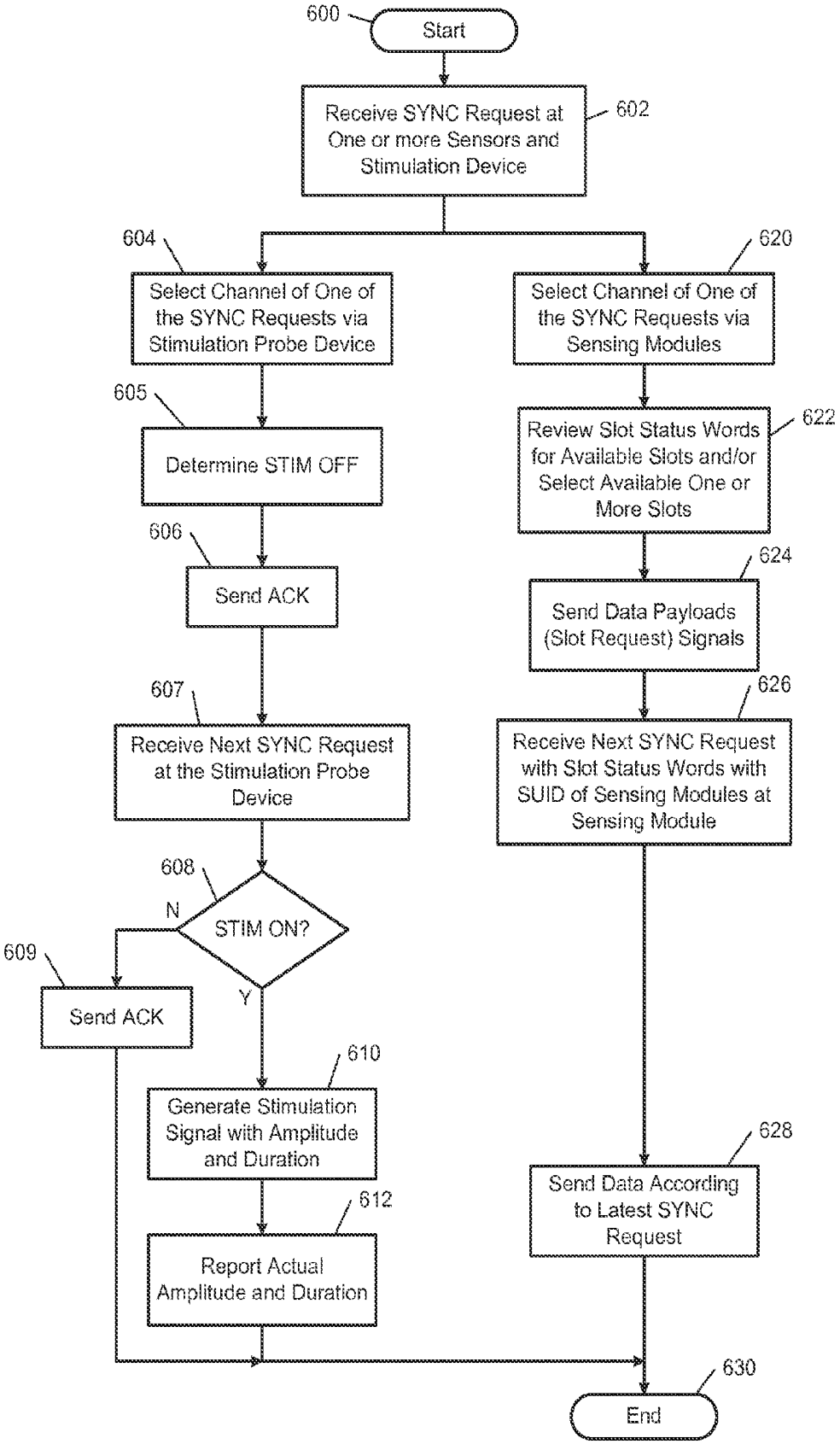

600
Start
Receive SYNC Request at One or more Sensors and Stimulation Device
602
604
Select Channel of One of the SYNC Requests via Stimulation Probe Device
620
Select Channel of One of the SYNC Requests via Sensing Modules
605
Determine STIM OFF
622
Review Slot Status Words for Available Slots and/or Select Available One or More Slots
606
Send ACK
624
Send Data Payloads (Slot Request) Signals
607
Receive Next SYNC Request at the Stimulation Probe Device
626
Receive Next SYNC Request with Slot Status Words with SUID of Sensing Modules at Sensing Module
608
N
STIM ON?
Y
609
Send ACK
610
Generate Stimulation Signal with Amplitude and Duration
628
Send Data According to Latest SYNC Request
612
Report Actual Amplitude and Duration
630
End

FIG. 19

WIRELESS SENSORS AND CORRESPONDING SYSTEMS AND METHODS FOR INTRA-OPERATIVE NERVE ROOT DECOMPRESSION MONITORING

CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] The present disclosure is related to U.S. patent application Ser. No. 14/455,258 filed on Aug. 8, 2014, U.S. patent application Ser. No. 14/455,285 filed on Aug. 8, 2014, and U.S. patent application Ser. No. 14/455,313 filed on Aug. 8, 2014. The entire disclosures of the applications referenced above are incorporated herein by reference.

FIELD

[0002] The present disclosure relates to nerve integrity monitoring systems and devices.

BACKGROUND

[0003] The background description provided herein is for the purpose of generally presenting the context of the disclosure. Work of the presently named inventors, to the extent the work is described in this background section, as well as aspects of the description that may not otherwise qualify as prior art at the time of filing, are neither expressly nor impliedly admitted as prior art against the present disclosure.

[0004] Prior to and/or during surgery, nerves may be compressed. During and/or subsequent to surgery the nerves may then be decompressed due to removal of material compressing the nerve and/or surrounding tissue. For example, when a channel of a nerve root is being compressed due to a degenerative or split disc, the disc can be removed and a spacer may be inserted to increase the size of the channel allowing decompression of the nerve root. A current standard of care for spinal nerve root decompression does not include intra-operative monitoring techniques to determine how much decompression of a nerve is required to achieve a positive outcome. Traditionally, spinal surgeons relieve pressure on a nerve root in a subjective manner and arbitrarily determine "how much" decompression provides a positive outcome based on surgical experience. One technique that has been suggested for monitoring decompression includes monitoring electromyographic (EMG) nerve root potentials. This includes using EMG sensors attached to a patent and wired to an EMG monitoring device to detect EMG activity. This technique has associated limitations and disadvantages. EMG signals generated by the EMG sensors tend to be noisy due to the wires connecting the EMG sensors to the EMG monitoring device. The EMG monitoring device has a low sensitivity to changes in the EMG signals. Decompression is detected based on small changes in EMG signals. As a result, decompression estimates generated based on the monitored changes in the EMG signals can be inaccurate.

[0005] A nerve integrity monitoring (NIM) system can include a stimulation probe device, sensors, an electrode connection box, and an EMG monitoring device. The stimulation probe device is used to stimulate nerve and/or muscle activity. As an example, a stimulation probe device may include a stimulating electrode tip. A surgeon may touch a location on a patient with the electrode tip to provide a voltage and/or current to the location and stimulate nerve activity and as a result a muscle response (or muscle activity). A reference patch may be attached to the patient away from (i) the sensors, and (ii) an area being stimulated. An electrode of the reference patch can be at a reference potential. The sensors can include electrodes that are attached to the patient and used to monitor the muscle activity. A voltage potential between the electrode tip of the stimulation probe device and the reference patch and voltage potentials indicated by outputs of the sensors may be provided via wires to the electrode connection box. The wires are plugged into respective jacks in the electrode connection box. The electrode connection box can have channels respectively for: a voltage potential of the stimulation probe device; a voltage potential of the reference patch; and output voltages of the sensors. The electrode connection box may filter signals received from the stimulation probe device and sensors and provide corresponding signals to the EMG monitoring device. Depending on the surgical procedure being performed, a large number of cables may be used to transmit information between (i) the stimulation probe device and sensors and (ii) the electrode connection box. As an example, 1-32 channels may be used during a surgical procedure. As an other example, more than 32 channels may be used. Each of the channels may correspond to a respective twisted pair cable (each cable having a twisted pair of wires). Each of the cables connected to the sensors is secured to a patient via the electrodes of the sensors, extends away from the patient, and is routed outside of a sterile field (or environment) in which the patient is located to the EMG monitoring device.

SUMMARY

[0006] A sensor is provided that includes an array of pins, a sensing element, a control module, and a physical layer module. The array of pins or needles is configured to be inserted in tissue of a patient. The sensing element is separate from the array of pins or needles and is configured to (i) detect a first parameter of the tissue, and (ii) generate a first signal indicative of the first parameter. The control module is configured to (i) receive the first signal, (ii) monitor a second parameter of the tissue based on a second signal received from the array of pins or needles, and (ii) generate a third signal based on the first signal and the second parameter, where the third signal is indicative of a level of decompression of a nerve of the patient. The physical layer module is configured to wirelessly transmit the third signal from the sensor to a console interface module or a nerve integrity monitoring device.

[0007] In other features, a method of operating a sensor is disclosed herein. The method includes: detecting a first parameter of a tissue of a patient via a first sensing element of the sensor; generating a first signal indicative of the first parameter; monitoring a second parameter of the tissue based on a second signal received from an array of pins or needles, where the array of pins or needles is configured to be inserted in the tissue, and where the array of pins or needles are separate from the first sensing element; generating a third signal based on the first signal and the second parameter, where the third signal is indicative of a level of decompression of a nerve of the patient; and wirelessly transmitting the third signal from the sensor to a console interface module or a nerve integrity monitoring device.

[0008] Further areas of applicability of the present disclosure will become apparent from the detailed description, the

claims and the drawings. The detailed description and specific examples are intended for purposes of illustration only and are not intended to limit the scope of the disclosure.

BRIEF DESCRIPTION OF DRAWINGS

[0009] FIG. **1** is a perspective view of a wireless nerve integrity monitoring (WNIM) system incorporating sensors in accordance with the present disclosure.

[0010] FIG. **2** is a functional block diagram of a sensing module, a console interface module and a NIM device in accordance with the present disclosure.

[0011] FIG. **3** is a functional block diagram of another sensing module and another NIM device in accordance with the present disclosure.

[0012] FIG. **4** is a functional block diagram of another sensing module in accordance with the present disclosure.

[0013] FIG. **5** is a functional block diagram of a stimulation probe device in accordance with the present disclosure.

[0014] FIG. **6** is a functional block diagram of a portion of the stimulation probe device in accordance with the present disclosure.

[0015] FIG. **7** is a top view of a sensor in accordance with the present disclosure.

[0016] FIG. **8** is a side view of the sensor of FIG. **7**.

[0017] FIG. **9** is a side view of the sensor of FIG. **7**.

[0018] FIG. **10** is a bottom view of the sensor of FIG. **7**.

[0019] FIG. **11** is a perspective view of a sensing array including sensing elements and devices in accordance with the present disclosure.

[0020] FIG. **12** is an exploded view of the sensing array of FIG. **11**.

[0021] FIG. **13** is a top view of the sensing array of FIG. **11**.

[0022] FIG. **14** is a signal flow diagram illustrating a sensor joining and communicating in a WNIM system in accordance with the present disclosure.

[0023] FIG. **15** is a signal flow diagram illustrating a stimulation device joining and communicating in a WNIM system in accordance with the present disclosure.

[0024] FIG. **16** illustrates an implementation of a sensor and a sensing array in accordance with an embodiment of the present disclosure.

[0025] FIG. **17** illustrates a method of operating a sensor and a console interface module and/or NIM device in accordance with the present disclosure.

[0026] FIG. **18** illustrates a method of powering-up a sensor in accordance with the present disclosure.

[0027] FIG. **19** illustrates a WNIM method of operating a stimulation probe device, one or more sensors, and a console interface module and/or NIM device in accordance with the present disclosure.

[0028] In the drawings, reference numbers may be reused to identify similar and/or identical elements.

DESCRIPTION

[0029] Any clutter and/or time inefficiencies in an operating room that can be eliminated and/or minimized is advantageous to both hospital personal and a patient. Traditional nerve integrity monitoring (NIM) systems including EMG sensors have extensive cabling. Most of the cabling corresponds to transporting or delivery evoked response signals from sensors to a NIM device, as a result of stimulated nerve activity in muscles of a patient. Various techniques are disclosed below, which reduce and/or eliminate cables used in a NIM system, reduce and/or minimize certain time inefficiencies associated with current NIM systems, minimize noise, increase sensitivity to changes in EMG signals, and minimize power consumption.

[0030] Examples are also disclosed below that provide sensors, systems and methods including intra-operative monitoring of relevant physiological parameters to achieve predictive, accurate and positive decompression outcomes. Nerve integrity monitoring is performed during spinal decompression to enhance predictive positive outcomes. Wireless NIM sensors and systems are disclosed that provide increased sensitivity and signal discrimination.

[0031] FIG. **1** shows a wireless nerve integrity monitoring (WNIM) system **10**. The WNIM system **10**, as shown, includes sensors **12**, a stimulation probe device **14**, a wireless interface adaptor (WIA) **16** and a NIM device **18**. The WIA **16** includes a console interface module (CIM), which is shown in FIG. **2**, and an interface **20** (e.g., a 32-pin connector) for connecting to the NIM device **18**. The WIA **16** is shown as being plugged into a back side of the NIM device **18**. Although the WIA **16** is shown as being plugged into the NIM device **18** via the interface **20**, the WIA **16** may be separate from the NIM device **18** and wirelessly communicate with the NIM device **18**. The sensors **12** and the stimulation probe device **14** wirelessly communicate with the CIM and/or the NIM device **18**. In one embodiment, the WIA **16** is connected to the NIM device **18** and wirelessly communicates with the sensors **12** and the stimulation probe device **14**. Information described below as being transmitted from the NIM device **18** to the CIM may then be relayed from the CIM to the sensors **12** and/or the stimulation probe device **14**. Information and/or data described below as being transmitted from the sensors **12** and/or the stimulation probe device **14** to the CIM may then be relayed from the CIM to the NIM device **18**.

[0032] The WIA **16**: transfers signals between (i) the NIM device **18** and (ii) the sensors **12** and the stimulation probe device **14**; and/or adds additional information to the signals received from the NIM device **18** prior to forwarding the signals to the sensors **12** and/or stimulation probe device **14**, as described below. The WIA **16** may: operate essentially as a pass through device; be a smart device and add and/or replace information provided in received signals; and/or generate signals including determined information based on received signals. For example, the WIA **16** may receive a payload request signal from the NIM device **18** and determine a delay time between when the payload request was received and when a next synchronization (SYNC) request signal is to be transmitted. This is described in further detail with respect to FIGS. **14** and **19**. The WIA **16** allows the NIM device **18** to be compatible with legacy hardware. The WIA **16** may be unplugged from the NIM device **18** and a traditional electrode connection box may be connected to the WIA **16** using the same interface of the NIM device **18** as the WIA **16**. The WIA **16** replaces cables traditionally connected between (i) a NIM device **18** and (ii) sensors **12** and a stimulation probe device **14**. This eliminates wires traversing (extending from within to outside) a sterile field in which a patient is located.

[0033] As another example, the WIA **16** may receive signals from the sensors **12** and/or the stimulation probe device **14**. The signals from the sensors **12** and/or the stimulation probe device **14** may indicate first parameters

and/or the WIA device **16** may determine second parameters based on the received signals. The first parameters may include, for example, voltages, frequencies, current levels, durations, amplitudes, temperatures, impedances, resistances, wavelengths, etc. The second parameters may include, for example, durations, oxygen levels, temperatures, impedances, pH levels, accelerations, amplitudes, etc. The received signals and/or the determined information may be forwarded to the NIM device **18** for evaluation and/or for display on the screen of the NIM device **18**.

[0034] Although one type of sensor **12** is shown in FIG. **1**, other types of sensors and/or configurations of the sensor **12** may be incorporated in the WNIM system **10**. The sensors **12** may include respective pins and/or needles that are inserted into, for example, muscle tissue of a patient. The sensors **12** may be adhered to skin of a patient over, for example, muscle tissue. The sensors **12** may, for example, be used to detect the first parameters including voltage potentials and/or current levels passed between pins of the sensors **12**. As shown below, the sensors may include one or more arrays of pins and/or needles. Voltage potentials, impedances, and/or current levels between selected pairs of the pins and/or needles in the arrays may be monitored. This may include monitoring various pin (and/or needle) combinations in a single array and/or pin (and/or needle) combinations of pins (and/or needles) in different arrays. For example, a voltage potential between a first pin (and/or needle) in a first array and a second pin (and/or needle) in a second array may be monitored. The sensors **12** may each include any number of pins and/or needles. The pins and needles may be referred to as electrodes.

[0035] The sensors **12** are used to digitize nerve and/or muscle activity and wirelessly transmit this information to the CIM and/or the NIM device **18**. The sensors **12** may alert the CIM and/or the NIM device **18** of bursts (e.g., increases in voltages of evoked response signals) in nerve and/or muscle activity. An evoked response signal refers to a signal generated in a tissue of a patient as a result of a stimulation signal generated by the stimulation probe device **14**.

[0036] The stimulation probe device **14** is used to stimulate nerves and/or muscle in the patient. The stimulation probe device **14** includes: a housing **30** with a grip **32**; one or more electrodes **34** (shown having two electrodes); a switch **36**; a control module (an example of which is shown in FIG. **5**); and an input **38** for connection to a reference pad (or patch) **40**, via a cable **42**. Although the stimulation probe device **14** is shown having a bifurcated tip with two electrodes **34**, the stimulation probe device **14** may have one or more electrodes **34**. The electrodes **34** are separated and insulated from each other and may extend within a tube **44** to the housing **30**. The switch **36** may be used to turn ON the stimulation probe device **14** and/or to apply a stimulation pulse to the electrodes **34**. The stimulation pulse may be manually generated by actuating the switch **36** or may be generated via the NIM device **18** and/or the WIA **16** via the CIM. The NIM device **18** and/or the CIM may signal the control module of the stimulation probe device **14** to generate one or more stimulation pulses to stimulate one or more nerves and/or muscles in proximity of the electrodes **34**. The reference patch **40** is used to provide a reference voltage potential. One or more voltage potentials between one or more of the electrodes **34** and the reference patch **40** may be determined by: the control module of stimulation probe device **14**; a control module of the NIM device **18** (examples of which are shown in FIGS. **2-3**); and/or a control module of the CIM (examples of which are shown in FIGS. **2-3**).

[0037] The stimulation probe device **14** may wirelessly transmit information to the CIM and/or NIM device **18**. The information may include: timing information; voltage potentials between the electrodes **34**; voltage potentials between the reference patch **40** and one or more of the electrodes **34**; number of stimulation pulses; pulse identifiers (IDs); voltages and current levels of stimulation pulses generated; and amplitudes, peak magnitudes and/or durations of stimulation pulses generated. The timing information may include: start and end times of stimulation pulses; durations of stimulation pulses; and/or time between stimulation pulses. In another embodiment, the WIA **16** is not included in the WNIM system **10**. In this embodiment, the NIM device **18** wirelessly communicates directly with the sensors **12** and the stimulation probe device **14**. This may include communication with the sensors **12** and the stimulation probe device **14** shown in FIG. **1** and/or communication with other sensors and/or stimulation devices. The WNIM system **10** may include any number of sensors and/or stimulation probe devices.

[0038] Referring now to FIGS. **1** and **2**, which show a sensing module **50**, a CIM **52** and a NIM device **54**. The sensing module **50** wirelessly communicates with the CIM **52** and/or with the NIM device **54** via the CIM **52**. The sensing module **50** may be included in any of the sensors disclosed herein including the sensors shown in FIGS. **1** and **7-9**. The CIM **52** may be included in the WIA **16** of FIG. **1**.

[0039] The sensing module **50** includes a control module **56** (e.g., a microprocessor), a memory **58**, and a physical layer (PHY) module **60** (e.g., a transceiver and/or radio). The control module **56** detects (i) electromyographic signals generated in tissue of a patient via sensing elements **61** (e.g., pins, needles, electrodes, and/or flexible circuit with electrodes), (ii) voltage potentials, current levels, and/or impedances between selected pairs of the sensing elements **61**. The electromyographic signals may be in the form of voltage signals having voltage potentials. One or more of the voltage signals and/or current levels may be from photodiodes and/or photodetectors, which may be included in the sensing elements **61**. The control module **56** may also drive illuminating devices **62** (e.g., lasers, light emitting diodes (LEDs), etc.). The voltage signals and/or current levels generated via the photodiodes and/or photodetectors may be light emitted by the illuminating devices **62** and reflected off of tissue of a patient and detected by the photodiodes and/or photodetectors. The photodiodes may be used to detect color and/or wavelength of reflected light. Oxygen content levels may be determined based on amplitudes of the voltage signals generated by the photodiodes.

[0040] The control module **56** includes a font end receive module **63**, a front end transmit module **64**, and a baseband module **66**. The front end receive module **63** may include one or more of each of an amplifier, a modulator, a demodulator, a filter, a mixer, a feedback module, and a clock. The front end transmit module **64** may include one or more of each of a modulator, an amplifier, and a clock. The baseband module **66** may include an upconverter and a downconverter. The front end receive module **63** may modulate, demodulate, amplify, and/or filter signals received from the sensing elements prior to generating an output for the baseband module **66**. The front end transmit module **64**

transmits stimulation signals to selected ones of the sensing elements **61** (e.g., selected pins and/or needles) and/or control operation of the illuminating devices **62**. The front end transmit module **64** may modulate stimulation signals provided to the sensing elements and/or modulate illumination signals generated by the illuminating devices **62**. Stimulation signals and/or illumination signals may not be modulated. The filtering performed by the front end transmit module **63** may include bandpass filtering and/or filtering out (i) frequencies of the amplified signals outside of a predetermined frequency range, and (ii) a direct current (DC) voltage. This can eliminate and/or minimize noise, such as 60 Hz noise. The front end receive module **63** generates baseband signals based on the signals received by the front end receive module **63**.

[0041] The baseband module **66** may include an analog-to-digital (A/D) converting module **70** (e.g., an A/D converter) and convert the baseband signals (analog signals) to digital baseband (BB) signals. The BB module **66** and/or the A/D converting module **70** may sample the output of the front end receive module **63** at a predetermined rate to generate frames, which are included in the digital BB signals. By A/D converting signals at the sensor as opposed to performing an A/D conversion at the CIM **52** or the NIM device **54**, opportunities for signal interference is reduced. The BB module **66** may include a multiplexer **67** for multiplexing (i) signals generated by the front end receive module **63**, and/or (ii) generated based on the signals generated by the front end receive module **63**.

[0042] The BB module **66** may then upconvert the digital BB signal to an intermediate frequency (IF) signal. The BB module **66** may perform direct-sequence spread spectrum (DSSS) modulation during upconversion from the digital BB signal to the IF signal. The BB module **66** may include a mixer and oscillator for upconversion purposes. The BB module **66** and/or the control module **56** may compress and/or encrypt BB signals transmitted to the PHY module **60** prior to upconverting to IF signals and/or may decompress and/or decrypt signals received from the PHY module **60**.

[0043] The BB module **66** may provide a received signal strength indication (RSSI) indicating a measured amount of power present in a RF signal received from the CIM **52**. This may be used when determining which of multiple CIMs the sensor is to communicate with. The control module **56** may select a CIM corresponding to a SYNC request signal and/or a payload request signal having the most power and/or signal strength. This may include (i) selecting a channel on which the SYNC request signal and/or the payload request signal was transmitted, and (ii) communicating with the CIM on that channel. This allows the control module **56** to select the closest and proper CIM. This selection may be performed when the sensor has not previously communicated with a CIM, is switching to a different WNIM network, and/or has been reset such that the sensor does not have a record of communicating with a CIM. In one embodiment, the sensors are unable to be reset.

[0044] The memory **58** is accessed by the control module **56** and stores, for example, parameters **72**. The parameters **72** may include parameters provided in SYNC request signals and/or parameters associated with signals generated via the sensing elements **61**. The parameters may include voltages, current levels, amplitudes, peak magnitudes, pulse durations, temperatures, pH levels, frequencies, impedances, resistances, oxygen levels, perfusion and/or conduction rates, etc.

[0045] The PHY module **60** includes a transmit path **74** (or transmitter) and a receiver path **76** (or receiver). The transmit path **74** includes a modulation module **78** (e.g., a modulator) and an amplification module **80** (e.g., an amplifier). The modulation module **78** modulates and upconverts the IF signal to generate a radio frequency (RF) signal. This may include Gaussian frequency-shift keying (GFSK) modulation. The modulation module **78** may include, for example, a filter, a mixer, and an oscillator (collectively identified as **82**). The amplification module **80** may include a power amplifier **84**, which amplifies the RF signal and transmits the RF signal via the antenna **86**.

[0046] The receiver path **76** includes a second amplification module **90** and a demodulation module **92** (e.g., a demodulator). The amplification module **90** may include a low-noise amplifier (LNA) **94**. The second amplification module **90** amplifies RF signals received from the CIM **52**. The demodulation module **92** demodulates the amplified RF signals to generate IF signals. The IF signals are provided to the BB module **66**, which then downconverts the IF signals to BB signals. The demodulation module **92** may include, for example, a filter, a mixer, and an oscillator (collectively identified as **96**). The A/D converting module **70** may include a digital-to-analog (D/A) converter to convert the BB signals to analog signals. The RF signals received from the CIM **52** may include, for example, SYNC request signals or portions thereof.

[0047] The CIM **52** includes a PHY module **100**, a control module **102**, a memory **104**, and a NIM interface **106** (e.g., 32 pin connector). The PHY module **100** includes a receive path (or receiver) **108** and a transmit path (or transmitter) **110**. The receive path **108** includes an amplification module **112** and a demodulation module **114**. The amplification module **112** amplifies RF signals received from the sensing module **50** and/or from other sensor modules and/or stimulation probe devices. The amplification module **112** may include a LNA **115**. The demodulation module **114** demodulates and downconverts the amplified RF signals to generate IF signals. The demodulation module **114** may include a filter, mixer, and an oscillator (collectively referred to as **117**). The transmit path **110** includes a modulation module **116** and an amplification module **118**. The modulation module **116** modulates and upconverts IF signals from the control module **102** to generate RF signals. This may include Gaussian frequency-shift keying (GFSK) modulation. The modulation module **116** may include, for example, a filter, a mixer, and an oscillator (collectively identified as **119**). The amplification module **118** transmits the RF signals to the sensing module **50** via an antenna **120** and/or to other sensor modules and/or stimulation probe devices. The amplification module **118** may include a power amplifier **121**.

[0048] The control module **102** includes a BB module **124** and a filtering module **126**. The BB module **124** converts IF signals received from the PHY module **100** to BB signals and forwards the BB signals to the filtering module **126**. The BB module may demultiplex an IF signal and/or a BB signal to provide multiple IF signals and BB signals. The BB module **124** also converts BB signals from the filtering module **126** to IF signals, which are forwarded to the modulation module **116**. The BB module **124** may include a

D/A converting module **128**, a demultiplexer **129**, and/or a fast Fourier transform (FFT) module **131**.

[0049] The D/A converting module **128** may include an A/D converter to convert analog signals from the filtering module **126** to digital signals. The D/A converting module **128** may include a D/A converter to convert digital signals from the PHY module **100** to analog signals. In one embodiment, the BB module **124** does not include the D/A converting module **128** and digital signals are passed between the filtering module **126** and the PHY module **100**. The demultiplexer **129** may demultiplex the analog signals and/or the digital signals. The FFT module **131** perform a FFT of the analog signals and/or the digital signals for spectral waveform analysis including frequency content monitoring.

[0050] The BB module **124** may attenuate signals received from the demodulation module **114**. The filtering module **126** may be a bandpass filter and remove frequencies of signals outside a predetermined range and/or DC signals. This can eliminate and/or minimize noise, such as 60 Hz noise. The BB module **124** and/or the control module **102** may compress and/or encrypt signals transmitted to the modulation module **116** and/or decompress and/or decrypt signals received from the demodulation module **114**. Although the CIM **52** is shown as being connected to the NIM device **54** via the NIM interface **106**, the CIM **52** may be separate from the NIM device **54** and wirelessly communicate with the NIM device **54** via the PHY module **100**.

[0051] The memory **104** is accessed by the control module **102** and stores, for example, parameters **130**. The parameters **130** may include parameters provided in SYNC request signals and/or parameters indicated in and/or generated based on the signals received via the sensing elements **61**. The parameters **130** may include voltages, current levels, temperatures, oxygen levels, wavelengths, pH levels, impedances, resistances, acceleration values, amplitudes, peak magnitudes, pulse durations, etc. and may include or be the same as the parameters **72**. The memory may also store synchronization requests **132**, which are defined below.

[0052] The NIM device **54** may include a control module **140**, a PHY module **142**, a CIM interface **144**, a display **146** and a memory **148**. The control module **140**: generates payload request signals; receives data payload signals from the sensing module **50** and/or other sensing modules and stimulation probe devices via the CIM **52**; and displays signals and/or other related information on the display **146**. The displayed signals and/or information may include the parameters **130** and/or information generated based on the parameters **130**, which may include oxygen levels, pH levels, and/or other parameters that may be determined based on the parameters **130**. The PHY module **142** may transmit signals to and receive signals from the control module **140** via the interfaces **106**, **144** as shown or wirelessly via an antenna (not shown). The memory **148** is accessed by the control module **140** and stores the parameters **130** and may store payload requests **150**, which are defined below.

[0053] The control modules **56**, **126**, the BB modules **66**, **128**, the PHY modules **60**, **100**, and/or one or more modules thereof control timing of signals transmitted between the sensing module **50** and the CIM **52**. This is described in further detail below with respect to FIGS. **14-15** and **22**. The PHY modules **60**, **100** may communicate with each other in a predetermined frequency range. As an example, the PHY modules **60**, **100** may communicate with each other in 2.0-3.0 giga-hertz (GHz) range. In one embodiment, the PHY modules **60**, **100** transmit signals in a 2.4-2.5 GHz range. The PHY modules **60**, **100** may communicate with each other via one or more channels. The PHY modules **60**, **100** may transmit data at predetermined rates (e.g., 2 megabits per second (Mbps)). The CIM **52** and/or the NIM device **54** may set the frequency range, the number of channels, and the data rates based on: the number of sensor modules in and actively communicating in the WNIM system **10**; the number of stimulation probe devices in and actively communicating in the WNIM system **10**; the types of the sensors; the number of channels per sensor; the speed per channel of each of the sensors; the number of channels per stimulation probe device, and/or the speed per channel of the stimulation probe devices.

[0054] Referring now to FIG. **1** and FIG. **3**, which shows the sensing module **50** and a NIM device **162**. The sensing module **50** includes the control module **56**, the memory **58** and the PHY module **60**. The control module **56** includes the front end receive module **63**, the front end transmit module **64**, and the BB module **66**. The control module **56** receives signals from the sensing elements **61** and controls operation of the illuminating devices **62**. The control module **56** reports data associated with the signals to the NIM device **162** via the PHY module **60**. The control module **56** also receives signals (e.g., synchronization request signals) from the NIM device **162** via the PHY module **60**.

[0055] The NIM device **162** includes a control module **164**, a memory **166**, a PHY module **168**, and the display **146**. Functionality of the CIM **52** of FIG. **2** is included in the NIM device **162**. The PHY module **168** includes a receive path **170** (or receiver) and a transmit path **172** (or transmitter). The receive path **170** includes an amplification module **174** and a demodulation module **176**. The amplification module **174** via a LNA **175** amplifies RF signals received from the sensing module **50** and/or from other sensor modules and/or stimulation probe devices. The demodulation module **176** demodulates and downconverts the amplified RF signals to generate IF signals. The transmit path **172** includes a modulation module **178** and an amplification module **180**. The modulation module **178** and the amplification module **180** may operate similar to the modulation module **116** and the amplification module **118**. The amplification module **118** may include a power amplifier **182** and transmits RF signals via an antenna **183** to the sensing module **50** and/or to other sensor modules and/or stimulation probe devices.

[0056] The control module **164** includes a BB module **184** and a filtering module **186**. The BB module **184** converts IF signals received from the PHY module **168** to BB signals and forwards the BB signals to the filtering module **186**. The BB module **184** may demultiplex the IF signals and/or the BB signals. The BB module **184** also converts BB signals from the filtering module **186** to IF signals, which are forwarded to the modulation module **178**. The BB module **184** may include a D/A converting module **188** and/or a demultiplexer **185**. The D/A converting module **188** may include an A/D converter to convert analog signals from the filtering module **186** to digital signals. The demultiplexer **185** may demultiplex the analog and/or the digital signals. The D/A converting module **188** may include a D/A converter to convert digital signals from the PHY module **168** to analog signals. In one embodiment, the BB module **184** does not include the D/A converting module **188** and digital signals are passed between the filtering module **186** and the

PHY module **168**. The BB module **184** may attenuate signals received from the demodulation module **176**. The filtering module **186** may be a bandpass filter and remove frequencies of signals outside a predetermined range and/or DC signals. This can eliminate and/or minimize noise, such as 60 Hz noise. The BB module **184** and/or the control module **164** may compress and/or encrypt signals transmitted to the modulation module **178** and/or decompress and/or decrypt signals received from the demodulation module **176**.

[0057] Referring now to FIGS. **2-3**, the BB module **66** of the sensing module **50** may provide a received signal strength indication (RSSI) indicating a measured amount of power present in a RF signal received from the NIM device **162**. This may be used when determining which of multiple NIM devices to communicate with. The control module **56** may select a NIM device corresponding to a SYNC request signal and/or a payload request signal that has the most power and/or signal strength. This may include selecting a channel on which the SYNC request signal and/or the payload request signal was transmitted and communicating with the CIM **52** and/or the NIM device **162** on that channel. This allows the control module **56** to select the closest and proper NIM device. This selection may be performed when the corresponding sensor has not previously communicated with the NIM device **162** and/or other NIM devices and/or has been reset such that the sensor does not have a record of communicating with the NIM device **162** and/or other NIM devices.

[0058] The memory **166** may store the parameters **130**, the payload requests **150** and/or the SYNC requests **132**. The memory **166** may store the SYNC requests and may not store the payload requests. This is because the NIM device **162** may generate SYNC requests and not payload requests.

[0059] Referring now to FIGS. **1** and **4**, which show a sensing module **200**. The sensing module **200** may be included in any of the sensors (e.g., the sensors **12** of FIG. **1**) disclosed herein and/or replace any of the sensing modules (e.g., the sensing module **50** of FIGS. **2-3**) disclosed herein. The sensing module **200** may include the control module **202**, a PHY module **204**, a power module **206**, a power source **208**, a temperature sensing module **210**, an A/D converter **212**, and an accelerometer **214** (e.g., a 3-axis accelerometer) or other motion sensor (e.g., a gyro). The motion sensor **214** includes motion sensing elements (e.g., electrodes) **215** for generating a signal indicative of motion and/or acceleration. Although the sensing module **200** is shown as having the temperature sensing module **210**, the sensing module **200** may not include the temperature sensing module **210**. The temperature sensing module **210** may be replaced with a temperature sensor, such as an infrared temperature sensor, as shown in FIG. **9**. In one embodiment, the sensing module **200** includes the temperature sensing module **210** and the temperature sensor. Although shown separate from the control module **202**, the PHY module **204**, the power module **206**, the temperature sensing module **210** and/or the A/D converter **212** may be included in and as part of the control module **202**.

[0060] The control module **202** includes the front end modules **63**, **64** and the BB module **66** of FIG. **2**. The PHY module **204** includes the modulation module **78**, the demodulation module **92** and the amplification modules **80**, **90** of FIG. **2**.

[0061] The control module **202**, the PHY module **204**, the temperature sensing module **210**, and the A/D converter **212** operate based on power from the power module **206**. The power module **206** receives power from the power source (e.g., a battery). The power module **206** may include a switch **216** as shown (or a pull-tab) to turn ON and/or OFF the power module **206** and thus turn ON and/or OFF the sensing module **200** and/or the corresponding sensor. The switch **216** may be manually operated or may be operated by the power module **206**, the control module **202** and/or the PHY module **204**. In one embodiment, the switch **216** is manually operated and at least partially exposed on an exterior of the sensing module **200** and/or corresponding sensor housing. In another embodiment, the switch **216** includes one or more transistors located in the control module **202**, the PHY module **204**, and/or in the power module **206**, as shown. If included in one of the modules **202**, **204**, **206**, the switch **216** is not exposed on an exterior of the sensing module **200** and/or the corresponding sensor housing. The state of the switch **216** may be controlled by the control module **202**, the PHY module **204**, and/or the power module **206** based on signals received from the sensing elements **61**, the CIM **52**, and/or the NIM device **162** of FIGS. **2-3**. Transitioning the switch **216** via one of the modules **202**, **204**, **206** from a first state to a second state to turn ON at least a portion of the sensor and/or at least a portion of the one or more of the modules **202**, **204**, **206** may be referred to as an "auto-start".

[0062] The sensing module **200** may operate in: a high power mode (fully powered mode), a low (or idle) power mode (partially powered or transmitting less frequently then when in the high power mode), a sleep mode, or OFF. Operation in and transition between these modes may be controlled by one or more of the modules **202**, **204**, **206**. As an example, the sensor may be OFF (or dormant) while being shipped and/or not in use. The sensor may also be OFF if: not yet communicated with a CIM and/or NIM device; a connection has not yet been established between the sensing module **200** and a CIM and/or NIM device; the sensor has not yet been assigned to a CIM and/or NIM device; and/or the sensor has not yet been assigned one or more time slots in which to communicate with a CIM and/or NIM device.

[0063] Transitioning to the low power mode, the sleep mode and/or to OFF decreases power consumption and can aid in minimizing size of the power source **208**. While partially powered, the control module **202** and/or portions of the control module **202** and the PHY module **204** may be deactivated. The receiver path of the PHY module **204** may remain activated to (i) receive signals from the CIM **52** and/or portions of the control module **202**, and (ii) detect electromyographic signals. The transmit path **74** of the PHY module **204** and/or other portions of the sensor that are not experiencing activity may be deactivated. Transitioning between the stated modes is further described below.

[0064] When a surgery is performed, an operating room is generally kept at a low temperature. This in turn can decrease temperature of a patient. Studies have shown that if a patient is kept warm (e.g., within a predetermined range of a predetermined temperature or a normal body temperature, such as 98.6° F.) better outcomes are achieved. To maintain a temperature of a patient, heaters may be used to blow warm air under the patient and/or heat portions of a table on which a patient is lying. The patient may also be covered or wrapped in blankets. If a heater is broken, accidentally disconnected, not setup properly and/or is operating improperly, the temperature of the patient can drop.

Unfortunately, there can be a long lag time from when the heaters fail to when a decrease in the temperature of the patient is detected. By the time the decrease in the temperature of the patient is detected by, for example, a surgeon or surgical assistant, the temperature of the patient may have been below the predetermined range for an extended period of time.

[0065] To aid in early detection of changes in temperatures of a patient, a sensor and/or sensing module may include the temperature sensing module, which may be used to detect a temperature where the sensor is located. This temperature may be based on or represent a temperature of a portion of a patient on which the sensor is attached. While the temperature sensor may not be in direct contact and/or directly indicate a temperature of the portion of the patient, the temperature sensor can provide a temperature signal indicative of an average temperature in a proximate area of the temperature sensor. The temperature may also be used for other tasks disclosed herein, such as to determine levels of nerve decompression, as described below.

[0066] Referring again also to FIG. **1**, one or more of the sensors **12** may include a temperature sensing module (e.g., the temperature sensing module **210**) and/or a motion sensor (e.g., an accelerometer or gyro sensor). By including temperature sensing modules in sensors, temperatures of various points on a patient may be monitored. This further aids in early detection of changes in temperatures of a patient. The sensors provide an earlier indication of a temperature issue than a sensor used to detect a change in a core body temperature of the patient, as the limbs or exterior of the body tends to decrease in temperature quicker than the core body temperature. The core body temperature may refer to, for example, an internal temperature within a trunk (or chest) of the body.

[0067] The temperature sensing module **210** may include a first transistor **220** and a second transistor **222**. The first transistor **220** may be transitioned between states to supply current to the second transistor **222**. This turns ON the temperature sensing module **210**. The second transistor **222** is configured to detect a temperature. As an example, the first transistor **220** may be a metal-oxide-semiconductor field-effect transistor (MOSFET) and includes a drain, a gate and a source. The second transistor **222** may be a bipolar junction transistor (BJT) and includes a collector, a base and an emitter. The transistors **220**, **222** are shown for example purposes only, one or more of the transistors **220**, **222** may be replaced with other transistors or other similarly operating circuitry. The drain is connected to and receives current from the power module **206**. The gate is connected to and receives a control signal from the control module **202**. The source of the first transistor **220** is connected to the collector and the base. The collector is connected to a ground terminal **224**. The collector and the emitter are also connected to the A/D converter **212**.

[0068] The second transistor **222** is connected in a diode configuration. Temperature dependence of the base-to-emitter voltage (Vbe) is the basis for temperature measurement. The base-to-emitter voltage Vbe is dependent on temperature while (i) the power source **208** and the power module **206** supply a constant level of current to the collector via the first transistor **220**, and (ii) a voltage across the base and the collector is zero. The voltage across the base (or collector) and the emitter is detected by the A/D converter. The detected voltage is converted to a temperature via the control module **202**. The control module **202** receives a digital signal from the A/D converter and determines the temperature. The temperature may be determined using, for example, expression 1, where A is a predetermined multiplier constant and B is a predetermined offset constant.

$$A \cdot Vbe + B \quad [1]$$

[0069] In addition to detecting signals from the sensing elements **61** and temperature, the sensing module **200** may also detect other parameters, such as heart rate, respiration rate, and/or muscle spasms. These parameters may be determined via one or more of the control modules **202**, **102**, **140**, **164** of the sensor, the CIM **52** and the NIM devices **54**, **162** of FIGS. **2-3**. The NIM devices **54**, **162** may generate an alert signal and/or display these parameters on the display **146**. This information may also be used to provide an early indication that a patient is coming out from anesthesia prematurely. The sensing elements **61** may be monitored for EMG purposes as well as for heart rate, respiration rate, and/or muscle spasms purposes. To detect this information, the sensor may be attached to (or mounted on) a trunk of a patient.

[0070] A heart rate may be in a same frequency band as an electromyographic signal. A heart rate is periodic unlike an electromyographic signal. A voltage potential detected as a result of a beating heart may have a larger amplitude (or magnitude) than amplitudes (or magnitudes) of an electromyographic signal. A respiration rate is typically in a lower frequency band than an electromyographic signal. A muscle spasm may have a distinguishable frequency and/or distinguishable frequency band. Thus, one or more of the control modules **202**, **102**, **140**, **164** may distinguish between signals or portions of signals corresponding to a heart rate, a respiration rate, and an electromyographic signal based on these differences. If the control module **202** of the sensor detects heart rate, respiration rate, and/or muscle spasms, the control module **202** may wirelessly transmit this information to the CIM **52** and/or one of the NIM devices **54**, **162**. The NIM devices **54**, **162** may then display this information and/or generate an alert signal if one or more of these parameters are outside of respective predetermined ranges and/or thresholds.

[0071] In addition to or as an alternative to monitoring the sensing elements **61** to detect heart rate, respiration rate, and/or muscle spasms, the sensor includes a motion sensor. As similarly described above, one or more of the control modules **202**, **102**, **140**, **164** may monitor signals from the motion sensor (e.g., acceleration signals generated by an accelerometer) to detect activity of muscle firing, heart rate, respiration rate, and/or muscle spasms. The acceleration information, muscle firing activity, heart rate, respiration rate, and/or muscle spasm information determined based on the acceleration signals may be wirelessly transmitted from the sensor and/or PHY module **204** to the CIM **52** and/or one of the NIM devices **54**, **162**.

[0072] As is further described below with respect to FIG. **18**, the sensor may "self-awake". In other words, the sensor may automatically transition from being OFF or being in the low power (or sleep) mode to being powered ON and being in the high power mode when attached to a patient. For example, while not attached to a patient, there is an "open" circuit between two of the sensing elements **61**. Thus, an impedance between two of the sensing elements **61** is high (e.g., greater than 10 kilo-Ohms (kOhms)). Subsequent to

attaching the sensor to the patient, an impedance between the two of the sensing elements **61** is low (e.g., less than 1 kOhms) and/or significantly less then when the sensor was not attached. This difference in impedance can be detected and cause the power module **206** and/or the control module **202** to switch operating modes.

[0073] In another embodiment, the two of the sensing elements **61** and corresponding impedance between the two of the sensing elements **61** operate as a switch to activate the power module **206**. Upon activation, the power module **206** may supply power to the control module **202** and/or the PHY module **204**.

[0074] In yet another embodiment, the power module **206** (or analog front end) is configured to generate a DC voltage while the sensor is not attached to a patient. Generation of the DC voltage may be based on the impedance between the two of the sensing elements **61**. This DC voltage is detected by the control module **202**. The control module **202** remains in the low power (or sleep) mode while receiving the DC voltage. The power module **206** ceases to provide the DC voltage when the electrodes are attached to the patient. This causes the control module to transition (i) from being OFF to being in the low power mode or high power mode, or (ii) from being in a sleep mode to being in the low power mode or the high power mode.

[0075] The control module **202** and/or the power module **206** may periodically transition between operating in a low power (or sleep) mode and the high power mode to check the impedance between the two of the sensing elements **61** and whether the DC voltage is provided. This may occur every predetermined period (e.g., 30-60 seconds). In another embodiment, in response to the two of the sensing elements **61** being attached to a patient, the power module **206** may transition (i) from not supplying power to the control module **202**, the PHY module **204** and/or portions thereof to (ii) supplying power to the control module **202**, the PHY module **204** and/or portions thereof.

[0076] Although the modules **204**, **206**, **210** and the A/D converter **212** are shown as being separate from the control module **202**, one or more of the modules **204**, **206**, **210** and the A/D converter **212** or portions thereof may be incorporated in the control module **202**. Signal lines **221** are shown between the sensing elements **61** and the control module **202**. A third signal line **223** may be included for noise feedback cancellation.

[0077] Referring now to FIGS. **1-3** and FIG. **5**, a stimulation probe device **230** is shown, which may be in wireless communication with the CIM **52** and/or one of the NIM devices **54**, **162**. The stimulation probe device **230** provides pulses of current to stimulate nerves. The stimulation probe device **230** wirelessly receives signals from the CIM **52** and/or one of the NIM devices **54**, **162** indicating timing, amplitudes and rates for the pulses generated by the stimulation probe device **230**. The stimulation probe device **230** attempts to provide the pulses with the indicted timing and amplitudes and at the rate (or rates) indicated. The stimulation probe device **230** also monitors the actual timing, amplitudes and rates of the pulses and provides feedback of this information to the CIM **52** and/or one of the NIM devices **54**, **162**.

[0078] The stimulation probe device **230** includes a control module **232**, a memory **234**, a PHY module **236**, a stimulating module **238**, electrodes **240**, a power module **242**, and a power source **244**. The stimulating module **238** receives power from the power module **242** and generates stimulation signals via the electrodes **240**, which are supplied to tissue of a patient. Although the modules **236**, **238**, **242** are shown as being separate from the control module **232**, one or more of the modules **236**, **238**, **242** or portions thereof may be incorporated in the control module **232**. The stimulating module **238** may detect a voltage supplied to the electrodes **240** and/or voltage potentials applied across two of the electrodes **240** and generate stimulation information signals indicating the same. The stimulating module **238** may include a current-to-voltage conversion module **246** for measuring current supplied to one or more of the electrodes **240** and generate a stimulation information signal indicating the same. The stimulation information signals may be provided to the control module **232**.

[0079] The control module **232** wirelessly communicates with the CIM **52** and/or one or more of the NIM devices **54**, **162** via the PHY module **236** and an antenna **248**. The control module **232** includes a filtering module **250** and a BB module **252**. The filtering module **250** may operate as a bandpass filter and filter out frequencies of the amplified signals outside of a predetermined frequency range and a direct current (DC) voltage. This can eliminate and/or minimize noise, such as 60 Hz noise. The filtering module **250** may receive stimulation information signals from the stimulating module **238** and convert the stimulation information signals and/or signals generated based on the stimulation information signal to BB signals. The stimulating module **238** may monitor and indicate to the control module **232** actual voltages, current levels, amplitudes, and durations of stimulation pulses via the stimulation information signals. The control module **232** may then transmit this information via the PHY module **236** to the CIM **52** and/or one of the NIM device **54**, **162**.

[0080] The BB module **252** may include an analog-to-digital (A/D) converting module **254** and convert the BB signals from the filtering module **250** to digital BB signals. The BB module **252** and/or the A/D converting module **254** may sample the output of the filtering module **250** at a predetermined rate to generate frames, which are included in the digital BB signal. By A/D converting signals at the sensor as opposed to performing an A/D conversion at the CIM **52** or one of the NIM devices **54**, **162**, opportunities for signal interference is reduced.

[0081] The BB module **252** may then upconvert the digital BB signal to an intermediate frequency (IF) signal. The BB module **252** may perform DSSS modulation during upconversion from the digital BB signal to the IF signal. The BB module **252** may include a mixer and oscillator for upconversion purposes. The BB module **252** and/or the control module **232** may compress and/or encrypt BB signals transmitted to the PHY module **236** prior to upconverting to IF signals and/or may decompress and/or decrypt signals received from the PHY module **236**.

[0082] The BB module **252** may provide a received signal strength indication (RSSI) that indicates a measured amount of power present in a received RF signal. This may be used when determining which of multiple CIMs and/or NIM devices to communicate with. The control module **232** may select a CIM and/or a NIM device corresponding to a SYNC request signal and/or a payload request signal having the most power and/or signal strength. This may include selecting a channel on which the SYNC request signal and/or the payload request signal was transmitted and communicating

with the CIM or the NIM device on that channel. This allows the control module **232** to select the closest and proper CIM and/or NIM device. This selection may be performed when the stimulation probe device has not previously communicated with a CIM and/or a NIM device and/or has been reset such that the stimulation probe device does not have a record of communicating with a CIM and/or a NIM device.

[0083] The memory **234** is accessed by the control module **232** and stores, for example, parameters **260**. The parameters **260** may include parameters provided in SYNC request signals and/or parameters associated with stimulation pulses generated via the electrodes **240**. The parameters associated with stimulation pulses may include voltages, wavelengths, current levels, amplitudes, peak magnitudes, pulse durations, etc.

[0084] The PHY module **236** includes a transmit path **262** (or transmitter) and a receiver path **264** (or receiver). The transmit path **262** includes a modulation module **266** and an amplification module **268**. The modulation module **266** modulates the IF signal to upconvert the IF signal to a RF signal. This may include GFSK modulation. The modulation module **266** may include, for example, a filter, a mixer, and an oscillator. The amplification module **268** may include a power amplifier **269**, which amplifies the RF signal and transmits the RF signal via the antenna **248**.

[0085] The receiver path **262** includes a second amplification module **270** and a demodulation module **272**. The second amplification module **270** may include a LNA **274**. The second amplification module **270** amplifies RF signals received from the CIM. The demodulation module **272** demodulates the amplified RF signals to generate IF signals. The IF signals are provided to the BB module **252**, which then downconverts the IF signals to BB signals. The A/D converting module **254** may include a D/A converter to convert the BB signals to analog signals. The RF signals received from the CIM **52** may include, for example, SYNC request signals or portions thereof.

[0086] The power module **242** receives power from the power source **244** and supplies the power to the stimulating module **238**, the control module **232** and the PHY module **236**. The power module **242** may include a switch **276**. The switch **276** may be actuated to generate stimulation pulses. When the switch **276** is closed or toggled and/or when the control module **232** generates a control signal commanding generation of one or more stimulation pulses, the power module **242** and/or the control module **232** signals the stimulating module **238** to generate the one or more stimulation pulses. The timing, amplitude, and/or duration of each of the stimulation pulses may be based on information received from the CIM **52** and/or one of the NIM devices **54**, **162**. Frequency of the stimulation pulses and/or time between the stimulation pulses may also be controlled and based on corresponding information received from the CIM **52** and/or one of the NIM devices **54**, **162**.

[0087] Referring also to FIG. **6**, which shows a portion **279** of the stimulation probe device **230**. The stimulation probe device **230** includes the control module **232**, the stimulating module **238**, the electrodes **240**, the power module **242** with the switch **276**, and the power source **244**. The control module **232** may be connected to the reference patch **40**. In one embodiment, the stimulating module **238** is connected to the reference patch **40**. The stimulating module **238** may include the current-to-voltage conversion module **246**, a boost module **280**, and a D/A converter **282**. The current-to-voltage conversion module **246** converts a current supplied to the electrodes **240** to a voltage, which is detected by the control module **232**. The control module **232** may include an A/D converter to convert a voltage signal received from the current-to-voltage conversion module **246** to a digital signal.

[0088] The D/A converter **282** may convert an analog control signal from the control module **232** to a digital control signal. The digital control signal is provided to the boost module **280** and sets a current level, a voltage, and a duration of one or more stimulation pulses to be generated by the boost module **280** via the electrodes **240**. The boost module **280** generates stimulation signals having the stimulation pulses to be supplied to the electrodes **240**. The stimulation signals have increase voltage, current and/or power over other signals (e.g., signals transmitted between other modules and/or RF signals) transmitted in the WNIM system **10**. The increased voltage, current and/or power generates the stimulation pulses to stimulate tissue (nerve or muscle tissue) of a patient. The boost module **280** receives power from the power module **242**. The control module **232** may control the power module **242** to supply a selected amount of current to the boost module **280** for generation of the stimulation signals.

[0089] The control module **232** controls sampling timing of the A/D converter **254** and stimulation pulse timing of the D/A converter **282**. The control module **232** may also control and/or perform encryption of data generated by the stimulation probe device **230** prior to transmission of the data to the CIM **52** and/or one or more of the NIM devices **54**, **162**. The control module **232** may further control operation of the PHY module **236**.

[0090] Although not shown, the reference patch **40** may be replaced with and/or configured as a "smart" reference patch that is configured to wirelessly communicate with the stimulation probe device **230**. The smart reference patch may, for example, be configured similar to the sensing module **50** of FIGS. **2-3** and may include one or more electrodes, a control module and a PHY module having a transmitter path. The control module and the transmitter path of the reference patch **40** may be configured similar to and operate similar to the control module **56** and the transmit path **74** of the sensing module **50** of FIG. **2** or **3**. The control module of the reference patch **40** may be connected to the one or more electrodes and detect and wirelessly transmit a reference voltage at the one or more electrodes to the stimulation probe device **230**. The reference voltage may be transmitted via the transmitter path of the reference patch **40**. The control module of the reference patch **40** may generate a reference voltage signal that indicates the reference voltage. The reference voltage may be a constant voltage or may vary depending on the state of the patient in an area where the reference patch **40** is attached.

[0091] The stimulating module **238** and/or the stimulation probe device **230** may generate stimulation signals, which may be detected via at least some of the sensing elements **61** of FIGS. **2-4** during decompression of one or more nerves. Conduction speed (sometimes referred to as conduction velocity or conduction rate) from when a stimulation signal is provided via the electrodes **240** and/or at least some of the sensing elements **61** to when a control module (e.g., one of the control modules **56**, **202**) detects the stimulation signal may be monitored. The healthier the nerve and/or tissue, typically the quicker the conduction speed. The control

module may determine the difference in time from when the stated events occur and based on this information determine the conduction speed.

[0092] FIGS. **7-10** show a sensor **290** that may replace any of the sensors **12** of FIG. **1** and includes multiple layers including a top control layer **292**, an interposer layer **294** and a bottom sensing layer **296**. The top control layer **292** may include a power source **298**, a control module **300**, a radio **302**, and/or a motion sensor **304**. The motion sensor **304** includes motion sensing elements **305**. The power sources **298** may supply power to the control module **300**, the radio **302** and/or other components in the sensor **290**. The bottom sensing layer **296** may be attached to tissue of a patient and include one or more sensors, which may be connected to the control module **300** by traces, vias, conductive balls, wire bonds, and/or other conductive elements within the interposer layer **294**. The sensors may include one or more sensing arrays (two sensing arrays **306**, **308** are shown) and one or more other sensors (an infrared temperature sensor **310** and a pH sensor **312** are shown).

[0093] The sensing arrays **306**, **308** and/or other sensing arrays disclosed herein may include pins **314**, which are inserted into tissue of a patient and used to detect voltages, current levels, impedances, and/or resistances of between selected pairs of the pins **314** and corresponding portions of the tissue. The pins **314** may be used to generate electromyography signals. The pins **314** may be used as stimulation electrodes to provide stimulation pulses to the selected portions of the tissue. The sensing arrays **306**, **308** and/or other sensing arrays discloses herein may include sensing elements and/or devices other than the pins **314** (e.g., electrodes, needles, conductive elements, etc.). Examples of the other sensing elements are shown in FIGS. **11-13**. The sensing arrays **306**, **308** and/or other sensing arrays discloses herein may be of various sizes and have any number of pins. In one embodiment, the pins of the sensing arrays **306**, **308** are used to detect voltages, current levels, impedances, and/or resistances. In another embodiment, one of the sensing arrays **306** is used to detect voltages, current levels, impedances, and/or resistances while the other sensing array is used to provide stimulation pulses. In yet another embodiment, selected pins of each of the sensing arrays **306**, **308** are used to detect voltages, current levels, impedances, and/or resistances while the same and/or other selected pins of the sensing arrays **306**, **308** are used to provide stimulation pulses.

[0094] The infrared temperature sensor **310** has infrared sensing elements **311** (e.g., diodes capable of detecting infrared energy) detects temperature of tissue and generates a temperature signal indicative of the temperature. The infrared temperature sensor **310** may detect infrared energy emitted from the tissue within a predetermined infrared band. As a nerve is decompressed, perfusion occurs, which increases blood flow and oxygen levels and as a result increases temperature of the tissue of and around the nerve. Thus, the temperature of the tissue is indicative of the state of decompression and/or level of perfusion of the tissue. In addition or as an alternative to the infrared temperature sensor **310** a heat sensitive camera may be used to monitor small temperature changes associated with changes in perfusion.

[0095] The pH sensor (or neuropathy sensor) **312** includes a needle **316** and a flex circuit **318**. The pH sensor **312** detects pH levels in tissue of a patient. The needle **316** may be inserted in the tissue when the sensor **290** is attached to the tissue. The needle **316** guides the flex circuit **318** into the patient. The flex circuit **318** may include pH sensing elements (e.g., electrodes **319**) between which current is supplied. The flex circuit **318** performs electrochemical impedance spectroscopy techniques to measure pH levels of target tissue. This may include supplying current to the electrodes and monitoring changes in conductivity levels of the tissue. Presence of different chemicals in the tissue changes impedance of the tissue and as a result conductivity of the tissue. For example, if tissue of a patient exhibits poor perfusion, the patient may develop neuropathy (or diabetic neuropathy due to lack of blood flow), which includes accumulation of nitrous oxide and associated chemicals with nitrogen. This results in an acidic reaction that is directly related to a pH level, which can be detected using the flex circuit **318**.

[0096] The upper control layer **292** may be covered with a silicone based overmold material. The interposer layer **294** may be an insulative layer including an insulative material. The bottom sensing layer (or base layer) may be a substrate having an adhesive material on a bottom side for attachment to tissue of a patient.

[0097] FIGS. **11-13** show an example sensing array **320**, which may replace any of the sensing arrays disclosed in FIGS. **8-10**. The sensing array **320** includes an interposer substrate **322** and a base substrate **324**. The interposer substrate **322** may be connected to the bottom sensing layer **296** by a first set of conductive balls (or solder bumps) **326**. As an alternative, the sensing array **320** may be located away from the bottom sensing layer **296** and may be connected to the bottom sensing layer **296** via conductive elements and/or a flex circuit. The interposer substrate **322** may be connected to the base substrate **324** by a second set of conductive balls (or solder bumps) **328**. The second set of conductive balls **328** provide interconnections between (i) pins **330** on the base substrate **324**, and (ii) conductive elements within the interposer substrate **322**. The sensing array **320** may include any number of pins, which may be in an array having rows and columns. Each of the rows and columns has corresponding ones of the pins. One or more of the pins **330** may be replaced with needles. The pins **330** may be conically-shaped as shown. Length of the pins and/or needles may be based on whether the pins and/or needles are being used (i) more as surface electrodes placed above a nerve bundle of interest, or (ii) more for selective monitoring and deeper signal detection. The pins and/or needles may be used for monitoring prior to, during and/or subsequent to surgery. The shorter the pins and/or needles the more of an average of signals from a nerve bundle is generated due to the pins and/or needles being further from, for example, neurons of the nerve bundle.

[0098] The interposer substrate **322** includes conductive elements connecting the first set of conductive balls **326** to the second set of balls **328**. One or more of the substrates **322**, **324** may be incorporated in the bottom sensing layer **296** of FIGS. **8-9** and/or a substrate of the bottom sensing layer **296**. The base substrate **324** may be formed of, for example, glass, silicon, sapphire, and/or other suitable materials. The base substrate **324** and/or a portion of the base substrate **324** may be transparent to allow for passage of light.

[0099] The sensing array **320** may include a vertical-cavity surface-emitting laser (VCSEL) **332** and a photodiode detector (or other light detecting device) **334** or other optical

and/or perfusion sensor. The VCSEL **332** and the photodiode detector **334** may be located between the substrates **322**, **324** and in an area between some of the conductive balls in the second set of conductive balls **328**. The base substrate **324** may operate as a translucent lens allowing light emitted by the VCSEL **332** to pass through the base substrate **324** reflect off of tissue of a patient and be detected by the photodiode detector **334**. The portion of the base substrate **324** that is transparent may be located in a center of the base substrate **324**, as shown. Wire bonds **336** may connect photodiodes and/or conductive elements of the photodiode detector **334** to conductive elements in the interposer substrate **322**. The photodiode detector **334** may have one or more photodiodes.

[0100] The VCSEL **332** and the photodiode detector **334** may be used to detect changes in wavelength of light reflected off of tissue and/or blood. The changes in wavelength correspond to changes in color, which relates to changes in blood flow, pressure of blood flow, and/or oxygen levels in the blood. As more blood flows the pressure of the blood flow increases, which provides an increase in a pulsified amplitude of a received signal. As another example, the more red the color of the reflected light, the more blood flowing in the tissue.

[0101] The sensing array **320** may be used at a skin interface, as well as within a body of a patient. The sensing array **320** may be in direct contact with a monitored structure within the patient. The substrates **322**, **324** may have predetermined lengths, widths and depths (or heights). An example length L, width W, and depth D are shown in FIG. **13**. As an example, lengths and widths of the substrates **322**, **324** may be 4 millimeter (mm)×4 mm.

[0102] In addition to being used to detect the above-stated parameters, one or more of the pins **330** may be used to detect temperature of tissue within the patient. Thus, each of the pins **330** may be used for multiple purposes. The pins may be used for nerve integrity monitoring, perfusion monitoring, decompression monitoring, etc. Impedance of tissue changes during perfusion. This may be detected using the pins **330**. Different sets of the pins **330** may be used for different purposes or each set of the pins **330** may be used for all of the stated purposes. The pins **330** may be inserted in muscle/tissue being monitored. Each of the pins **330** may be used for monitoring one or more parameters. In one embodiment, a respective number of pins are allocated for each parameter monitored. Each parameter monitored may have a same or different number of allocated pins.

[0103] Additional details of the wireless protocol are described below with respect to FIGS. **14** and **15**. FIG. **14** shows a signal flow diagram illustrating a sensor **400** joining a WNIM network and communicating in a WNIM system with a CIM and/or a NIM device (collectively designated **402**). The sensor **400** may refer to any sensor disclosed herein. Similarly, the CIM and/or NIM device **402** may refer to any CIM and/or NIM device disclosed herein. Before a sensor responds to a SYNC request with a data payload, a joining process is performed. Joining establishes a link between the sensor and a CIM and/or NIM device and together the sensor and the CIM and/or NIM device (and/or other sensors and/or stimulation probe devices linked to the CIM and/or NIM device) provide a WNIM network. FIG. **14** shows an example sequence of events performed for the sensor **400** to join the WNIM network and also how different modes of operation are obtained.

[0104] A SYNC request signal **404** is transmitted from the CIM and/or NIM device **402** and includes a word for each time slot in a corresponding SYNC interval and is periodically and/or continuously updated and transmitted to indicate the statuses of the slots. To join the WNIM network, the sensor **400** checks all the available slots and selects the time slot in which to transmit a data payload signal to the CIM and/or NIM device **402**. Prior to transmitting the data payload, the sensor **400** sends a join request **406** to join the WNIM network and communicate in the selected time slot. The join request **406** may be transmitted in the selected time slot and indicates a sensor unique identifier (SUID) of the sensor, the selected time slot, the type of the sensor, a minimum data rate, and/or a maximum data rate of the sensor. In one embodiment, the sensor **400** sends the SUID in the selected time slot and the CIM and/or NIM device **402** has a record of the type and data rates of the sensor.

[0105] Based on the join request **406**, the CIM and/or NIM device **402** fills an appropriate slot status word with the SUID from the sensor **400**. The CIM and/or NIM device **402** may then send an updated SYNC request **408** with the updated slot status word indicating designation of the selected time slot to the sensor **400**. The sensor **400** receives the updated SYNC request with the SUID in the corresponding slot status word and responds by sending a data payload to the CIM and/or the NIM device **402** in the selected slot. If more than one slot is selected and/or designated to the sensor **400**, the sensor **400** may transmit one or more data payloads in the slots selected and/or designated to the sensor **400** (data payloads in slot **1** are designated **410** and data payloads in other slots are designated **411**). The time slots may be associated with one or more channels of the sensor **400**. The transmission of the SYNC requests and the data payloads may be periodically transmitted over a series of periodic SYNC intervals (or RF frames). Once linked to the CIM and/or NIM device **402**, the sensor **400** may now be controlled by the CIM and/or NIM device **402** via transmission of updated SYNC requests. The CIM and/or NIM device **402** may control, for example, output data rates and transitions between power modes of the sensor **400**. As an example, the CIM and/or NIM device **402** may update the output data rate from 10 kHz to 5 kHz for the time slot of the sensor **400** by transmitting an updated SYNC request **412**. Sensors linked to the CIM and/or NIM device **402** inspect control bits (e.g., bits of the slot status words) in SYNC requests to determine respective operating and/or power modes. The sensors then transition to the indicated operating and/or power modes.

[0106] FIG. **15** shows a signal flow diagram illustrating a stimulation probe device **420** joining a WNIM network and communicating in a WNIM system to a CIM and/or NIM device (collectively designated **422**). The stimulation probe device **420** may refer to any stimulation probe device disclosed herein. The CIM and/or NIM device **422** may refer to any CIM and/or NIM device disclosed herein. Generation of stimulation pulses may be initiated at the NIM device and/or CIM **422**. The NIM device may issue a payload request with bits **15** of status words indicating generation of a stimulation pulse. The status words may include: a CIM and/or NIM status word; slot status words; and stimulation probe status word. Based on the payload request, the CIM may generate a SYNC request **424** also having bits **15** of status words set to ON to indicate generation of a stimulation pulse. Both the payload request and the SYNC request may

indicate a delay, an amplitude of the stimulation pulse, and/or a duration of the stimulation pulse via corresponding words **13-15**. In response to bits **15** indicating a stimulation pulse is to be generated, one or more sensors corresponding to the stimulation probe device **420** and/or being used to monitor the stimulation pulse to be generated may transition to the HIGH power mode. Upon transitioning to the HIGH power mode, the sensors may generate and transmit data payloads at predetermined default frequencies and/or at frequencies indicated by bits **11**:**10** of the status words of the SYNC request.

[0107] In response to the SYNC request **424**, the stimulation probe device **420** generates a stimulation pulse, which is provided to a patient. To achieve an accurate timing and measurement of the stimulation pulse in relationship to an evoked response, the delay period provided in the SYNC request **424** is monitored by the stimulation probe device **420**. The stimulation probe device **420** generates a response signal **426** indicating the amplitude and duration of the stimulation pulse as applied to the patient.

[0108] Subsequent to the response signal **426** from the stimulation probe device **420**, the NIM device and/or CIM **422** generates a payload request (or SYNC request) **428** with the stimulation bits **15** low (or OFF). In response to the received payload request (or SYNC request) the stimulation probe device **420** sends an acknowledgement (ACK) signal **430** to the CIM and/or NIM device **422**. Generation of payload request (or SYNC requests) and ACK signals may be repeated until a next stimulation pulse is to be generated in which case the stimulation process may be repeated. The repeated tasks and/or similar tasks performed by a subsequent process are designated with the same numbers **424**, **426**, **428**, **430**.

[0109] As described above, the CIMs, NIM devices, sensors, reference patches, and stimulation probe devices disclosed herein may communicate with each other using bits within payload requests, SYNCH requests, data payloads, and response signals. The CIMs and/or NIM devices may initiate communication by a sending a payload request (SYNC request). The data payload may include one 16-bit word for payload validation. The 16 bit-word may include a SUID or a stimulator unique identifier (STIMUID). When the CIM and/or NIM device receives a data payload, the CIM and/or NIM device compares the SUID or the STIMUID with an expected SUID or STIMUID stored in memory of the CIM and/or NIM device. The SUID or STIMUID may have been stored in the memory when the sensor or stimulation probe device joined the corresponding WNIM network. If the comparison indicates a match, the data in the data payload may be displayed at the NIM device.

[0110] Likewise, when the sensor receives the SYNC request, the sensor compares a console unique identifier (CUID) of the CIM and/or NIM device provided in the SYNC request with an expected CUID stored in a memory of the sensor. The CUID may have been stored in the memory when the sensor joined the corresponding WNIM network. If the comparison of the CUIDs indicates a match, the sensor may respond, depending on mode status bits within a slot status word of the SYNC request, with one or more data payloads in the appropriate time slots following the SYNC request. The mode status bits may be the bits of the slot status word indicating a data rate and/or whether a stimulation pulse is to be generated.

[0111] FIG. **16** shows an example implementation of the sensor **290** and/or the sensing array **320** for detecting nerve root decompression. The sensor **290** and/or the sensing array **320** may be located on peripheral muscle tissue **340** downstream and away from a nerve root **342** of a nerve **344**. The nerve root **342** refers to a portion of the nerve **344** near a spinal cord **346**. Although the sensor **290** and/or the sensing array **320** are shown as being near certain neurons **348** of the nerve, the sensor **290** and/or the sensing array **320** may be located elsewhere. The sensor **290** may wirelessly communicate with a CIM and/or NIM device. A signal showing this communication is designated **349**.

[0112] A decompression procedure may be performed to relieve nerve root impingement (designated by arrows **350**). Nerve conduction to associated muscle groups is enhanced during decompression resulting in minute and/or incremental changes in perfusion and temperature. These are further enhanced as a healing process progresses. Sensors disclosed herein are used for nerve integrity monitoring and to detect these changes in perfusion and temperature.

[0113] For an evoked response, a stimulation signal may be generated and applied to the nerve root upstream (closer to the spinal cord) or downstream (further away from the spinal cord) than the compressed portion of the nerve. As an example, a stimulation probe device disclosed herein may be used to apply a stimulation signal to the nerve root (i) between the spinal cord and the compressed portion of the nerve, or (ii) downstream from the compressed portion of the nerve.

[0114] The systems, devices and modules disclosed herein may be operated using numerous methods, in addition to the methods described above, some additional example methods are illustrated in FIGS. **17-19**. In FIG. **17**, a method of operating a sensor and a CIM and/or NIM device is shown. Although the following tasks are primarily described with respect to the implementations of FIGS. **1-13** and **16**, the tasks may be easily modified to apply to other implementations of the present disclosure. The tasks may be iteratively performed.

[0115] The method may begin at **500**. The method may begin prior to, during and/or subsequent to an operation and/or procedure on a patient being performed. As an example, the method may begin prior to, during and/or subsequent to a procedure to provide nerve root decompression and/or decompression of a portion of a nerve. Basic nerve root compression/decompression physiology and etiology assumes the nerve root is impinged typically by a degenerative spinal disc or lamina. To relieve the impingement, there are 3 common types of spinal decompression procedures: (i) Laminotomy/foraminotomy—shaving off part of a lamina to create a larger opening to relieve a pinched nerve; (ii) Laminectomy—complete removal of a lamina (lamina refers to bone over the nerve root); and (iii) Discectomy—removal of a part of a disc that is compressing a nerve.

[0116] Nerve root activity prior to, during, and/or subsequent to decompression is monitored using the wireless NIM systems sensors and systems disclosed herein including detecting and displaying changes in spectral content, temperature, acceleration values, perfusion, pH levels, and nerve conduction speed (or velocity). Other parameters disclosed above may also be monitored and/or displayed. Typically, as the impingement is relieved, spectral content decreases and nerve conduction speed increases. Wireless

NIM provides increased sensitivity to signal changes. This is at least partially due to the elimination of "antenna effects" associated with cables/wires of a hardwired system.

[0117] At **501**, a control module (e.g., one of the control modules **56**, **202**) or a front end transmit module (e.g., the front end transmit module **64**) controls one or more illuminating devices (e.g., the VCSEL **332**) to generate illumination signals. The illumination signals are emitted at tissue of concern.

[0118] At **502**, signals are generated via sensing elements (e.g., the sensing elements **61** of FIG. **1** and/or the pins, photodiodes, temperature sensor, motion sensor of the sensor **290** and/or sensing array **320** of FIGS. **7-13**). The signals may include electromyographic signals, voltage signals, current signals, and/or other signals indicative of detected parameters disclosed herein. The signals may be generated due to, for example, generation of one or more stimulation pulses. The stimulation pulses may be generated and controlled by a front end transmit module (e.g., the front end transmit module **64**) of the sensor or may be generated by a stimulation probe device operating according to, for example, the method of FIG. **19**. The stimulation pulses and/or current applied may be modulated and controlled by the front end transmit module. The signals are detected by a control module (e.g., one of the control modules **56**, **202**). The control module may perform a fast Fourier transform (FFT) on receive voltage signals to determine spectral content, frequencies and corresponding amplitudes of the signals. Predetermined frequency ranges may be monitored to detect nerve activity (e.g., a frequency range of 10 Hertz (Hz) to 1 kilohertz (kHz) may be monitored).

[0119] At **504**, a front end receive module (e.g., the front end receive module **63**) adjusts gain of the signals to generate amplified signals. At **506**, the front end receive module filters the signals. This may include bandpass filtering amplified signals. The filtering removes unwanted information. At **508**, a BB module (e.g., the BB module **66**) generates a BB signal based on the filtered and amplified signals.

[0120] At **509**, the baseband module and/or the control module may determine parameters based on the amplified and/or filtered signals. This may include determining parameters disclosed above including impedances, resistances, current levels, voltage potentials, pulse durations, frequencies, spectral content, amplitudes, perfusion levels, temperatures, oxygen levels, decompression levels, etc. The baseband module and/or control module may quantify energy in a predetermined frequency band (e.g., 10-1 kHz). The decompression levels may be determined based on (i) one or more of these parameters, (ii) the quantified energy levels, and (iii) one or more tables relating the parameters and/or mathematical relationships between the parameters. Tables and/or mathematical expressions may be used to determine and/or calculate the decompression levels based on parameters, the quantified energy levels and/or the one or more tables relating the parameters and/or mathematical relationships between the parameters. For example, decompression levels may be determined based on conduction speeds, temperatures, perfusion levels, pH levels, motion signals, etc.

[0121] Prior to the baseband module upconverting signals and/or the parameters determined at **509** and for improved signal discrimination, any of this information may be modulated at a first frequency, amplified and then demodulated at a second frequency. This may be referred to as a neuromodulation process. The second frequency is different than the first frequency. The control module and/or baseband module may perform as a frequency selective signal monitor and utilize a heterodyning chopper-stabilized amplifying technique to convert a selected frequency band of a physiological signal to baseband for analysis. The physiological signal may include a bioelectrical signal, which may be analyzed in one or more selected frequency bands to select a stimulation electrode combination. The control module may analyze a characteristic of the bioelectrical signal in the selected frequency band. The second frequency may be selected such that the demodulation substantially centers a selected frequency band of the signal in a baseband frequency range.

[0122] Impedance of the tissue of concern may be measured using stimulation currents generated prior to task **502** and modulated at frequencies in different frequency ranges. In addition, the stimulation current frequency that is delivered to measure impedance may differ between patients and may depend on the region of the patient in which the impedance is measured.

[0123] The front end receive module, front end transmit module and/or control module may operate as an impedance sensor and produce an alternative current (AC) modulated signal that is AC coupled to an amplifier through the tissue of the patient. In this case, the stimulation current is modulated to modulate amplitude of a voltage across points of the tissue, thereby chopping the impedance signal produced by application of the stimulation current to the tissue. Thus, the patient is not exposed to a direct current (DC) signal. Moreover, the modulated signal applied to the tissue may not substantially excite the tissue, thereby decreasing a likelihood that the patient may experience discomfort or other detrimental effects from the modulated signal.

[0124] At **510**, a modulation module (e.g., the modulation module **78**) may modulate and upconvert the resulting BB signal to generate an RF signal. At **514**, a PHY module (e.g., one of the PHY modules **60**, **204**) and/or an amplification module (e.g., the amplification module **80**) transmits the RF signal from the sensing module to a CIM and/or NIM device.

[0125] At **516**, the CIM and/or NIM device receives the RF signal from the sensing module and amplifies the RF signal. At **518**, a demodulation module (e.g., one of the demodulation modules **114**, **176**) downconverts the RF signal to generate a second BB signal. At **522**, a BB module (e.g., one of the BB modules **128**, **184**) at the CIM and/or NIM device may attenuate the second BB signal, as described above. At **524**, a filtering module (e.g., one of the filtering modules **126**, **186**) filters the attenuated second BB signal to generate a second filtered signal. This may include bandpass or low pass filtering.

[0126] At **526**, the second filtered signal may be provided from the CIM to the NIM device. At **527**, the CIM and/or NIM devices may determine parameters based on the BB signal and/or filtered signal generated at **524**, **526**. This may include determining parameters disclosed above including impedances, resistances, current levels, voltage potentials, pulse durations, frequencies, spectral content, amplitudes, perfusion levels, temperatures, oxygen levels, decompression levels, conduction speed, etc. The control module may quantify energy in a predetermined frequency band (e.g., 10-1 kHz). The decompression levels may be determined

based on (i) one or more of these parameters, (ii) the quantified energy levels, and (iii) one or more tables relating the parameters and/or mathematical relationships between the parameters. For example, decompression levels may be determined based on conduction speeds, temperatures, perfusion levels, pH levels, motion signals, etc.

[0127] At **528**, the CIM and/or NIM devices may display the second filtered signal, detected parameters and/or parameters determined based on the detected parameters, such as the parameters determined at **509** and **527**. The filtered signal, the detected parameters, and/or the determined parameters may be presented graphically and/or over live images of an area of a patient as to prevent the surgeon from removing his/her eyes from the surgical site. A plot of energy in a band of interest may be plotted. One or more tones of varying frequency may also be generated to indicate one or more of the filtered signal, the detected parameters, and/or the determined parameters. This may be done via a display (e.g., the display **146**) and/or other user interface. A numerical score may be generated by, for example, the control module of the CIM and/or NIM devices to indicate nerve performance. The numerical score allows a surgeon to quickly and easily determine nerve performance. The nerve performance may be based on intrinsic activity of the nerve and/or external stimulus. The nerve performance may be related to monitoring naturally occurring nerve activity and/or monitoring the nerve itself without generation of stimulation pulses/signals. In addition or alternatively, the nerve performance may be an evoked response to stimulation pulses/signals. The nerve performance may be based on EMG activity from an associated muscle group, mechanical movement (detectable via a motion sensor), temperature change, color change, etc. As similar method as that shown with respect to FIG. **17** may be performed for data requested and received from a stimulation probe device.

[0128] The control modules of the CIM and/or NIM devices may: determine baseline values for one or more of the parameters disclosed herein; during or subsequent to a surgery, compare the baseline values respectively to detected values of the one or more parameters; and based on the comparisons, generate signals or indicate whether positive results exist for tasks performed during the surgery. As an example, a positive result may indicate whether a certain amount of nerve decompression has occurred. Differences between the baseline values and the detected values and/or differences between the baseline values and values generated based on the detected values may be compared to predetermined values and/or ranges corresponding to positive results. The baseline values and detected values may be aggregated and analyzed as a whole to determine results of a surgery or one or more tasks performed during surgery. The results may be displayed in real time during and/or subsequent to the surgery. The predetermined values and/or ranges may correspond to a degree of nerve decompression, correspond to full nerve decompression, or other positive result. As an example, the differences may indicate an extent of nerve decompression and/or whether nerve decompression has not occurred. The baseline values may be measured values that are measured prior to, at a beginning, during, at an end of and/or subsequent to a surgery and may be based on feedback signals generated by any of the sensors disclosed herein. The method may end at **530**.

[0129] The above-described method of monitoring decompression subsequent to surgery is beneficial because compressed nerves may not immediately response to decompression. It may be months after surgery for a full recovery and the nerves to be fully decompressed. The described method may also be beneficial to indicate when nerve recovery has reached a plateau or peak level. In an intra-operative scenario, there may be an immediate change in nerve performance. In this case, a surgeon may be notified in real time using the above-described method of nerve performance.

[0130] In FIG. **18**, a method of powering-up a sensor is shown. Although the following tasks are primarily described with respect to the implementations of FIGS. **1-13**, the tasks may be easily modified to apply to other implementations of the present disclosure. The tasks of FIG. **18** may be iteratively performed. The method may begin at **550**.

[0131] At **552**, an electromyographic signal is generated and/or an impedance between electrodes decreases due to attachment of the sensor to a patient. At **554**, a power module (e.g., the power module **206**) determines whether the impedance is less than a predetermined impedance (or threshold). If the impedance is less than the predetermined impedance, task **560** may be performed as shown, or alternatively task **556** may be performed. If the impedance is greater than or equal to the predetermined impedance, one or more of tasks **560**, **561**, **562**, **564** may be performed. Although tasks **560**, **561**, **562**, **564** are shown, any one of the tasks may not be performed and/or may be skipped. Also, tasks **560**, **561**, **562**, **564** may be performed in a different order.

[0132] At **560**, a control module (e.g., one of the control modules **56**, **202**) determines whether a DC voltage (may be referred to as an output voltage or output voltage signal) has been received from a power module (e.g., the power module **206**), as described above. If a DC voltage is not received task **556** may be performed. If a DC voltage is received, task **561** is performed.

[0133] At **556**, a sensing module of the sensor transitions to a LOW power mode or a HIGH power mode, which may include powering ON a portion, all, or a remaining portion of the control module and/or the PHY module. As an example, if a stimulation pulse is to be generated, the power module may transition to the HIGH power mode and power ON all or a remaining portion of the control module and/or the PHY module that are not already powered ON. Subsequent to task **556**, the method may end at **558**. Subsequent to task **556**, the control module may proceed to, for example, task **504** of FIG. **17**.

[0134] At **561**, the power module may determine whether a voltage potential across the electrodes is greater than a predetermined voltage and/or has a magnitude that is greater than a predetermined magnitude. If the voltage potential is greater than the predetermined voltage and/or the magnitude is greater than the predetermined magnitude, task **556** may be performed; otherwise task **562** may be performed. In one embodiment, a stimulation probe device is used to activate sensors. The stimulation probe device generates an initial stimulation pulse to active the sensors. Additional stimulation pulses may be generated after the sensors are activated. The power module may detect the initial stimulation pulse by monitoring the voltage at the electrodes and/or amplified signals generated based on the voltage detected at the electrodes.

[0135] At **562**, the power module may determine whether an amount of current received from one of the electrodes is

greater than a predetermined current level. If the amount of current is greater than the predetermined current level, task **556** may be performed; otherwise task **564** may be performed. As stated above, a stimulation probe device may generate an initial stimulation pulse to activate sensors. The power module may detect the initial stimulation pulse by monitoring current received from one or more of the electrodes and/or amplified signals generated based on the current received from the one or more electrodes. In one embodiment, tasks **561** and/or **562** are performed and tasks **554** and/or **560** are not performed.

[0136] At **564**, the power module refrains from generating the output voltage (or output signal) and the sensing module refrains from transitioning to the low power mode or the high power mode and remains in the sleep mode and/or low power mode. Subsequent to task **564**, task **552** may be performed as shown or the method may end at **558**.

[0137] In FIG. **19**, a WNIM method of operating a stimulation probe device, one or more sensors, and a console interface module and/or NIM device is shown. Although the following tasks are primarily described with respect to the implementations of FIGS. **1-13** and **16**, the tasks may be easily modified to apply to other implementations of the present disclosure. The tasks of FIG. **19** may be iteratively performed. The following tasks provide an example of initial power-ON and continuous and initial generation of periodic SYNC requests. The method may begin at **600**. At **602**, sensors and one or more stimulation probe devices receive one or more SYNC requests from one or more CIMs and/or NIM devices. The control modules of the NIM devices may generate payload request signals requesting data payloads from sensors and stimulation probe devices. The control modules of the CIMs may each generate a SYNC request signal, which may be transmitted periodically (e.g., once every predetermined or SYNC) period).

[0138] At **604**, a stimulation probe device selects a broadcast channel of one of the SYNC requests based on, signal strengths of the SYNC requests as received by the stimulation probe device. The stimulation probe device may hop through channels in a table to receive the SYNC requests. The broadcast channel of the SYNC request with the greatest signal strength is selected. The stimulation probe device may determine whether there is more than one stimulation probe device in the WNIM network of the selected SYNC request. If there is more than one stimulation probe device, an available time slot is selected by the stimulation probe device that is joining the WNIM network. This may be accomplished similar to how a sensor selects a time slot, as described above.

[0139] At **605**, the stimulation probe device joining the WNIM network determines that a stimulation pulse is not to be generated based on corresponding status bits of the SYNC request of the selected broadcast channel. At **606**, the stimulation probed device sends an ACK signal to the CIM and/or a NIM device of the selected broadcast channel.

[0140] At **607**, the stimulation probe device receives an updated SYNC request from the CIM and/or NIM device of the selected broadcast channel.

[0141] At **608**, the stimulation probe device that has joined the WNIM network determines whether a stimulation pulse is to be generated based on corresponding status bits of the updated SYNC request of the selected broadcast channel. If a stimulation pulse is requested to be generated, task **610** is performed, otherwise task **609** is performed. At **609**, the stimulation pulse device sends an ACK signal to the CIM and/or NIM device of the selected broadcast channel.

[0142] At **610**, the stimulation pulse device generates a stimulation pulse signal based on stimulation information words in the SYNC request. The stimulation pulse signal may be provided to electrodes (e.g., electrodes **240**), which may include pin style electrodes; "cuff" style electrodes, or other suitable electrodes. The stimulation pulse signal may be generated according to a delay period, an amplitude, and/or a duration provided in the SYNC request. The stimulation pulse signal may include a modulated stimulation current that creates a voltage potential between points on tissue of a patient. The modulation of the stimulation current may be controlled by a control module of the stimulation probe device. The stimulation pulse signal is applied to evoke a response from a nerve. Conduction velocity may be determined based on time between (i) when the stimulation probe signal is generated and/or applied and (ii) when a sensor (e.g., the sensor **290**) detects the evoked response. The conduction velocity may be determined, for example during one of the tasks **509**, **527**.

[0143] At **612**, the stimulation probe device reports a measured (or detected) amplitude and duration of the generated stimulation pulse to the CIM and/or the NIM device in a designated time slot of the periodic SYNC interval. This may occur in the same periodic SYNC interval as the SYNC request. Task **607** may be performed subsequent to task **612** or the method may end at **630** as shown.

[0144] At **620**, each of the sensing modules selects a broadcast channel of a SYNC request with greatest signal strength. The sensing modules may hop through channels in tables stored in the sensing modules to find and select the broadcast channel. At **622**, each of the sensing modules of the sensors selects one or more time slots and/or checks statuses of time slots as indicated in the SYNC request of the selected broadcast channel. If a sensing module has not linked up previously to the CIM and/or the NIM device communicating the selected broadcast channel, then the sensing module selects an available time slot. If a sensing module has previously linked up to the CIM and/or NIM device, then the sensing module checks a status of the previously selected time slot to assure that the time slot is still designated to the sensing module. If the time slot is no longer designated to the sensing module, the sensing module may select another available time slot.

[0145] Multiple time slots may be designated to a sensing module based on a type of the corresponding sensor without the sensing module having previously requested multiple time slots. For example, if the sensor has multiple channels and/or is to be assigned multiple time slots, the CIM and/or NIM device may update slot status words accordingly based on a single slot request. The sensing module may then detect that multiple slots have been assigned during review of slot status words in a subsequent SYNC request.

[0146] At **624**, the sensing modules may send data payloads in the respectively selected time slots. This serves dual purposes. In addition to providing data corresponding to signals detected at electrodes of the sensors, the sent data payloads serve as a request for the selected time slots. At **626**, the sensing modules may receive a next updated SYNC request from the CIM and/or NIM device. The next updated SYNC request may indicate SUIDs of the sensing modules

in slot status words. Task **626** may be performed while task **607** is performed. Tasks **626** and **607** may refer to the same updated SYNC request.

[0147] At **628**, the sensing modules send data payloads in the designated time slots according to the updated SYNC request to the CIM and/or NIM device. Task **628** may be performed subsequent to task **610**. Task **626** may be performed subsequent to task **628** or the method may end at **630** as shown. Although not shown in FIG. **19**, some of the tasks may be iteratively performed for subsequent SYNC request signals and/or generation of additional stimulation pulses.

[0148] The above-described tasks of FIGS. **17-19** are meant to be illustrative examples; the tasks may be performed sequentially, synchronously, simultaneously, continuously, during overlapping time periods or in a different order depending upon the application. Also, any of the tasks may not be performed or skipped depending on the implementation and/or sequence of events.

[0149] A method of operating a sensor is disclosed herein. The method includes: detecting a first parameter of a tissue of a patient via a first sensing element of the sensor; generating a first signal indicative of the first parameter; monitoring a second parameter of the tissue based on a second signal received from an array of pins or needles, where the array of pins or needles is configured to be inserted in the tissue, and where the array of pins or needles are separate from the first sensing element; generating a third signal based on the first signal and the second parameter, where the third signal is indicative of a level of decompression of a nerve of the patient; and wirelessly transmitting the third signal from the sensor to a console interface module or a nerve integrity monitoring device.

[0150] The method may include determining the level of decompression based on the first signal and the second signal, where the third signal indicates the level of decompression. The method may further include: receiving power from a power source within the sensor and at a front end module; and generating a stimulation signal to be applied to the tissue via the array of pins or needles, where the first signal is indicative of a temperature of the tissue, an oxygen level of the tissue, or a pH level of the tissue, and the second signal is an evoked response to the stimulation signal and is an electromyography signal.

[0151] The method may include: generating a motion signal indicative of muscle activity; and generating a pH signal indicative of a pH level of the tissue, where the first signal is indicative of a temperature of the tissue; determining a perfusion level based on the first signal or the second signal; determining a conduction speed based on the second signal and a time when a stimulation signal was previously generated; receiving the motion signal; emitting light via a light emitting device at the tissue; detecting portions of the light reflected off of the tissue; generating a fourth signal indicative of a wavelength and corresponding intensity of the light reflected off of the tissue; and generating the third signal based on the motion signal, the pH level, the perfusion level, the conduction speed and the fourth signal.

[0152] The method may include emitting light through the at least a portion of a first substrate and at the tissue, where the array of pins or needles are included in a sensing array, and where the sensing array includes (i) the first substrate attached to the array of pins or needles, wherein at least a portion of the first substrate is transparent, and (ii) a second substrate connected to the first substrate by conductive elements. The method may further include: detecting a reflected portion of the light reflected back through the first substrate; generating a fourth signal based on the detected reflected portion of the light reflected back through the first substrate; and generating the third signal based on the fourth signal.

[0153] The method may include: monitoring the second parameter and a third parameter of the tissue based on a fourth signal received from a second array of pins or needles; and generating the third signal based on the second parameter and the third parameter.

[0154] The method may include: generating a payload request at the nerve integrity monitoring device, wherein the payload request (i) requests a data payload from the sensor in a wireless nerve integrity monitoring network, and (ii) indicates whether a stimulation probe device is to generate a stimulation pulse; wirelessly transmitting the payload request to the sensor and the stimulation probe device or transmitting the payload request to the console interface module; and in response to the payload request, (i) receiving the data payload from the sensor at the nerve integrity monitoring device, and (ii) receiving stimulation pulse information from the stimulation probe device. The third signal includes the data payload. The data payload includes data corresponding to an evoked response of the patient. The evoked response is generated based on the stimulation pulse.

[0155] The method may include: receiving a payload request from the nerve integrity monitoring device at the console interface module; generating a synchronization request including information in the payload request, wherein the synchronization request (i) requests a data payload from the sensor in a wireless nerve integrity monitoring network, and (ii) indicates whether a stimulation probe device is to generate a stimulation pulse; wirelessly transmitting the synchronization request to the sensor and the stimulation probe device; and in response to the synchronization request, (i) wirelessly receiving the data payload from the sensor, and (ii) wirelessly receiving stimulation pulse information from the stimulation probe device. The third signal includes the data payload. The data payload includes data corresponding to an evoked response of the patient. The evoked response is generated based on the stimulation pulse.

[0156] The method may include: determining baseline values for the first parameter and the second parameter; during or subsequent to a surgery, comparing the baseline values respectively to the first parameter and the second parameter; and based on the comparisons, generating the third signal or indicating whether positive results exist for tasks performed during the surgery. The systems and methods disclosed herein may be used for monitoring decompression pre, during and post an operation and/or procedure. The sensors may be used on brain tissue, muscle tissue, nerve tissue, and/or other tissue of a patient. The systems and methods may be used to monitor decompression of nerves near or at a predetermined distance away from a spinal cord.

[0157] The wireless communication and corresponding systems and devices disclosed herein provide several advantages. For example, the wireless communication and corresponding systems and devices provide improved signal-to-noise ratios due at least partially to elimination of large loops of wire associated with traditional systems. The wireless communication and corresponding systems and devices also

electrically isolate a patient from monitoring devices. This provides improved safety by minimizing the amount of electrical current that may be supplied to a patient.

[0158] The wireless communications described in the present disclosure can be conducted in full or partial compliance with IEEE standard 802.11-2012, IEEE standard 802.16-2009, IEEE standard 802.20-2008, and/or Bluetooth Core Specification v4.0. In various implementations, Bluetooth Core Specification v4.0 may be modified by one or more of Bluetooth Core Specification Addendums 2, 3, or 4. In various implementations, IEEE 802.11-2012 may be supplemented by draft IEEE standard 802.11ac, draft IEEE standard 802.11ad, and/or draft IEEE standard 802.11ah.

[0159] The foregoing description is merely illustrative in nature and is in no way intended to limit the disclosure, its application, or uses. The broad teachings of the disclosure can be implemented in a variety of forms. Therefore, while this disclosure includes particular examples, the true scope of the disclosure should not be so limited since other modifications will become apparent upon a study of the drawings, the specification, and the following claims. It should be understood that one or more steps within a method may be executed in different order (or concurrently) without altering the principles of the present disclosure. Further, although each of the embodiments is described above as having certain features, any one or more of those features described with respect to any embodiment of the disclosure can be implemented in and/or combined with features of any of the other embodiments, even if that combination is not explicitly described. In other words, the described embodiments are not mutually exclusive, and permutations of one or more embodiments with one another remain within the scope of this disclosure.

[0160] Spatial and functional relationships between elements (for example, between modules, circuit elements, semiconductor layers, etc.) are described using various terms, including "connected," "engaged," "coupled," "adjacent," "next to," "on top of," "above," "below," and "disposed." Unless explicitly described as being "direct," when a relationship between first and second elements is described in the above disclosure, that relationship can be a direct relationship where no other intervening elements are present between the first and second elements, but can also be an indirect relationship where one or more intervening elements are present (either spatially or functionally) between the first and second elements. As used herein, the phrase at least one of A, B, and C should be construed to mean a logical (A OR B OR C), using a non-exclusive logical OR, and should not be construed to mean "at least one of A, at least one of B, and at least one of C."

[0161] In this application, including the definitions below, the term "module" or the term "controller" may be replaced with the term "circuit." The term "module" may refer to, be part of, or include: an Application Specific Integrated Circuit (ASIC); a digital, analog, or mixed analog/digital discrete circuit; a digital, analog, or mixed analog/digital integrated circuit; a combinational logic circuit; a field programmable gate array (FPGA); a processor circuit (shared, dedicated, or group) that executes code; a memory circuit (shared, dedicated, or group) that stores code executed by the processor circuit; other suitable hardware components that provide the described functionality; or a combination of some or all of the above, such as in a system-on-chip.

[0162] The module may include one or more interface circuits. In some examples, the interface circuits may include wired or wireless interfaces that are connected to a local area network (LAN), the Internet, a wide area network (WAN), or combinations thereof. The functionality of any given module of the present disclosure may be distributed among multiple modules that are connected via interface circuits. For example, multiple modules may allow load balancing. In a further example, a server (also known as remote, or cloud) module may accomplish some functionality on behalf of a client module.

[0163] The term code, as used above, may include software, firmware, and/or microcode, and may refer to programs, routines, functions, classes, data structures, and/or objects. The term shared processor circuit encompasses a single processor circuit that executes some or all code from multiple modules. The term group processor circuit encompasses a processor circuit that, in combination with additional processor circuits, executes some or all code from one or more modules. References to multiple processor circuits encompass multiple processor circuits on discrete dies, multiple processor circuits on a single die, multiple cores of a single processor circuit, multiple threads of a single processor circuit, or a combination of the above. The term shared memory circuit encompasses a single memory circuit that stores some or all code from multiple modules. The term group memory circuit encompasses a memory circuit that, in combination with additional memories, stores some or all code from one or more modules.

[0164] The term memory circuit is a subset of the term computer-readable medium. The term computer-readable medium, as used herein, does not encompass transitory electrical or electromagnetic signals propagating through a medium (such as on a carrier wave); the term computer-readable medium may therefore be considered tangible and non-transitory. Non-limiting examples of a non-transitory, tangible computer-readable medium are nonvolatile memory circuits (such as a flash memory circuit, an erasable programmable read-only memory circuit, or a mask read-only memory circuit), volatile memory circuits (such as a static random access memory circuit or a dynamic random access memory circuit), magnetic storage media (such as an analog or digital magnetic tape or a hard disk drive), and optical storage media (such as a CD, a DVD, or a Blu-ray Disc).

[0165] The apparatuses and methods described in this application may be partially or fully implemented by a special purpose computer created by configuring a general purpose computer to execute one or more particular functions embodied in computer programs. The apparatuses and methods may be implemented in, for example, a handheld instrument, a tablet, a smart phone, a cellular phone, and/or other computing device. The functional blocks, flowchart components, and other elements described above serve as software specifications, which can be translated into the computer programs by the routine work of a skilled technician or programmer.

[0166] The computer programs include processor-executable instructions that are stored on at least one non-transitory, tangible computer-readable medium. The computer programs may also include or rely on stored data. The computer programs may encompass a basic input/output system (BIOS) that interacts with hardware of the special purpose computer, device drivers that interact with particu-

lar devices of the special purpose computer, one or more operating systems, user applications, background services, background applications, etc.

[0167] The computer programs may include: (i) descriptive text to be parsed, such as HTML (hypertext markup language) or XML (extensible markup language), (ii) assembly code, (iii) object code generated from source code by a compiler, (iv) source code for execution by an interpreter, (v) source code for compilation and execution by a just-in-time compiler, etc. As examples only, source code may be written using syntax from languages including C, C++, C#, Objective C, Haskell, Go, SQL, R, Lisp, Java*, Fortran, Perl, Pascal, Curl, OCaml, Javascript®, HTML5, Ada, ASP (active server pages), PHP, Scala, Eiffel, Smalltalk, Erlang, Ruby, Flash®, Visual Basic®, Lua, and Python®.

[0168] None of the elements recited in the claims are intended to be a means-plus-function element within the meaning of 35 U.S.C. §112(f) unless an element is expressly recited using the phrase "means for," or in the case of a method claim using the phrases "operation for" or "step for."

What is claimed is:

1. A sensor comprising:
an array of pins or needles configured to be inserted in tissue of a patient;
a first sensing element separate from the array of pins or needles and configured to (i) detect a first parameter of the tissue, and (ii) generate a first signal indicative of the first parameter;
a control module configured to (i) receive the first signal, (ii) monitor a second parameter of the tissue based on a second signal received from the array of pins or needles, and (ii) generate a third signal based on the first signal and the second parameter, wherein the third signal is indicative of a level of decompression of a nerve of the patient; and
a physical layer module configured to wirelessly transmit the third signal from the sensor to a console interface module or a nerve integrity monitoring device.

2. The sensor of claim **1**, wherein:
the control module is configured to determine the level of decompression based on the first signal and the second signal; and
the third signal indicates the level of decompression.

3. The sensor of claim **1**, further comprising:
a power source; and
a front end module configured to (i) receive power from the power source, and (ii) generate a stimulation signal to be applied to the tissue via the array of pins or needles,
wherein the second signal is an evoked response to the stimulation signal.

4. The sensor of claim **1**, wherein:
the first signal is indicative of a temperature of the tissue, an oxygen level of the tissue, or a pH level of the tissue; and
the second signal is an electromyography signal.

5. The sensor of claim **1**, further comprising:
a motion sensing element configured to generate a motion signal; and
a pH sensing element configured to generate a pH signal indicative of a pH level of the tissue,
wherein
the first signal is indicative of a temperature of the tissue, and
the control module is configured to
determine a perfusion level based on the first signal or the second signal,
determine a conduction speed based on the second signal and a time when a stimulation signal was previously generated,
receive the motion signal, and
generate the third signal based on the motion signal, the pH level, the perfusion level, and the conduction speed.

6. The sensor of claim **1**, further comprising:
a light emitting device configured to emit light at the tissue; and
a photodiode configured to (i) detect portions of the light reflected off of the tissue, and (ii) generate a fourth signal indicative of a wavelength and corresponding intensity of the light reflected off of the tissue,
wherein the control module is configured to generate the third signal based on the fourth signal.

7. The sensor of claim **1**, comprising a sensing array, wherein:
the sensing array comprises
a first substrate, wherein at least a portion of the first substrate is transparent,
the array of pins or needles attached to the first substrate,
a second substrate connected to the first substrate by conductive elements,
an illuminating device configured to emit light through the at least a portion of the first substrate and at the tissue, and
a photodiode configured to (i) detect a reflected portion of the light reflected back through the first substrate, and (ii) generate a fourth signal; and
the control module is configured to generate the third signal based on the fourth signal.

8. The sensor of claim **7**, further comprising a base, wherein:
the conductive elements include a first set of conductive balls; and
the second substrate is connected to the base via a second set of conductive balls.

9. The sensor of claim **8**, further comprising:
a control layer comprising the control module; and
an interposer layer disposed between the control layer and the base, wherein the control module is connected to the sensor and the second set of conductive balls via interconnections within the interposer layer.

10. The sensor of claim **1**, further comprising a second array of pins or needles, wherein the control module is configured to (i) monitor the second parameter or a third parameter of the tissue based on a fourth signal received from the second array of pins or needles, and (ii) generate the third signal based on the second parameter or the third parameter.

11. The sensor of claim **10**, wherein the control module is configured to (i) monitor the second parameter and the third parameter of the tissue based on the fourth signal, and (ii) generate the third signal based on the second parameter and the third parameter.

12. A system comprising:
the sensor of claim **1**; and
the console interface module or the nerve integrity monitoring device.

13. The system of claim 12, comprising the nerve integrity monitoring device, wherein the nerve integrity monitoring device comprises:

a second control module configured to generate a payload request, wherein the payload request (i) requests a data payload from the sensor in a wireless nerve integrity monitoring network, and (ii) indicates whether a stimulation probe device is to generate a stimulation pulse; and

a second physical layer module configured to

(i) wirelessly transmit the payload request to the sensor and the stimulation probe device, or (ii) transmit the payload request to the console interface module, and

in response to the payload request, (i) receive the data payload from the sensor, and (ii) receive stimulation pulse information from the stimulation probe device, wherein the third signal includes the data payload, wherein the data payload includes data corresponding to an evoked response of the patient, and wherein the evoked response is generated based on the stimulation pulse.

14. The system of claim 12, comprising the console interface module, wherein the console interface module comprises:

a second control module configured to (i) receive a payload request from the nerve integrity monitoring device, and (ii) generate a synchronization request including information in the payload request, wherein the synchronization request (i) requests a data payload from the sensor in a wireless nerve integrity monitoring network, and (ii) indicates whether a stimulation probe device is to generate a stimulation pulse; and

a second physical layer module configured to

wirelessly transmit the synchronization request to the sensor and the stimulation probe device, and

in response to the synchronization request, (i) wirelessly receive the data payload from the sensor, and (ii) wirelessly receive stimulation pulse information from the stimulation probe device, wherein the third signal includes the data payload, wherein the data payload includes data corresponding to an evoked response of the patient, and wherein the evoked response is generated based on the stimulation pulse.

15. The system of claim 12, wherein the console interface module or the nerve integrity monitoring device is configured to:

determine baseline values for the first parameter and the second parameter;

during or subsequent to a surgery, compare the baseline values respectively to the first parameter and the second parameter; and

based on the comparisons, generating the third signal or indicating whether positive results exist for tasks performed during the surgery.

16. A method of operating a sensor, the method comprising:

detecting a first parameter of a tissue of a patient via a first sensing element of the sensor;

generating a first signal indicative of the first parameter;

monitoring a second parameter of the tissue based on a second signal received from an array of pins or needles, wherein the array of pins or needles is configured to be inserted in the tissue, and wherein the array of pins or needles are separate from the first sensing element;

generating a third signal based on the first signal and the second parameter, wherein the third signal is indicative of a level of decompression of a nerve of the patient; and

wirelessly transmitting the third signal from the sensor to a console interface module or a nerve integrity monitoring device.

17. The method of claim 16, further comprising:

receiving power from a power source within the sensor and at a front end module; and

generating a stimulation signal to be applied to the tissue via the array of pins or needles,

wherein

the first signal is indicative of a temperature of the tissue, an oxygen level of the tissue, or a pH level of the tissue,

the second signal is an evoked response to the stimulation signal and is an electromyography signal.

18. The method of claim 16, further comprising:

generating a motion signal indicative of muscle activity;

generating a pH signal indicative of a pH level of the tissue,

wherein the first signal is indicative of a temperature of the tissue;

determining a perfusion level based on the first signal or the second signal;

determining a conduction speed based on the second signal and a time when a stimulation signal was previously generated;

receiving the motion signal;

emitting light via a light emitting device at the tissue;

detecting portions of the light reflected off of the tissue;

generating a fourth signal indicative of a wavelength and corresponding intensity of the light reflected off of the tissue; and

generating the third signal based on the motion signal, the pH level, the perfusion level, the conduction speed and the fourth signal.

19. The method of claim 16, further comprising:

emitting light through the at least a portion of a first substrate and at the tissue,

wherein the array of pins or needles are included in a sensing array, and

wherein the sensing array comprises

the first substrate attached to the array of pins or needles, wherein at least a portion of the first substrate is transparent, and

a second substrate connected to the first substrate by conductive elements;

detecting a reflected portion of the light reflected back through the first substrate;

generating a fourth signal based on the detected reflected portion of the light reflected back through the first substrate; and

generating the third signal based on the fourth signal.

20. The method of claim 16, further comprising:

monitoring the second parameter and a third parameter of the tissue based on a fourth signal received from a second array of pins or needles; and

generating the third signal based on the second parameter and the third parameter.

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专利名称(译)	用于术中神经根减压监测的无线传感器和相应的系统和方法		
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[标]申请(专利权)人(译)	华沙整形外科股份有限公司		
申请(专利权)人(译)	华沙整形外科，INC.		
当前申请(专利权)人(译)	华沙整形外科，INC.		
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外部链接	Espacenet USPTO		

摘要(译)

一种传感器，包括引脚阵列，传感元件，控制模块和物理层模块。销或针阵列配置成插入患者的组织中。传感元件与针或针阵列分开，并配置成（i）检测组织的第一参数，以及（ii）产生指示第一参数的第一信号。控制模块被配置成（i）接收第一信号，（ii）基于从针或针阵列接收的第二信号监测组织的第二参数，以及（ii）基于第一信号产生第三信号信号和第二参数，其中第三信号指示患者神经的减压水平。物理层模块被配置为将来自传感器的第三信号无线传输到控制台接口模块或神经完整性监测设备。