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(54) Title: ADAPTIVE RFID READER

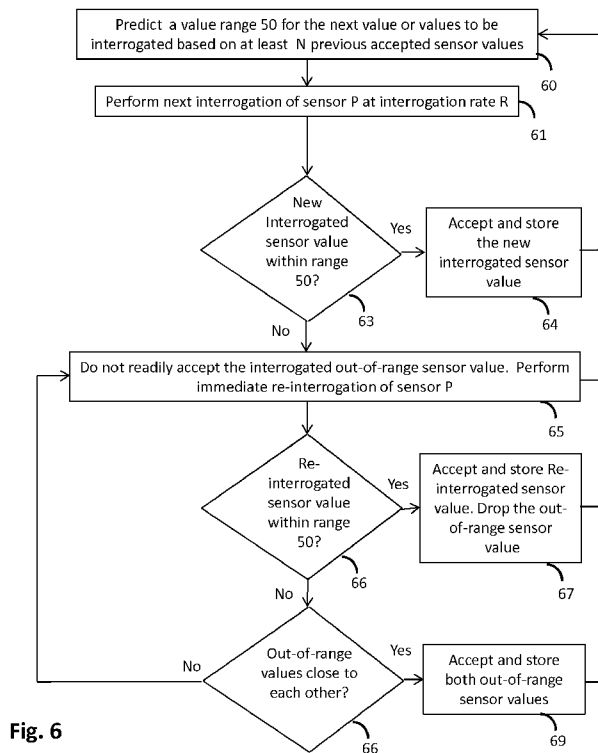


Fig. 6

(57) Abstract: In a system having a radio frequency identification (RFID) reader and at least one passive RFID sensor tag, the RFID reader sends a radio frequency interrogation signal from to the passive RFID sensor tag having a sensor that provides a sensor value. The RFID reader receives from the passive RFID tag a backscattered radio frequency signal carrying the sensor value. An interrogation rate of the sensor tag, an accuracy of interrogation and/or a power of the radio frequency interrogation signal transmitted to the sensor tag is controlled based on a statistical analysis of the multiple received sensor values, multiple interrogations and/or a signal-to-noise ratio (60-69).

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ADAPTIVE RFID READER

FIELD OF THE INVENTION

The present invention relates to passive wireless sensors, particularly passive radio frequency identification (RFID) sensors, RFID sensor systems, and RFID readers for passive RFID sensor tags.

BACKGROUND OF THE INVENTION

Sensor is a device that transforms a measured quantity into a readable format, typically into an electrical signal. Nowadays, there are commercially available sensors virtually for any measurement purpose. According to the connectivity, sensors can be divided into wireless and wired sensors. Wired sensors are connected via wiring harnesses or cable assemblies to a reader device. Wireless sensors can be read without a physical connection to the sensor, and are often realized equipping the sensor with a radio transceiver. The transmitted radio signal is interpreted by a receiver which converts the wireless signal into a desired output. Wireless operation can be beneficial in many applications, where wired connection is difficult for example due to harsh operating conditions (like temperature and pressure), rotating parts, or cost and complexity of wiring. However, wireless sensors also have some drawbacks such as limited lifetime due to battery, limited read-out distance due to attenuation and interference, security issues because of the uncontrollable propagation of the signal and potentially low speed of communication. Based on the power source and communication principle, wireless sensors can be divided into three categories: active sensors, semi-passive sensors and passive sensors.

Active wireless sensors usually have both a radio transceiver and an on-board battery that is used to power up the transceiver. Active wireless sensors, having their own power sources, can use powerful transmitters and sensitive receivers. However, the battery on board limits the life time and also increases the size and weight. Due to more complex circuit, the price of an active sensor can be much higher than that of a passive sensor.

Semi-passive wireless sensors do not contain a radio transceiver, but are equipped with a battery. The battery is used to power up an integrated circuitry (IC) and enables the sensors to operate independently of the reader device or to maintain memory in the sensor. Semi-passive battery-assisted sensors utilize modulated backscattering technique for communication. This

means that semi-passive sensors do not require any power from the on-board battery for transmission, but the sensor simply reflects back some of the power emitted by the reader device.

Unlike the active and semi-passive sensors, passive sensors do not
5 require an on-board battery. Therefore they can be less complex, smaller, more inexpensive, and their lifetime is not limited by the power supply. The typical read-out distance of passive wireless sensors is between 10 cm and 3 m. Passive wireless sensors can be divided into four main categories: radio frequency identification (RFID) tags, electrical resonance circuit sensors, sur-
10 face acoustic wave (SAW), harmonic sensors and intermodulation sensors.

RFID is an identification technology that uses radio waves to communicate between tags and a reader and it is used to identify items. There are a few advantages of RFID over optical barcode identification such as no line-of-sight is required between the reader device and the tag, and the RFID read-
15 er can also read hundreds of tags at a time. Passive RFID tags utilize the modulated backscattering communication principle which is illustrated in Figure 1. When a tag 10 communicates with an RFID reader 11, it modulates the received signal 12 and reflects a portion of it 13 back to the reader. A typical passive tag consists of an antenna connected to an application specific micro-
20 chip. When wirelessly interrogated by an RFID transceiver, or reader, the RFID tag antenna receives power and RF signals from the RFID reader and provides them to the chip. The chip processes the signals and sends the requested data back to the RFID reader. The backscattered signal is modulated according to the transmitted data. The highest operation frequency and read-out distance
25 of RFID are limited by the rectified power for the integrated circuit (IC) and are a few GHz and 5–10 m, respectively.

RFID is mostly used for identification. RFID tags are equipped with a rewritable memory, which enables the reusability features of RFID tags, but they are not useful for measuring external quantities. RFID has also been
30 shown to be suitable for sensing by equipping an RFID tag with an external sensor and digital logic to read the external sensor. The advantage of this approach is that it would use a generic sensor element and thus would be well suited for a very broad range of applications. In this approach, however, an additional A/D converter and digital circuitry has to be included to the tag in
35 order to enable sensor read-out. Increased power consumption due to the additional electronics reduces the read-out range significantly (e.g., from 5 m to

0.3 m with an 8-bit A/D converter). An additional sensor element further increases power consumption. Implementation considerations of the A/D converter and additional digital circuits are discussed in [1]: Chapter 9 "Smart RFID Tags", in the book "Development and Implementation of RFID Technology", ISBN 978-3-902613-54-7, February 2009, I-Tech, Vienna, Austria.
5 http://www.intechopen.com/books/development_and_implementation_of_rfid_technology.

US2013/0099897 discloses an RFID reader, an RFID chip, and an antenna electrically coupled to the RFID chip and configured to receive signals
10 from and transmit signals to the RFID reader. The RFID chip is provided with an electrical interface to a sensing material. The RFID chip is configured to modulate a signal received from a reader and to drive the sensing material with the modulated signal. The sensing material has a variable electrical property,
15 such that the backscattered modulated signal will change according to the condition of the sensing material. Regardless of the nature of the sensing material, it interacts with the modulated signal from the RFID chip and returns the signal to the RFID chip. The returned signal is passed from the RFID chip to the antenna via the backscatter modulator and then transmitted back to the RFID reader. Alternatively, the signal processed by the sensing material is
20 used to modulate the input impedance of the RFID chip, with a signal from the RFID chip being backscattered to the RFID reader by the antenna to determine the condition of the sensing material.

Chen et al, Coupling Passive Sensors to UHF RFID Tags, Radio and Wireless Symposium (RWS), 2012 IEEE, 15-18 Jan. 2012, Santa Clara,
25 255 – 258, explores the possibility of coupling passive sensor data to existing UHF RFID tags without designing a new tag ASIC. The existing UHF RFID system can be used to convey additional data by overlaying a coupling loop on the tag antenna and modulating vector backscatter. The impedance of the passive sensor carrying the sensor data influences the value of amplitude and
30 phase of the backscattering. For the transmission of the passive sensor data, the load of the passive sensor coupling module is switched between these three loads to provide the connection to one of the two reference impedances or the passive sensor. With two reference impedances, the impedance of the passive sensor is determined.

35 Guerin et al., A temperature and gas sensor integrated on a 915MHz RFID UHF tag, Wireless Information Technology and Systems (IC-

WITS), 2010 IEEE International Conference, Honolulu, Aug. 28 2010-Sept. 3 2010 discloses a passive wireless sensor utilizing the modulated backscattering principle. The modulation signal is generated by a voltage-controlled oscillator whose control voltage and thereby the output frequency is arranged to
5 change in function of the sensor value.

Co-pending PCT/FI2013/051214 discloses passive wireless sensor design that enables a radically increased reading distance of passive wireless sensors. The modulation signal is generated by an oscillator that includes a sensing element as a part of an oscillating circuit, such that the modulation
10 frequency is dependent on a sensed value of the sensing element. Thus, the sensor value is translated into a frequency of modulated analog signal which can be generated without an energy consuming AD conversion and with minimum number of extra component. As a result the reading distance can be increased up to several meters, to a room scale.

Reading passive RFID sensors requires "on-air" time for powering the sensor. The time needed can be very short, such as 2-3 ms, or relatively long, such as 10-50 ms, depending on the sensor used. The radio bandwidth available for RFID communication is not unlimited but actually very scarce. If multiple sensors must be interrogated very often, there is a lot of radio noise
20 within the RFID spectrum. If sensors can be interrogated less often, more radio spectrum can be freed to other readers and sensors for communication. It is difficult to determine how often the sensors should be interrogated to keep the required sensor values up to date. Another problem relates to the very nature of wireless communication. There is constant sporadic noise affecting to the
25 reading events. With moving objects there are also problems relating to a varying attenuation of the radio signal.

Different kind of algorithms has been created to tackle signal degradation, but they all need radio-level changes. Spatial multiplexing is a good way to improve radio communication. However, the spatial multiplexing is
30 quite hard to put into practice due to complex electronics and calculations. Another typical way of managing link level problem is managing the signal power. Varying signal power eases to keep battery consumption minimal and reducing RF noise. An example of this approach is disclosed in US7825806.

Thus, there is a need for new techniques for adapting the interrogation
35 of sensors to the varying radio-level conditions and interference.

BRIEF DESCRIPTION OF THE INVENTION

An object of the present invention is to provide a new technique for adapting the interrogation of sensors to the varying radio-level conditions and interference.

5 The objects of the invention are achieved by a method, a reader and a system according to the attached independent claims. The preferred embodiments of the invention are disclosed in the dependent claims.

10 An aspect of the invention is a method of controlling interrogation of sensor values in a system having a radio frequency identification (RFID) reader and at least one passive RFID sensor tag having at least sensing element that provides a value of a quantity sensed by the sensing element, comprising

 sending a radio frequency interrogation signal from the RFID reader to the passive RFID sensor tag;

15 receiving at the RFID reader from the passive RFID tag a backscattered radio frequency signal carrying the value of the sensed quantity;

20 controlling an interrogation rate of the sensing element and/or accuracy of received values of the sensed quantity and/or a power of the radio frequency interrogation signal transmitted to the sensing element based on an analysis of i) the multiple received values of the sensed quantity and/or ii) multiple interrogations and/or iii) a signal-to-noise ratio.

 In an embodiment, the statistical analysis comprises comparing a new interrogated value and/or a signal-to-noise ratio of a new interrogated value with a criterion created based on the multiple received values of the sensed quantity and/or multiple interrogations.

25 In an embodiment, the criterion comprises at least one of a predicted value or value range of the value of a sensed quantity, a variance of a sensed quantity, a long-time average of a variance of a sensed quantity, an average of a signal-to-noise ratio of the backscattered signal over multiple integrations of the sensing element.

30 In an embodiment, the controlling comprises

 a) maintaining the interrogation rate of the sensing element, if a new interrogated value of the sensed quantity is acceptable according to said statistical analysis;

35 c) increasing at least temporarily the interrogation rate of the sensing element, if a new interrogated value of the sensed quantity is not acceptable according to said statistical analysis.

In an embodiment, the controlling comprises associating a new interrogated value of the sensed quantity with an accuracy information based on a signal-to-noise ratio of the backscattered signal, and/or rejecting a new interrogated value of the sensed quantity based on a signal-to-noise ratio of the backscattered signal, and/or adjusting a new interrogated value of the sensed quantity with an accuracy information based on a signal-to-noise ratio of the backscattered signal to improve accuracy.

In an embodiment, the controlling comprises

a) predicting a value range for a next value or next values to be interrogated from the sensing element based on a plurality of previous interrogated values of the quantity sensed by the sensing element;

b) maintaining the interrogation rate of the sensing element, if a new interrogated value of the sensed quantity falls within the predicted value range of the sensing element;

c) increasing at least temporarily the interrogation rate of the sensing element, if a new interrogated value of the sensed quantity falls out of the predicted value range of the sensing element.

In an embodiment, the increasing at least temporarily the interrogation rate of the sensing element comprises immediately reinterrogating the sensing element.

In an embodiment, the increasing at least temporarily the interrogation rate of the sensing element comprises performing immediate reinterrogations of the sensing element until the interrogated value of the sensed quantity is acceptable according to said statistical analysis.

In an embodiment, the controlling comprises

a) predicting a value range for a next value or next values to be interrogated from the sensing element based on a plurality of previous interrogated values of the quantity sensed by the sensing element;

b) accepting a new interrogated value of the sensed quantity, if the new interrogated value falls within the predicted value range of the sensing element;

c) reinterrogating immediately the sensing element, if said new interrogated value of the sensed quantity falls out of the predicted value range of the sensing element;

d) accepting the reinterrogated value of the sensed quantity, if the reinterrogated value falls within the predicted value range of the sensing element.

ment, and dropping said new interrogated value;

5 e) accepting both said new interrogated value and said reinterrogated value of the sensed quantity, if also the reinterrogated value falls out of the predicted value range of the sensing element but said new interrogated value and said reinterrogated value are close to each other;

f) reinterrogating immediately the sensing element, if also said reinterrogated value of the sensed quantity falls out of the predicted value range of the sensing element and said new interrogated value and said reinterrogated value are close to each other;

10 g) continuing immediate reinterrogations of the sensing element until the reader obtains and accepts a reinterrogated value falling within the predicted value range or two reinterrogated values falling out of the predicted value range but being close to each other.

In an embodiment, the controlling comprises updating the predicted value with each accepted interrogated value of the sensed quantity.

In an embodiment, the controlling comprises
determining a long-time average of signal/noise ratio (SNR) of the backscattered signal during interrogation of the sensing element;
controlling the interrogation power and/or the interrogation rate of
20 the sensing element using the long-time average of the SNR as a control reference.

In an embodiment, the method comprises
determining a long-time average of a variance of the interrogated sensor values of the sensing element;
25 controlling the interrogation power and/or the interrogation rate of the sensing element using the long-time average of a variance of the interrogated sensor values as a control reference.

In an embodiment, the method comprises controlling the interrogation rate of the sensing element and the power of the radio frequency interrogation signal transmitted to the sensing element in parallel or in combination.

30 In an embodiment, the method comprises
determining a long-time averages of signal/noise ratio (SNR) of the backscattered signal during interrogation of the sensing element in function of a variance of the interrogated sensor values;

35 controlling the power of the radio frequency interrogation signal transmitted to the sensing element using as a control reference the long-time

average of the SNR corresponding a present variance of one or more latest interrogated sensor values;

determining a long-time average of a variance of the interrogated sensor values of the sensing element;

5 controlling the interrogation rate of the sensing element using the long-time average of a variance of the interrogated sensor values as a control reference.

10 In an embodiment, the method comprises controlling primarily the power of the radio frequency interrogation signal transmitted to the sensing element and controlling secondarily the interrogation rate of the sensing element.

 In an embodiment, the method comprises increasing the interrogation rate of the sensing element only if the power of the radio frequency interrogation signal cannot be increased.

15 In an embodiment, the method comprises the controlling comprises determining a signal/noise ratio (SNR) of the backscattered signal during interrogation of an interrogated sensor value;

 compensating an effect of a low signal/noise ratio (SNR) on the interrogated sensor value based on pre-stored compensation values and/or a compensation function, particularly if the power of the radio frequency interrogation signal cannot be increased.

20 In an embodiment, the method comprises the passive RFID sensor tag having an oscillator whose an oscillation frequency is dependent on a value of a quantity sensed by the sensing element;

25 the RFID reader receives from the passive RFID tag the backscattered radio frequency signal modulated with the oscillation frequency which is dependent on the value of the sensed quantity;

30 the RFID reader converts the oscillation frequency modulation of the backscattered signal into an actual value of the sensed quantity.

 An another aspect of the invention is an RFID reader implementing the method according to the above aspect of the invention.

35 Still another aspect of the invention is a system comprising an RFID reader and a computer device implementing the method to the above aspect of the invention.

BRIEF DESCRIPTION OF THE DRAWINGS

In the following the invention will be described in greater detail by means of preferred embodiments with reference to the drawings, in which

5 Figure 1 illustrates backscattering communication principle in an RFID system;

Figure 2 is a functional block diagram illustrating an example of an RFID tag architecture;

Figure 3 is a spectral graph that illustrates the communication principle for a RFID sensor;

10 Figure 4 is a functional block diagram illustrating an example of a an RFID reader architecture;

Figure 5 is a graph illustrating received sensor values v_1, v_2, \dots, v_{15} for fifteen consecutive interrogations I_1, I_2, \dots, I_{15} for one sensor;

15 Figure 6 illustrates a flow diagram illustrating an exemplary control procedure for an interrogation rate;

Figure 7 is a flow diagram illustrating another exemplary control procedure for an interrogation rate;

Figure 8A is a graph illustrating an acceptable signal-noise-ratio (SNR) of the received signal;

20 Figure 8B is a graph illustrating an unacceptable low signal-noise-ratio (SNR) of the received signal;

Figure 8C is a graph illustrating the time variance of a low signal-noise-ratio (SNR) of the received signal;

25 Figure 9A is a graph illustrating the effect of calculation of a wrong predicted value range based on the inaccurate sensor values due to an unacceptable low signal-noise-ratio (SNR);

Figures 9B and 9C are graphs illustrating a gradual change of the SNR with time and a corresponding gradual change in the sensor values;

30 Figure 10 is a flow diagram illustrating an exemplary control procedure for an interrogation power;

Figure 11 is a flow diagram illustrating still an exemplary combined control procedure wherein both the interrogation power and the interrogation rate are controlled;

35 Figure 12 is a flow diagram illustrating an exemplary control procedure wherein a statistical control of the interrogation rate R based on the interrogated sensor values is arranged to take into account an inaccuracy of the

interrogated sensor values possibly caused by the signal-noise-ratio (SNR);

Figures 13A and 13B are graphs illustrating a change of the SNR with time and a corresponding SNR compensation of the inaccurate sensor values;

5 Figure 14 is a flow diagram illustrating an exemplary control procedure wherein a statistical control of the interrogation rate R based on the interrogated sensor values is provided with a compensation of an inaccuracy of the interrogated sensor values due to the signal-noise-ratio (SNR);

Figure 15 is a flow diagram illustrating an exemplary method for
10 SNR compensation of interrogated values based on the SNR; and

Figure 16 is a flow diagram illustrating an exemplary method for providing SNR compensation values or an SNR compensation function.

DETAILED DESCRIPTION OF THE INVENTION

Referring to Figure 1, an RFID system typically comprises two basic
15 components: an RFID transponder or tag 10, which is located on the object to be identified or at a measurement point; an RFID interrogator or reader 11, which performs the interrogation of RFID tags. In a passive RFID system the RFID reader 11 supplies the tag 10 with essential power in order for it to perform modulation of the reader's interrogation signal. In the case of RFID sen-
20 sor tags, in addition to just providing a power source and medium for the RFID tags 10 to operate and transmit data, an RFID reader 11 may perform data transmission towards the tags 11 which is implemented, in most cases, as a modulation of the carrier signal.

Figure 2 shows a functional block diagram illustrating a further ex-
25 ample of radio frequency identity (RFID) tag architecture. In the illustrated example the RFID tag 10 may comprise an antenna 21 directly matched to the tag's front end impedance (matching circuit is not shown) to communicate with a RFID reader 11; an analogue RF front end that may typically contain rectifier circuitry 22 to convert RF power into a direct current (DC), a clock generator or
30 oscillator 23, a modulator 24 and a demodulator 25. There may also be a logic part or a digital control module 26 that may be configured to provide desired functions, such as to handle interrogating commands, execute the anti-collision protocol, perform the data integrity check, run memory read-write operations, and perform output control and data flow. The logic implementation usually
35 follows a defined standard and a certain associated protocol. Further, memory

storage 27 may be provided. Depending on a user's requirement, non-volatile memory storage may be needed if both read/write capability is implemented.

As discussed above, the passive RFID tags utilize the modulated backscattering principle for communication. When a tag communicates with a reader, it modulates the received signal and reflects a portion of it back to the reader. The RFID sensor is actuated using an radio frequency (RF) continuous wave (CW) signal transmitted from the reader 11. First, the RF signal is converted to DC voltage by a rectifier 22. The rectified voltage powers up an oscillator 23, which produces a low frequency sinusoid f_{OSC} at its output. Finally, the oscillation signal f_{OSC} is fed to the backscatter modulator 24 to realize the backscattering principle. The modulator 24 modulates the signals, and those going back to the antenna 21 depend on the matching between the antenna and the rectifier 21/modulator 24. As a consequence, there are sidebands or subcarriers $f_{CW} - f_{OSC}$ and $f_{CW} + f_{OSC}$ in the signal backscattered from the sensor, as illustrated in the Figure 3. f_{CW} and f_{OSC} represent the carrier frequency and oscillation frequency, respectively. The sidebands or subcarriers are offset from the carrier f_{CW} by the oscillation frequency f_{OSC} . The oscillation frequency f_{OSC} may also be referred to as a modulation frequency or a subcarrier frequency.

The clock frequency generation 23 may be realized with an oscillator whose frequency is dependent on a sensed value. This enables the sophisticated features of RFID and the possibility to measure external quantities without AD conversion. In exemplary embodiments, a sensing element is configured to an elementary part of an oscillating circuit of a tag oscillator such that the modulation frequency output from the oscillator is dependent on a sensed value. This enables the possibility to measure external quantities without practically any power consuming extra components. Examples of applicable oscillators may include an RC oscillator, a ring oscillator, an LC-oscillator, an RLC-oscillator, or any other resonant-based oscillator, such as an oscillator based on MEMS (microelectro-mechanical systems), SAW (surface acoustic wave), and BAW (bulk acoustic wave) resonators. The advantage of an RC-oscillator is that it can be integrated while it may have higher power consumption and reduced read-out distance in comparison with LC-oscillator or an RLC-oscillator, for example.

It should be appreciated that the intention is not to restrict the invention to any particular types of RFID sensor tags or any particular type of modu-

lation of a backscattered signal by a sensor tag. However, embodiments of the invention are particularly advantageous in applications where a modulation oscillation frequency of the RFID sensor tag is arranged to be dependent on a sensed value, i.e. a value range of sensed quantity is mapped to an oscillation frequency range, such as in PCT/FI2013/051214, and in Guerin et al.

5 An aspect of the invention is a reader for a passive wireless sensor according to the other aspect of the invention. Generally, an RFID reader is a specialized radio transmitter and receiver. Like all such devices, the reader must generate signals at a carrier frequency f_{CW} (e.g. around 800 - 900 MHz for typical UHF devices) and modulate this carrier signal to convey information to the tags. For passive tags, the reader may energize the tags with energy, receive the results and frequently handle the low-level anti-collision algorithms that allow the reader to read more than one tag at a time. In simple RFID systems, the reader's RF signal is a continuous wave (CW) signal or a pulsed on-off signal; in more sophisticated systems, the reader's RF signal can contain commands to the tag, instructions to read or write memory that the tag contains. The reader 11 may selectively receive and amplify responses from the tags, and convert the signal from the carrier frequency down to the much lower frequencies characteristic of the information contained in the received signal.

20 A general block diagram of an exemplary RFID reader is illustrated in Figure 4. An RFID reader 11 may comprise two main sections: a radio frequency (RF) front end 40 and a digital control section 41. The radio frequency (RF) front end 40 is used for RF signal transmission and reception. The RF front end 40 may comprise two separate signal paths to correspond with the two directional data flows from and to the RFID sensor(s) 10. A modulator 401 may modulate a local oscillator signal (the RF carrier signal f_{CW}) with a Tx data (such as commands) from the digital control section 41. The modulated signal is amplified by the power amplifier 402, and the amplified signal, i.e. the RF power (effective isotropic radiated power, EIRP) and possible reader's command is transmitted via the antenna ANT to the sensor 10 which is situated within the reading zone or interrogation zone. The receiver receives the analog back-scattered signals from the sensor 10 via the antenna ANT. A directional coupler or circulator 403 separates the amplified transmitted signal to the sensor 10 and the received weak back-scattered signal $f_{CW} \pm f_{OSC}$ from the sensor 10. The received backscattered signal is weak and low noise amplifiers

may be provided to increase the received signal's amplitude before and after the signal is demodulated in a demodulator 404. The demodulator 414 may then send the demodulated received signal RX data to the digital control section 41. Different demodulation techniques may be used when demodulating the data received from the transponder or tag 10. Examples of modulation and demodulation techniques used in RFID systems include binary phase shift keying (BPSK) and amplitude shift keying (ASK). The radiation intensity of the reader antenna ANT determines the interrogation range and zone. Depending on the RFID system's applications the RFID reader can be designed in different ways where the antenna's resonating frequency, gain, directivity and radiation pattern can vary.

The control section 41 of the RFID reader 11 may perform digital signal processing and procedures over the received (Rx) data from the RFID tag. Also, the control section 41 may enable the reader to communicate with the RFID tags wirelessly by performing modulation, anti-collision procedures and decoding the received data from the RFID tags 10. This data is usually used to interrogate tags (read) or to reprogram the tag (write). The control section 41 (e.g. a microprocessor) may usually include a digital signal processing (DSP) block 411, a memory block 412, a decoder block 413, an encoder block 414, and a communication interface block 415. The control section 41 may receive the received demodulated signal from the RF front end 40, and convert it to an equivalent digital signal. The decoder 413 may then decode the received signal to Rx data and the DSP 411 may perform data processing for the Rx data. The memory block 412 may store various data, such as interrogated Rx data, the reader's configuration parameters, sensor-specific parameters, etc. The encoder 414 of the control section 41 may encode a Tx data and output the encoded data to the RF front end 40 to modulate the carrier signal, when the control section 41 wants to send out a message or command to one particular tag or toward all of the tags 10 in the interrogation zone. Further, the control section 41 may control the RF transmission power of the RF front end 40, e.g. by controlling the gain of the power amplifier 402. All standard RFID digital communication may be received from wireless RFID sensors or tags 10 at carrier frequency f_{cw} (using an appropriate modulation technique) and processed with the demodulator 404 and decoder 413. All common RFID functionality can be implemented with a commercial RFID reader, such as Mercury6e (M6e) embedded UHF RFID reader module from ThingMagic, a division

of Trimble.

As discussed above, in a passive wireless sensor according to the first aspect of the invention the oscillation frequency f_{OSC} of the wireless sensor can be made dependent or sensitive on the measured quantity. In other words, the f_{OSC} is proportional to the sensed quantity at each specific moment. As also discussed above, the received back-scattered signal is modulated by the f_{OSC} , i.e. the received backscattered signal has a frequency $f_{CW} \pm f_{OSC}$. The sidebands are offset from the carrier f_{CW} by the oscillation frequency f_{OSC} , as illustrated in Figure 3.

According to an aspect of the invention the reader 11 may be arranged to detect the value of the sensed quantity based on the instantaneous oscillation frequency f_{OSC} . For example, a frequency f_{OSC} acquisition entity 405 may be provided to derive the f_{OSC} or a parameter representing it from the received backscattered signal. This information may be provided further to the control section 41 as illustrated by a signal 416. The entity 405 may optionally derive and provide further information regarding the received backscattered signal, such as a received signal level, a signal/noise ratio (SNR) of the received signal, etc. The f_{OSC} acquisition entity may, for example, comprise a down-mixer in which the received signal $f_{CW} \pm f_{OSC}$ is mixed with the carrier f_{CW} so that an oscillation frequency signal f_{OSC} is obtained. The frequency f_{offset} may then be measured with a suitable manner, e.g. with a frequency counting method. The f_{OSC} may also be detected directly from the received signal, e.g. by determining the phase shift between f_{CW} and $f_{CW} \pm f_{OSC}$, the phase shift being proportional to the oscillation frequency between f_{OSC} . The received signal level can be determined with any suitable signal level detector. Signal level information is already available in many commercial RFID readers

According to an aspect of the invention, the reader 11 is arranged to convert the sensor frequency modulation response of a sensor tag to a measurement value in sensor element-specific manner, e.g. based on sensor element-specific configuration information. The control section 41 may use the frequency-related information to derive the actual value of the sensed quantity. The control section 41 may have further information about the wireless sensor in question e.g. sensor elements available in the sensor tag, time needed to interrogate each of the sensor elements, etc. (also referred to as node configuration information), in order to, for example, convert this information into an actual value of the sensed quantity, make calibration operations, make calcula-

tions, etc.

The communication interface enables the reader 11 to communicate with upper level systems, such as a host computer or a software application 43, using appropriate connections and appropriate protocols, such as OPC (OLE (object linking and embedding) for Process Control). For example, the reader may be physically connected to a host computer using a serial connection, such as the RS-228 or USB serial connection. As another example, the reader may be connected to the host computer 43 via a wired or wireless network, whereby the reader behaves like a standard network device and do not require particular knowledge of the hardware and system configuration. The RFID readers may support multiple network protocols such as Ethernet, TCP/IP, UDP/IP, HTTP, LAN, WLAN and others. The host 43 may generally serve two main functions. First, it is receiving data from the readers and performing data processing such as filtering and collation. Secondly, it serves as a device monitor, making sure the reader is functioning properly, securely and with up to date instructions. An RFID reader may further comprise a power supply 44. The power supply 44 may be an appropriate AC/DC adapter connected to a power network, or a battery power source, for example. Alternatively, the reader may be powered over a communication network connection, such as Ethernet or USB.

Using a passive wireless sensor according to the first aspect of the invention and optionally a reader according to the second aspect of the invention, the reading distance of passive wireless sensors can be increased up to several meters, to a room scale. The increased reading distance makes it possible to read multiple passive wireless sensors (located within the increased reading range) with one and same reader. The multiple wireless sensors can have different types of sensing elements, different reading cycles, different sensor value formats/ranges, different temperature compensation arrangements, different calibration arrangements, or other sensor-specific parameters, characteristics or configurations. There can also be several sensor elements with different configurations and parameters in a single passive wireless sensor. Although the UHF RFID technology (such as the standard Class-1 Gen-2 anti-collision), for example, has tackled most of the issues concerning reading of multiple wireless tags, there is a need to provide methods, routines and arrangements for managing and reading multiple passive wireless sensors having different sensor characteristics.

During each interrogation, the reader 11 may send an RF interrogation message the sensor tag 10 provided with a sensing element 28 and receives a backscattered reply signal $f_{CW} \pm f_{OSC}$ from the sensor 10. The reader 11 may be arranged to detect the value v of the sensed quantity based on the instantaneous oscillation frequency f_{OSC} and store the sensor value. For example, a frequency f_{OSC} acquisition entity 405 may derive the f_{OSC} or a parameter representing it from the received backscattered signal, and forward it further to the control section 41 which may store it in the memory 412, as described with reference to Figure 4. Thus, each interrogation n of the sensor, wherein $n = 1, 2, 3, 4, \dots, N$, may produce one sensor value v_n for that sensor element, such that the reader will store a sequence of sensor values $\dots, v_{n-1}, v_n, v_{n+1}, \dots$, for each sensor around. The sensor elements are interrogated alternately one at time (a time multiplexing) but their interrogating rates may differ significantly from each other.

Interrogating or reading passive RFID sensors requires "on-air" time for powering the sensor. The time needed can be very short, such as 2-3 ms, or relatively long, such as 10-50 ms, depending on the sensor used. It is also important to note that the radio frequency signal power received at the tag and the power of the backscattered signal received at the reader falls rapidly with the distance between the reader and the tag. Therefore, the time required for powering the sensor may increase with the distance unless the transmission power of the reader is increased correspondingly. Moreover, the maximum allowed EIRP (equivalent isotropic radiated power), which determines the power of the signal transmitted by the reader in the direction of the tag, is typically limited by national regulations (e.g. in North America it is 4 W). In any case the power of the backscattered signal at the receiver is decreased with distance, which will increase the error rate. Further, due to a nature of wireless communication, there is constant sporadic noise affecting to the interrogation events.

The radio bandwidth available for RFID communication is not unlimited but actually very scarce. If multiple sensors must be interrogated very often, there is more radio noise within the RFID spectrum. If a sensor can be interrogated less often, e.g. the interrogation rate R of a sensor, (the number of interrogations per time unit) is decreased, more radio spectrum is freed to other readers and sensors for communication. An interrogation cycle $IC = 1/R$ is

the time duration from a start of an interrogation to a start of the next interrogation.

It is difficult to determine the minimum interrogation rate or cycle needed to keep the required sensor values up to date. In a control system, wherein the passive RFID sensor tag 10 may be a part of a control loop, the minimum interrogation cycle will be the required control cycle, but in most cases the reading is done more often.

According to an aspect of the invention, the interrogation rate is controlled based on a statistical analysis of the received sensor values in the reader. The interrogation rate may be at least temporally changed if the statistical analysis indicates that the received sensor value is obviously erroneous. This approach filters out sensor readings which are obviously defective.

An example of controlling an interrogation rate based on a statistical analysis of the received sensor values is illustrated in Figures 5 and 6. Figure 5 illustrates received sensor values v_1, v_2, \dots, v_{15} for fifteen consecutive interrogations I_1, I_2, \dots, I_{15} for one specific sensor. Similar presentation can be made for each sensor within an interrogation range. The sensor elements are interrogated alternately one at time (a time multiplexing) but their interrogating rates may differ significantly from each other. Figure 6 illustrates a flow diagram illustrating the exemplary control procedure for one specific sensor. Similar control procedure may be carried out separately for each sensor around.

In the beginning the reader 11 may store N values of previous interrogated sensor values from all sensors within the reading range of the reader 11. The number N of stored values can be a selectable parameter and different for different sensors, but an accuracy of the prediction is better if a higher number, preferably at least 10-20, of the last interrogated sensor values is stored. On basis of these N previous sensor values a value range 50 for the next value or values to be interrogated is predicted for the sensor (step 60 in Figure 6). Similarly, a respective value range 50 may be predicted separately for each sensor around. For example, the value range 50 may be predicted by predicting the next sensor value(s) and a tolerance allowed for the sensor value. The prediction 50 of a specific sensor may be updated each time a new interrogated sensor value from a respective is accepted and stored, such that the prediction may adapt to gradually changing sensor values. The prediction may be performed by an extrapolation, an interpolation, a linear regression, etc. of the stored values. The tolerance may be defined by a variance or a

similar statistical value.

In the interrogation I_1 a next sensor value v_1 is obtained from the sensor (step 61 in Figure 6). The reader 11 may check whether this next interrogated sensor value v_1 from a specific sensor falls within the predicted value range 50 of that sensor (step 63 in Figure 6). As the interrogated value v_1 is within the predicted value range 50, the integrated value v_1 is accepted and stored (step 64 in Figure 6), and the predicted value range 50 of the sensor is updated with the new sensor value v_1 (step 60 in Figure 6). The interrogation rate R of the sensor may be maintained unchanged. Also the next interrogations I_2, I_3, I_4, I_5 provide interrogated values v_2, v_3, v_4, v_5 which fall within the predicted sensor value range 50, and thereby the same procedure is repeated (steps 60-64 in Figure 6). The predicted sensor value range 50 adapts to the gradually falling sensor values, as illustrated in Figure 5.

In the interrogation I_6 the interrogated sensor value v_6 from the sensor is not within the predicted range 50 of the sensor P . As a result the interrogated sensor value v_6 is not readily accepted, but an immediate re-interrogation I_7 of the sensor may be made to obtain a new interrogated sensor value v_7 for comparison (step 65 in Figure 6). Thus the interrogation rate R of the sensor is temporarily increased. As this new interrogated value v_7 is within the predicted range 50, the new interrogated sensor value v_7 may be accepted and stored, and the previous out-of-range interrogated sensor value v_6 may be dropped (step 67 in Figure 6). The predicted value range 50 of the sensor may be updated with the new sensor value v_7 (step 60 in Figure 6). The allowed tolerance or deviation of the predicted sensor value may be fixed or dynamically adjusted. For example, the tolerance may be a statistical parameter, such as a variance of the N last stored sensor values.

Also the next interrogations $I_8, I_9, I_{10}, I_{12}, I_{13}$ provide interrogated values $v_8, v_9, v_{10}, v_{11}, v_{12}, v_{13}$ which fall within the predicted sensor value range 50, and thereby the same procedure is repeated (steps 60-64 in Figure 6). The predicted sensor value range 50 adapts to the gradually increasing sensor values but the interrogation rate R of the sensor may be maintained unchanged.

In the interrogation I_{14} the interrogated sensor value v_{14} from the sensor is not within the predicted range 50 of the sensor (step 63 in Figure 6). As a result the interrogated sensor value v_{14} is not readily accepted, but an immediate re-interrogation I_{15} of the sensor may be made to obtain a new interrogated sensor value v_{15} for comparison (step 65 in Figure 6). Thus the in-

terrogation rate R of the sensor is temporarily increased. However, now even the new immediately re-interrogated sensor value v_{15} is out of the predicted sensor value range 50 (step 66 in Figure 6). On the other hand, the new interrogated sensor value v_{15} is relatively close to the previous interrogated out-of-range sensor value v_{14} (e.g. within a tolerance) (step 68 in Figure 6), the reader 11 may assume that there is a real change in the sensed pressure values. Thus, both the previous out-of-range interrogated sensor value v_{14} and the new out-of-range interrogated sensor value v_{15} may be accepted and stored (step 69 in Figure 6). The predicted sensor value range 50 is step-wise adapted to the large rapid change of the sensor values (step 60 in Figure 6).

If in step 68, both the new immediately re-interrogated sensor value v_n and the last previous interrogated sensor value v_{n-1} are out of the predicted sensor value range and relatively far apart from each other (e.g. not within a tolerance), neither of the previous out-of-range interrogated sensor values v_n and v_{n-1} is immediately accepted but a further immediate re-interrogation of the sensor may be made to obtain a new interrogated sensor value v_{n+1} for comparison (step 65 in Figure 6). New re-interrogations may be done (steps 65, 66, 68) until a stable situation is achieved, e.g. two or more consecutive sensor values fall within the predicted sensor value range 50 (steps 66, 67) or are out-of-range values close enough each to other to be accepted as valid sensor values (steps 68, 69). Thus, the interrogation rate R of the sensor may be maintained increased until a good situation is found, and the interrogation rate R may then be decreased to a normal value (procedure returns to step 60).

Figure 7 illustrates a flow diagram illustrating another exemplary control procedure for one specific sensor. Similar control procedure may be carried out separately for each sensor around. In this example the statistical criterion is a variance of the interrogated sensor values.

In the beginning the reader 11 may store at least N values of previous interrogated sensor values from all sensors within the reading range of the reader 11. On basis of these N previous sensor values a long-time average of the variance of the interrogated sensor values is calculated for the sensor (step 70 in Figure 7). This long-time average is used as a reference value for variance in the control procedure. Similarly, a respective long-time average of the variance may be calculated separately for each sensor around. The long-time average of a specific sensor may be updated each time a new interrogated sensor value from a respective is accepted and stored, such that the average

may adapt to gradually changing sensor values.

Next interrogation is performed for the sensor at an interrogation rate R (step 71 in Figure 7). The short-time average of the variance of the sensor may be calculated each time a new interrogated sensor value is accepted and stored (step 72 in Figure 7). The short term variance may be calculated over a low number of previous interrogated sensor values. If the short-time average is substantially equal to the long-time reference variance (step 73 in Figure 7), the present interrogation rate R of the sensor is maintained (step 74 in Figure 7) and the procedure may return to step 70. If the short-time average is not substantially equal to the long-time reference variance (step 73 in Figure 7), it may be checked whether the short-time average is smaller or larger than the long-time reference variance (step 75 in Figure 7). If the short-time average is smaller than the long-time reference variance, the interrogation rate R of the sensor may be increased (step 76 in Figure 7) and the procedure may return to step 70. If the short-time average is larger than the long-time reference variance, the interrogation rate R of the sensor may be decreased (step 77 in Figure 7) and the procedure may return to step 70.

The above-illustrated exemplary embodiments for methods of controlling an interrogation rate based on a statistical analysis of the received sensor values method work fine, if we assume that signal-noise-ratio (SNR) of the received backscattered signal is acceptable, i.e. there is no inaccuracy in the sensed values due to a poor SNR. An acceptable signal-noise-ratio (SNR) of the received signal f_{OSC} is illustrated in Figure 8A. The signal power at the frequency f_{OSC} is well above the noise level. When signal-noise-ratio (SNR) of the received signal f_{OSC} is low, i.e. not acceptable, the signal power at the frequency f_{OSC} is close to the noise level, and the noise may produce some shift or error in the detected oscillation frequency f_{OSC} , e.g. a frequency f'_{osc} may be detected instead of the correct frequency f_{OSC} , as illustrated in Figure 8B. The frequency shifts due to the unacceptable low SNR may also vary with time as illustrated in Figure 8C. Such shifts in the detected oscillation frequency due to a low SNR may cause the reader 11 to interpret similar shift or change in the detected sensor values, although there is no corresponding change in the actual sensor value measured by the sensing element in the sensor tag 10. Moreover, due to the poor SNR, the reader 11 may perform the calculation of a predicted value range using inaccurate sensor values in the statistical operations, which may lead to an incorrect predicted value range.

Let us assume that in the example illustrated in Figure 5, the sensor values v9-v13 would have been received when the SNR is not acceptable and frequency shift occurs as illustrated in Figure 9A. Under acceptable SNR conditions, the sensor values v9-v13 fall within the predicted value range 50 of the sensor, as illustrated by dotted circles in Figure 9A. However, under unacceptable SNR conditions, the interrogated sensor value v9 does not fall within the predicted value range 50. Also the re-interrogated value v10 falls outside the predicted value range 50 but is relatively close to the previous out-of-range sensor value v9, and both values are readily accepted despite SNR is not acceptable. This situation may lead the reader to accept non-valid values as valid sensor values and it may also lead the reader to calculate wrong predicted value ranges, following wrong path. For example, in Figure 9A, a wrong predicted value range 90 is formed, as also the following interrogated sensor values v11-v13 are shifted close to the previous out-of-range values. Thus, erroneous sensor values will be systematically accepted. A shift of a single sensor value, e.g. v6, due to a spurious noise or interference will be filtered out by the statistical analysis.

As another example, Figures 9B and 9C illustrate a gradual change of the SNR with time and a corresponding gradual change in the sensor values v1-v10. During an acceptable SNR, accurate sensor values v1-v7 are detected and the predicted value range 50 is calculated correctly. However, when the SNR gradually changes more and more lower, the sensor values v8-v12 gradually become more and more inaccurate, and also the predicted value range 90 calculated based on the incorrect values gradually departs from the predicted value range 50 that would have been calculated based on correct sensor values detected during acceptable SNR condition.

According to a still another aspect of the invention a statistical control of the interrogation rate R based on the interrogated sensor values made in parallel with or in combination with an interrogation power control arranged to reduce the inaccuracy of the interrogated sensor values possibly caused by the signal-noise-ratio (SNR) of the received backscattered signal.

Figure 10 illustrates a flow diagram illustrating a statistical control of the interrogation power P_{int} that may be performed in parallel with a statistical control of the interrogation rate R. The exemplary power control procedure is illustrated for one specific sensor. Similar control procedure may be carried out separately for each sensor around. In this exemplary power control procedure

the statistical criterion is a long-time average of signal/noise ratio (SNR) of the backscattered signal during interrogation of a specific sensor, and the interrogation power is controlled. The instantaneous SNR values can be measured by an RF front end 60 of the reader 11, e.g. by an RX level detection unit 405, and provided to the digital control 41 for the control procedure.

In the beginning the reader 11 may store SNR values of at least N previous interrogations from each sensor within the reading range of the reader 11. On basis of these N previous SNR values a long-time average of the SNR is calculated for the sensor (step 100 in Figure 10). This long-time average is used as a reference value for the SNR in the control procedure. Similarly, a respective long-time average of the SNR may be calculated separately for each sensor around. The long-time average SNR of a specific sensor may be updated each time a new interrogated sensor value from a respective is accepted and stored, such that the average may adapt to gradually changing radio conditions, e.g. to changing distance.

Next interrogation is performed for the sensor with a transmitted interrogation power P_{int} (step 101 in Figure 10). A short-time average of the SNR of the sensor may be calculated each time a new interrogated sensor value is accepted and stored (step 102 in Figure 10). The short-time SNR may be calculated over a low number of previous interrogations. If the short-time average SNR is substantially equal to the long-time reference SNR (step 103 in Figure 10), the present interrogation power P_{int} is maintained for of the sensor (step 104 in Figure 10) and the procedure may return to step 100. If the short-time average SNR is not substantially equal to the long-time reference SNR (step 103 in Figure 10), it may be checked whether the short-time average SNR is smaller or larger than the long-time reference SNR (step 105 in Figure 10). If the short-time average SNR is smaller than the long-time reference SNR, the interrogation power P_{int} for the sensor may be increased (step 106 in Figure 10) and the procedure may return to step 100. If the short-time average SNR is larger than the long-time reference SNR, the interrogation power P_{int} for the sensor may be decreased (step 107 in Figure 10) and the procedure may return to step 100.

According to a still another aspect of the invention a statistical control of the interrogation rate R and a statistical control of the interrogation power P_{int} may be combined. For example, the controls may be combined such that the interrogation power control is a primary control and the interrogation

rate control is a secondary control. Thus, the quality of the received sensor data may be first attempted to improve with the interrogation power control, and the interrogation rate control is attempted if the interrogation power control is not possible or effective, e.g. the maximum allowed EIRP is reached. This approach may allow low interrogation rates and thereby more interrogated sensors. As another example, the controls may be combined such that the interrogation rate control is a primary control and the interrogation power control is a secondary control. Thus, the quality of the received sensor data may be first attempted to improve with the interrogation rate control, and the interrogation power control is attempted if the interrogation rate control is not possible or effective, e.g. the interrogation rate cannot be increased without decreasing the number of interrogated sensors. This approach may allow lower interrogation powers and lower radio interference.

Figure 11 illustrates a flow diagram illustrating still an exemplary combined control procedure for one specific sensor. Similar control procedure may be carried out separately for each sensor around. In this example the statistical criteria are a long-time average of signal/noise ratio (SNR) of the backscattered signal during interrogation of a specific sensor as well as a long-time average of variance of the interrogated sensor values, and both the interrogation power and the interrogation rate are controlled. The instantaneous SNR values can be measured by an RF front end 50 of the reader 11, e.g. by an RX level detection unit 405, and provided to the digital control 41 for the control procedure.

In the beginning the reader 11 may store SNR values of at least N previous interrogations from each sensor within the reading range of the reader 11 in function of a variance of the interrogated sensor values. In other words, a pair of SNR and variance may be stored for each interrogation. On basis of these N previous SNR values a long-time average of the SNR in a function of variance of the interrogated sensor values may be calculated for the sensor (step 110 in Figure 11) and stored, e.g. in a tabular format. There may be a number of bins of variance values, each bin covering a sub-range of a total range of variance values. The long-time average SNR for a specific bin may be calculated based on the SNR values whose corresponding variance value fall within the specific bin. These long-time averages are used as reference values for the SNR in the control procedure. Similarly, respective long-time averages of the SNR may be calculated separately for each sensor

around. The long-time averages SNR of a specific sensor may be updated each time a new interrogated sensor value from a respective is accepted and stored, such that the averages may adapt to gradually changing radio conditions, e.g. to changing distance.

5 Next interrogation is performed for the sensor with a transmitted interrogation power P_{int} and with interrogation rate R (step 111 in Figure 11). An SNR and a variance of the interrogation are measured or calculated (step 112 in Figure 11). If SNR of the interrogation is substantially equal to the long-time reference SNR corresponding to the variance of the interrogation (step 10 113 in Figure 11), the present interrogation power P_{int} (and optionally present interrogation rate) is maintained for the sensor (step 114 in Figure 11) and the procedure may return to step 110. If the SNR of the interrogation is not substantially equal to the long-time reference SNR corresponding to the variance of the interrogation (step 113 in Figure 11), it may be checked whether the 15 SNR of the interrogation is smaller or larger than the long-time reference SNR corresponding to the variance of the interrogation (step 115 in Figure 11). If the SNR of the interrogation is smaller than the long-time reference SNR corresponding to the variance of the interrogation, the interrogation power P_{int} for the sensor may be decreased (and optionally present interrogation rate R may 20 be maintained) (step 116 in Figure 11) and the procedure may return to step 110. If the SNR of the interrogation is larger than the long-time reference SNR corresponding to the variance of the interrogation and if the interrogation power P_{int} will not exceed the maximum allowed EIRP (step 117 in Figure 11), the interrogation power P_{int} for the sensor may be increased (and optionally present 25 interrogation rate R may be maintained) (step 118 in Figure 11) and the procedure may return to step 110. If the SNR of the interrogation is larger than the long-time reference SNR corresponding to the variance of the interrogation and if the interrogation power P_{int} would exceed the maximum allowed EIRP (step 117 in Figure 11), the interrogation power P_{int} for the sensor may not be 30 changed but the interrogation rate R of the sensor is adjusted (step 119 in Figure 11) and the procedure may return to step 110. The adjustment step 119 may increase the interrogation rate R of the sensor in order to adapt the reader to the low SNR. The adjustment step 119 may work in two directions based on an averaged variance reference. When the variance drops below its reference, 35 the reader may decrease the interrogation rate R , and vice versa, when the variance rises above its reference, the reader may increase the interrogation

rate R. The adjustment step 119 may be implemented, for example, as illustrated with reference to Figure 9. In embodiments of an adjustment of the interrogation rate R (step 119A) may also follow the step of maintaining the interrogation power P_{int} such that the interrogation rate can be controlled to its reference. Instead or additionally, the adjustment of interrogation rate R (step 119B) may follow also the step decreasing (step 116) and/or the step of increasing the interrogation power P_{int} .

A practical problem involved with using a power management to improve the SNR is that, in practice, the interrogation power employed by the RFID reader is the maximum allowed the maximum allowed EIRP (2W in EU and 4W in USA) in order to achieve as long read out distance as possible. In such case, the interrogation power cannot be increased any more.

According to a still another aspect of the invention a statistical control of the interrogation rate R based on the interrogated sensor values is arranged to take into account an inaccuracy of the interrogated sensor values possibly caused by the signal-noise-ratio (SNR) of the received backscattered signal. This approach is particularly advantageous, when the interrogation power employed by the RFID reader is the maximum allowed EIRP, or the power control cannot be or is not used for some other reason. The inaccuracy caused by the SNR may be taken into account in various ways in interpretation of sensor values without departing from the scope of the invention. In an embodiment, sensor values which are potentially inaccurate due to a low SNR may be rejected. In an embodiment, sensor values which are potentially inaccurate due to a low SNR may be corrected or compensated to reduce the inaccuracy. In an embodiment, sensor values which are potentially inaccurate due to a low SNR may be excluded from the sensor values which are employed in predicting a value range for the next value or values. In an embodiment, no actions may be made due to the low SNR immediately but the sensor values may be stored with information regarding their accuracy. The accuracy information may comprise SNR related information. An upper layer application or a user may utilize the accuracy information and the optional SNR information for further processing or analysis.

Figure 12 is a flow diagram illustrating an exemplary control procedure a statistical control of the interrogation rate R based on the interrogated sensor values is arranged to take into account an inaccuracy of the interrogated sensor values possibly caused by the signal-noise-ratio (SNR) by rejecting

out-of-range values. Similar control procedure may be carried out separately for each sensor around. In this example the statistical criterion is a variance of the interrogated sensor values.

In the beginning the reader 11 may store SNR values of at least N
5 previous interrogations from each sensor within the reading range of the reader 11. On basis of these N previous SNR values a long-time average of the SNR is calculated for the sensor (step 120 in Figure 12). This long-time average is used as a reference value for the SNR in the control procedure. Similarly, a respective long-time average of the SNR may be calculated separately for
10 each sensor around. The long-time average SNR of a specific sensor may be updated each time a new interrogated sensor value from a respective is accepted and stored, such that the average may adapt to gradually changing radio conditions, e.g. to changing distance.

The reader 11 may also store at least N values of previous interrogated sensor values from all sensors within the reading range of the reader 11.
15 The number N of stored values can be a selectable parameter and different for different sensors, but an accuracy of the prediction is better if a higher number, preferably at least 10-20, of the last interrogated sensor values is stored. On basis of these N previous sensor values a value range 50 for the next value or
20 values to be interrogated is predicted for the sensor (step 121 in Figure 12). Similarly, a respective value range 50 may be predicted separately for each sensor around. For example, the value range 50 may be predicted by predicting the next sensor value(s) and a tolerance allowed for the sensor value. The prediction 50 of a specific sensor may be updated each time a new interrogated
25 sensor value from a respective is accepted and stored, such that the prediction may adapt to gradually changing sensor values. The prediction may be performed by an extrapolation, an interpolation, a linear regression, etc. of the stored values. The tolerance may be defined by a variance or a similar statistical value.

30 Next interrogation is performed for the sensor (step 122 in Figure 12). A short-time average of the SNR of the sensor may be calculated each time a new interrogated sensor value is obtained (step 123 in Figure 12). The short-time SNR may be calculated over a low number of previous interrogations. A short-time SNR may also be an instantaneous SNR measured or
35 calculated for the new interrogated sensor value only.

If the short-time average SNR is smaller than the long-time reference SNR (step 124 in Figure 12), the new interrogated sensor value is determined to be not accurate enough (i.e. inaccurate) (step 125 in Figure 12) and the procedure proceeds to step 127. If the short-time average SNR is greater than to the long-time reference SNR (step 124 in Figure 12), the new interrogated sensor value is determined to be accurate enough (i.e. accurate) (step 126 in Figure 12) and the procedure proceeds to step 127.

Then reader 11 may first check whether this next interrogated sensor value from a specific sensor falls within the predicted value range 50 of that sensor (step 127 in Figure 12). If the new interrogated value is within the predicted value range 50, the new interrogated value is accepted and stored (step 128 in Figure 12) and the process may return to step 120.

If the new interrogated sensor value from the sensor is not within the predicted range 50 of the sensor (step 127), may proceed from step 127 to step 131.

However, in some embodiments, there may be optional steps 129 and 130 that are depicted with a dashed line. In the optional steps, if the new interrogated sensor value from the sensor is not within the predicted range 50 of the sensor (step 127), the reader 11 check whether the new interrogated value is determined to be accurate enough (step 129). If the new interrogated value is determined to be not accurate enough, the new interrogated value may be dropped as an inaccurate out-of-range value and the process may return to step 120. If the new interrogated sensor value is determined to be accurate enough, the process may proceed to step 131.

In step 131, the accurate out-of-range sensor value may not be readily accepted, but an immediate re-interrogation of the sensor may be made to obtain a new interrogated sensor value for comparison. Thus the interrogation rate R of the sensor is temporarily increased. Then the reader 11 may check whether this re-interrogated sensor value from the specific sensor falls within the predicted value range 50 of that sensor (step 132 in Figure 12). If the re-interrogated value is within the predicted range 50, the re-interrogated sensor value may be accepted and stored, and the previous out-of-range interrogated sensor value may be dropped (step 133 in Figure 6) and the process may return to step 120. However, if even the immediately re-interrogated sensor value is out of the predicted sensor value range 50 (step 132 in Figure 12), the reader 11 may check whether the re-interrogated sensor value is relatively

close to the previous interrogated out-of-range sensor value (e.g. within a tolerance) (step 134 in Figure 12). If the interrogated out-of-range values are not close to each other, the process may return to step 131 to perform re-interrogation. If the interrogated out-of-range values are close to each other,
5 both out-of-range sensor values may be accepted and stored (step 135) and the process may return to step 120.

In some embodiments, re-interrogation according to step 131 may include processing the re-interrogated sensor value in a similar manner as described for a new interrogated value with reference to steps 123-126. In other
10 words, a short-time average of the SNR may be calculated for the re-interrogated sensor value, the re-interrogated sensor value may be determined as an accurate or inaccurate based on the SNR.

Embodiments of the invention enable to distinguish between accurate or inaccurate sensor values. Inaccurate sensor values can be compensated or corrected, immediately or in post-processing. This can be accomplished based on the SNR due to the fact that the frequency f_{OSC} (and there
15 by the sensed value) drifts due to the increased noise. Hence, the more there is noise, the greater is the frequency shift from the accurate value. When the reader detects a big change in the sensor values, it may be due to poor SNR
20 (inaccurate results).

This phenomenon is illustrated in Figures 13A and 13B. Let us assume that the SNR changes as depicted by curve 136 in Figure 13A and the actual value of the sensed quantity at the sensor does not significantly change during the illustrated period of time. Thus, an accurate predicted value range
25 should be as indicated by the dashed lines 137 in Figure 13B. However due to the low short-time average of SNR of the backscattered signal received at the reader, it detects shifted inaccurate values and calculates an incorrect predicted value range 138 as shown by dotted lines in Figure 13B. Compensation, based on knowledge how the short-time average of SNR effects on the
30 sensor values v_1-v_{12} , may be applied to the inaccurate interrogated sensor values v_5-v_{11} . The resulting compensated sensor values are illustrated by dotted circles v_5-v_{11} and a predicted value range calculated based on these compensated sensor values is illustrated by the solid lines 139. It can be seen that the compensated sensor values are closer to the actual sensed values.
35 An exemplary compensation procedure is illustrated in Figure 15. An interrogated sensor value and a related short-time average SNR is obtained as a re-

sult of an interrogation (step 150). The reader determines a compensation value based on the short-time average SNR, for instance by means of pre-stored compensation values or by calculating with an SNR compensation function (step 151). Then the reader calculates the SNR compensated interrogated sensor value based on the compensation value or by calculating with an SNR compensation function (step 152).

Experiments have shown that the effect of the SNR on the interrogated sensor values can be determined or approximated in advance. For example, the effect of the SNR on the interrogated sensor values can be determined by introducing interference or noise when a sensor tag is interrogated while the actual sensor values are maintained unchanged, as illustrated in steps 160-161 in Figure 16. Thus, the error of sensor values in function of the SNR can be determined by comparing the interrogated sensor values with the actual sensor values (step 162). This error in function of the SNR can be used to derive and store the compensation values in function of the SNR level (step 163). The amount of compensation may be determined as a calibration procedure by a manufacturer or when the sensor and reader are installed. It is also possible to derive or define a compensation function that approximates a compensation required for an RFID sensor tag, and configure the reader or other application accordingly.

Figure 14 illustrates a flow diagram illustrating an exemplary control procedure a statistical control of the interrogation rate R based on the interrogated sensor values is arranged to take into account an inaccuracy of the interrogated sensor values possibly caused by the signal-noise-ratio (SNR) by compensating the inaccurate values based on the SNR. Similar control procedure may be carried out separately for each sensor around. In this example the statistical criterion is a variance of the interrogated sensor values.

Same reference numerals in Figures 12 and 13 refer to same or similar steps. In the exemplary method shown in Figure 13, the steps 123- 126 may be carried out in a similar manner as described with reference to Figure 12. From step 126, upon determining that the new interrogated sensor value is accurate enough, the procedure may proceed to step 127. For an accurate interrogated sensor values, the following steps 127-135 may be carried out as the corresponding steps in Figure 12.

From step 125, upon determining that the new interrogated sensor value is not accurate enough (i.e. it is inaccurate) (step 125 in Figure 12), the

reader may carry out compensation of the new interrogated sensor value based on the SNR (step 140) and the procedure may proceed to step 127. The following steps 127-135 may be carried out for the SNR compensated interrogated sensor value in a similar manner as for an original accurate interrogated value. For example, in step 127 it may be checked whether the SNR compensated interrogated sensor value falls within the predicted value range 50 of that sensor P. If the SNR compensated interrogated value is within the predicted value range 50, the SNR compensated interrogated value is accepted and stored (step 128 in Figure 12) and the process may return to step 120. If the SNR compensated interrogated sensor value from the sensor is not within the predicted range 50 of the sensor (step 127), may proceed from step 127 to step 131.

In some embodiments, re-interrogation according to step 131 may include processing the re-interrogated sensor value in a similar manner as described for a new interrogated value with reference to steps 123-125 and 140. In other words, a short-time average of the SNR may be calculated for the re-interrogated sensor value, the re-interrogated sensor value may be determined as an accurate or inaccurate based on the SNR, and the inaccurate re-interrogated sensor value may be compensated based on the SNR.

The SNR compensation step 140 may be implemented as illustrated in Figure 15, for example.

It should be appreciated the adaptive reader according to embodiments of the invention may be implemented with an RFID reader having sufficient computation capacity or with an RFID reader connected to a computing device that performs at least part of the computation required.

It will be obvious to a person skilled in the art that the inventive concept can be implemented in various obvious alternative ways. The invention and its embodiments are not limited to the examples described above but may vary within the scope of the claims.

CLAIMS

1. A method of controlling interrogation of sensor values in a system having a radio frequency identification (RFID) reader and at least one passive RFID sensor tag having at least sensing element that provides a value of a quantity sensed by the sensing element, comprising

5 sending a radio frequency interrogation signal from the RFID reader to the passive RFID sensor tag;

receiving at the RFID reader from the passive RFID tag a backscattered radio frequency signal carrying the value of the sensed quantity;

10 controlling an interrogation rate of the sensing element and/or accuracy of received values of the sensed quantity and/or a power of the radio frequency interrogation signal transmitted to the sensing element based on an analysis of i) the multiple received values of the sensed quantity and/or ii) multiple interrogations and/or iii) a signal-to-noise ratio.

15 2. A method as claimed in 1, wherein the statistical analysis comprises comparing a new interrogated value and/or a signal-to-noise ratio of a new interrogated value with a criterion created based on the multiple received values of the sensed quantity and/or multiple interrogations.

20 3. A method as claimed in 1 or 2, wherein the criterion comprises at least one of a predicted value or value range of the value of a sensed quantity, a variance of a sensed quantity, a long-time average of a variance of a sensed quantity, an average of a signal-to-noise ratio of the backscattered signal over multiple integrations of the sensing element.

25 4. A method as claimed in claim in any of claims 1-3, wherein the controlling comprises

maintaining the interrogation rate of the sensing element, if a new interrogated value of the sensed quantity is acceptable according to said statistical analysis;

30 increasing at least temporarily the interrogation rate of the sensing element, if a new interrogated value of the sensed quantity is not acceptable according to said statistical analysis.

35 5. A method as claimed in any of claims 1-4, wherein controlling comprises associating a new interrogated value of the sensed quantity with an accuracy information provided based on a signal-to-noise ratio of the backscattered signal, and/or rejecting a new interrogated value of the sensed quantity based on a signal-to-noise ratio of the backscattered signal, and/or adjusting a

new interrogated value of the sensed quantity based on a signal-to-noise ratio of the backscattered signal to improve accuracy.

6. A method as claimed in any of claims 1-5, wherein the controlling comprises

5 a) predicting a value range for a next value or next values to be interrogated from the sensing element based on a plurality of previous interrogated values of the quantity sensed by the sensing element;

b) maintaining the interrogation rate of the sensing element, if a new interrogated value of the sensed quantity falls within the predicted value
10 range of the sensing element;

c) increasing at least temporarily the interrogation rate of the sensing element, if a new interrogated value of the sensed quantity falls out of the predicted value range of the sensing element.

7. A method as claimed in claim 6, wherein the increasing at least
15 temporarily the interrogation rate of the sensing element comprises immediately reinterrogating the sensing element.

8. A method as claimed in any one of claims 6-7, wherein the increasing at least temporarily the interrogation rate of the sensing element comprises performing immediate reinterrogations of the sensing element until
20 the interrogated value of the sensed quantity is acceptable according to said statistical analysis.

9. A method as claimed in any one of claims 1-8, wherein the controlling comprises

25 a) predicting a value range for a next value or next values to be interrogated from the sensing element based on a plurality of previous interrogated values of the quantity sensed by the sensing element;

b) accepting a new interrogated value of the sensed quantity, if the new interrogated value falls within the predicted value range of the sensing element;

30 c) reinterrogating immediately the sensing element, if said new interrogated value of the sensed quantity falls out of the predicted value range of the sensing element;

d) accepting the reinterrogated value of the sensed quantity, if the reinterrogated value falls within the predicted value range of the sensing element, and dropping said new interrogated value;
35

e) accepting both said new interrogated value and said reinterrogated value of the sensed quantity, if also the reinterrogated value falls out of the predicted value range of the sensing element but said new interrogated value and said reinterrogated value are close to each other;

5 f) reinterrogating immediately the sensing element, if also said reinterrogated value of the sensed quantity falls out of the predicted value range of the sensing element and said new interrogated value and said reinterrogated value are close to each other;

10 g) continuing immediate reinterrogations of the sensing element until the reader obtains and accepts a reinterrogated value falling within the predicted value range or two reinterrogated values falling out of the predicted value range but being close to each other.

15 10. A method as claimed in any one of claims 6-9, wherein the controlling comprises updating the predicted value with each accepted interrogated value of the sensed quantity.

11. A method as claimed in any one of claims 1-10, wherein the controlling comprises

determining a long-time average of signal/noise ratio (SNR) of the backscattered signal during interrogation of the sensing element;

20 controlling the interrogation power and/or the interrogation rate of the sensing element using the long-time average of the SNR as a control reference.

25 12. A method as claimed in any one of claims 1-11, comprising determining a long-time average of a variance of the interrogated sensor values of the sensing element;

controlling the interrogation power and/or the interrogation rate of the sensing element using the long-time average of a variance of the interrogated sensor values as a control reference.

30 13. A method as claimed in any one of claims 1-12, comprising controlling the interrogation rate of the sensing element and the power of the radio frequency interrogation signal transmitted to the sensing element in parallel or in combination.

35 14. A method as claimed in claim 13, comprising determining a long-time averages of signal/noise ratio (SNR) of the backscattered signal during interrogation of the sensing element in function of a variance of the interrogated sensor values;

controlling the power of the radio frequency interrogation signal transmitted to the sensing element using as a control reference the long-time average of the SNR corresponding a present variance of one or more latest interrogated sensor values;

5 determining a long-time average of a variance of the interrogated sensor values of the sensing element;

controlling the interrogation rate of the sensing element using the long-time average of a variance of the interrogated sensor values as a control reference.

10 15. A method as claimed in claim 13 or 14, comprising controlling primarily the power of the radio frequency interrogation signal transmitted to the sensing element and controlling secondarily the interrogation rate of the sensing element.

15 16. A method according to claim 13, 14 or 15, comprising increasing the interrogation rate of the sensing element only if the power of the radio frequency interrogation signal cannot be increased.

17. A method as claimed in any one of claims 1-16, wherein the controlling comprises

20 determining a signal/noise ratio (SNR) of the backscattered signal during interrogation of an interrogated sensor value;

compensating an effect of a low signal/noise ratio (SNR) on the interrogated sensor value based on pre-stored compensation values and/or a compensation function, particularly if the power of the radio frequency interrogation signal cannot be increased.

25 18. A method as claimed in any one of claims 1-17, comprising the passive RFID sensor tag having an oscillator whose an oscillation frequency is dependent on a value of a quantity sensed by the sensing element;

30 the RFID reader receives from the passive RFID tag the backscattered radio frequency signal modulated with the oscillation frequency which is dependent on the value of the sensed quantity;

the RFID reader converts the oscillation frequency modulation of the backscattered signal into an actual value of the sensed quantity.

35 19. An RFID reader implementing the method as claimed in any one of claims 1-18.

20. A system comprising an RFID reader and a computer device implementing the method as claimed in any one of claims 1-18.

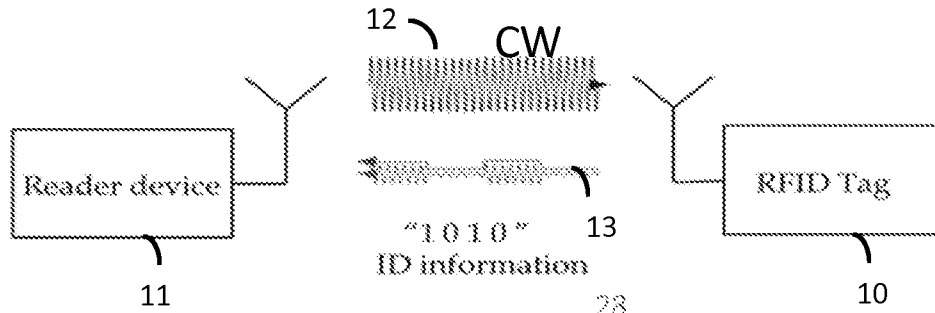


Fig. 1

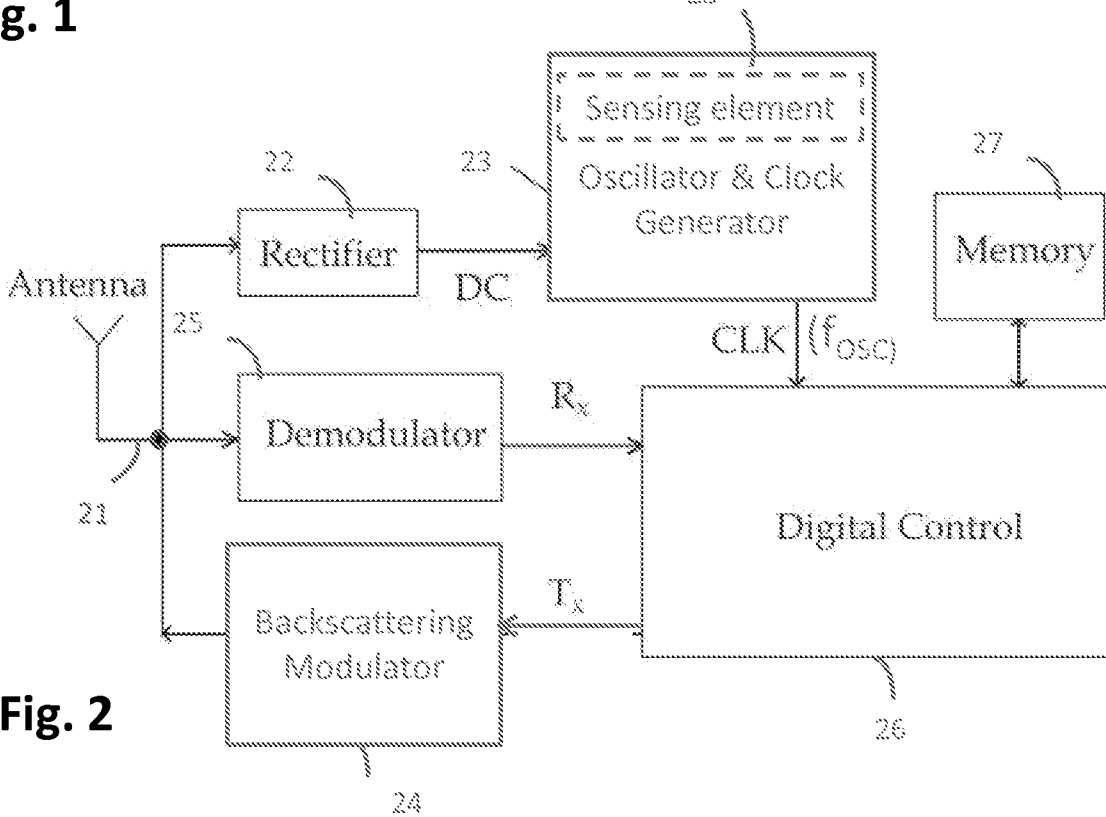


Fig. 2

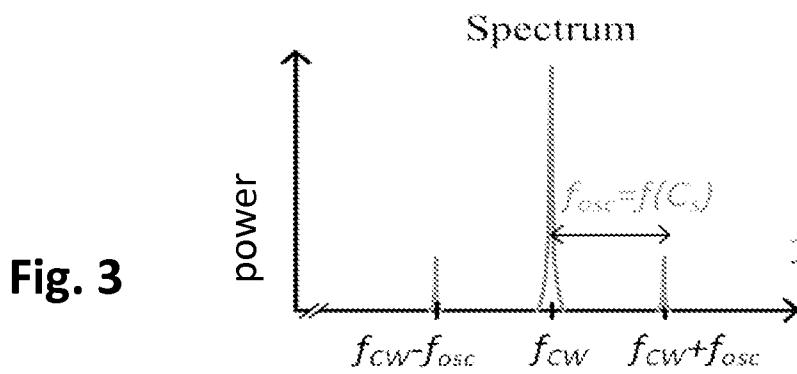


Fig. 3

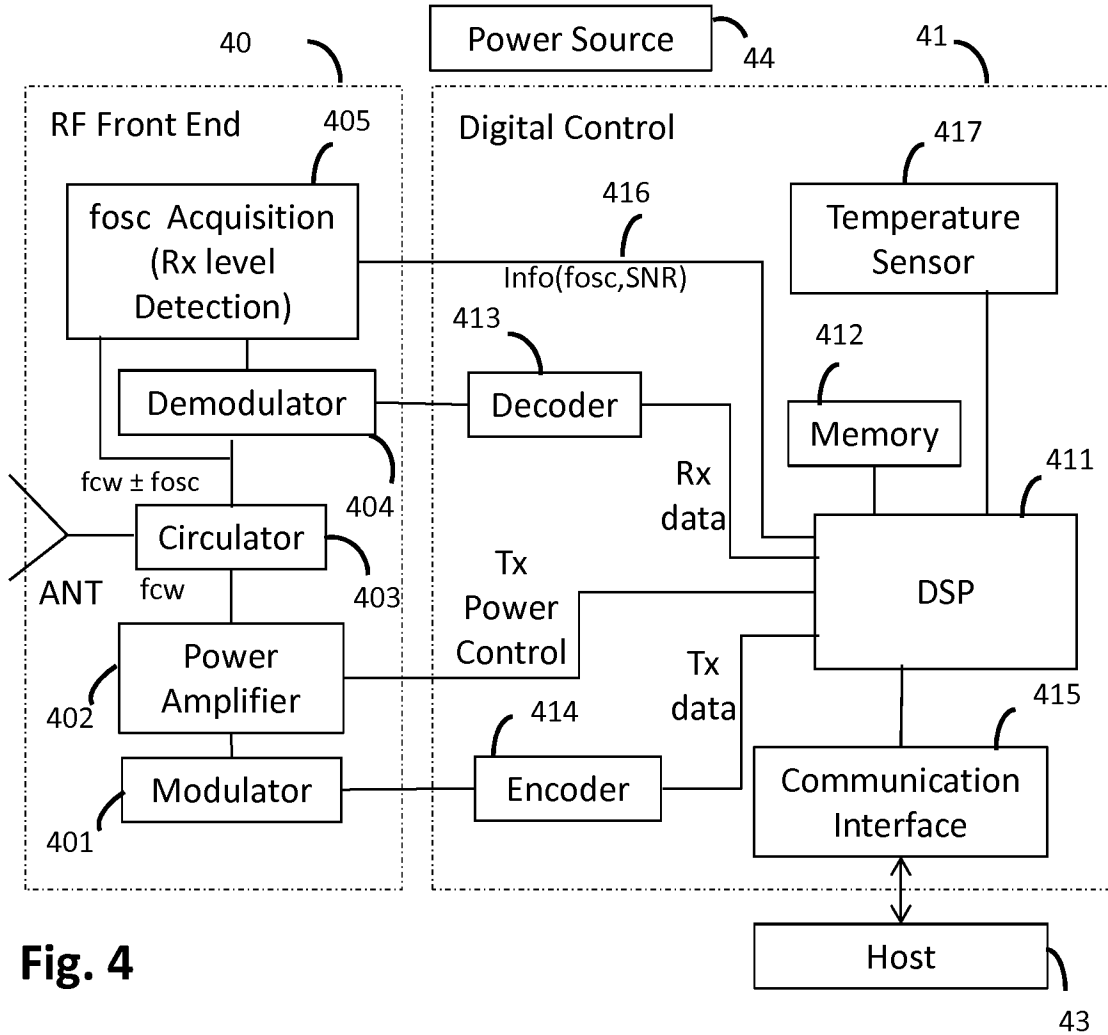


Fig. 4

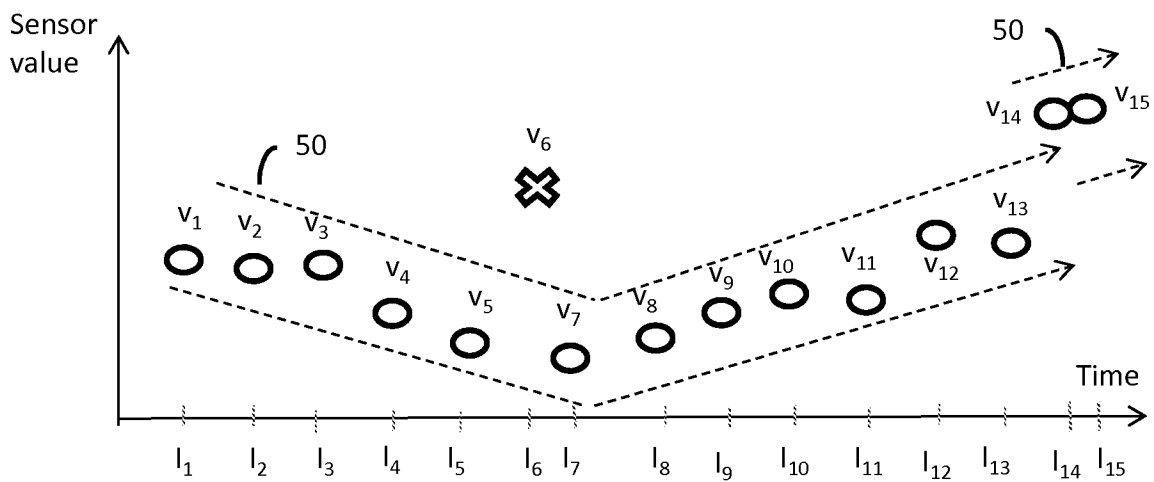


Fig. 5

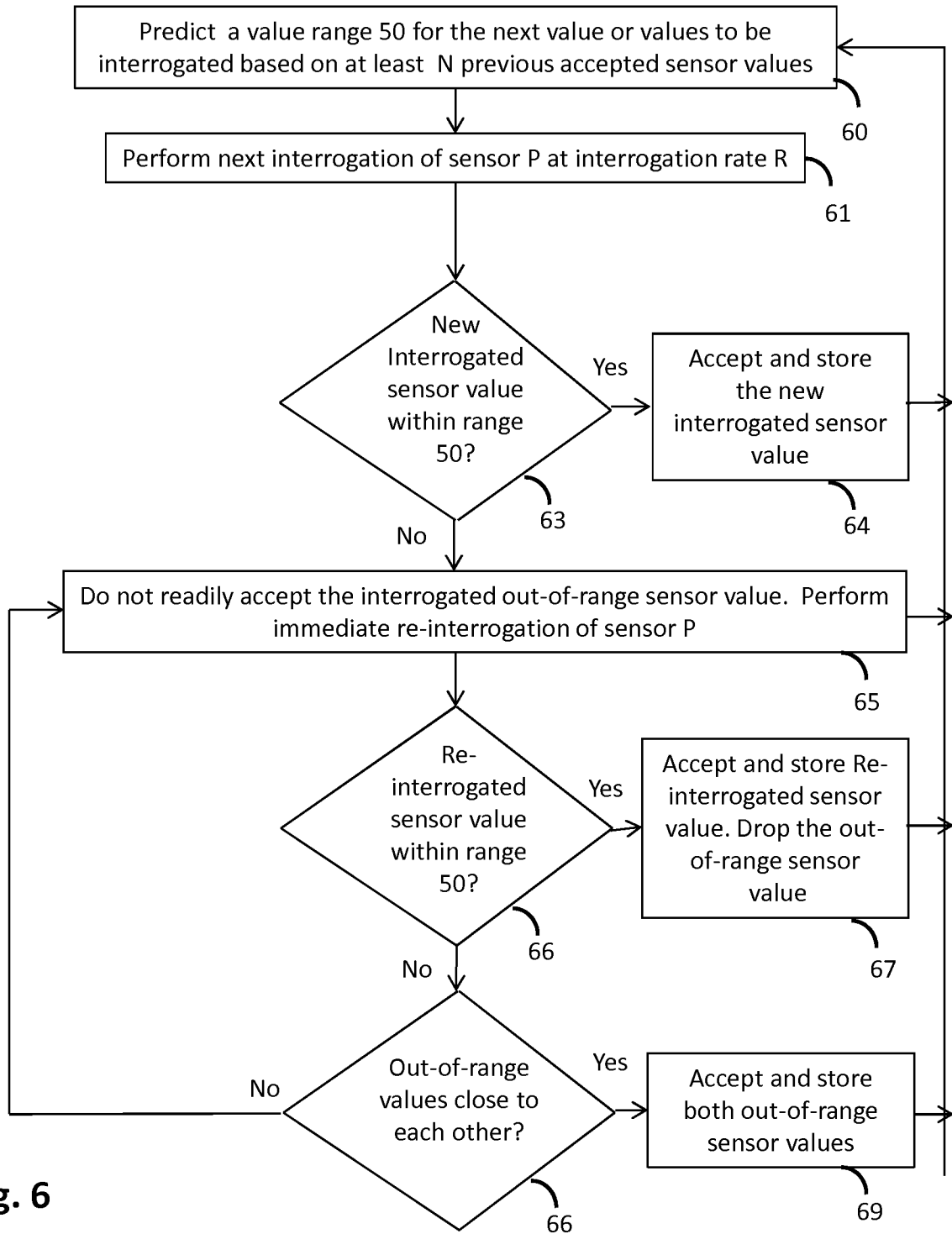


Fig. 6

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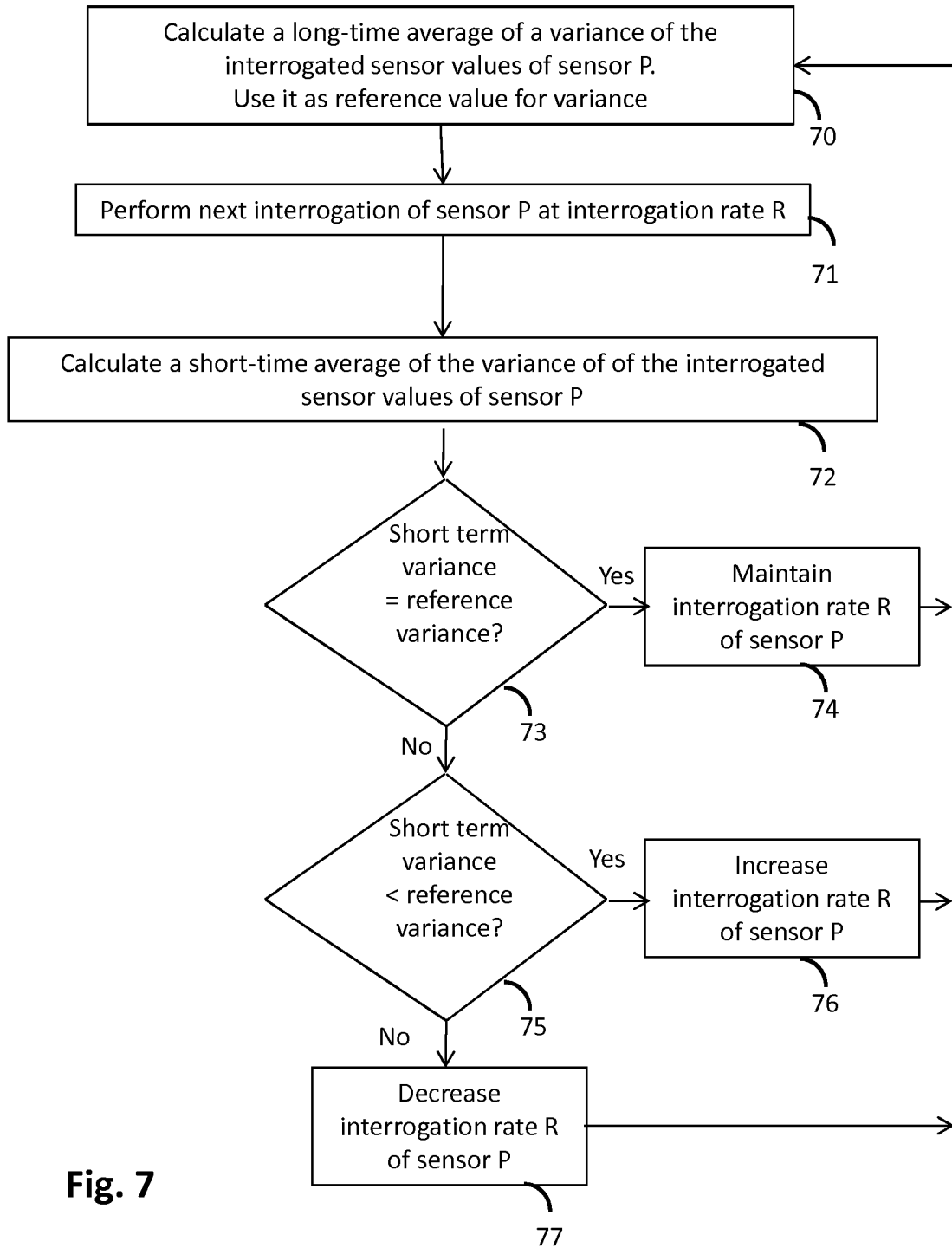


Fig. 7

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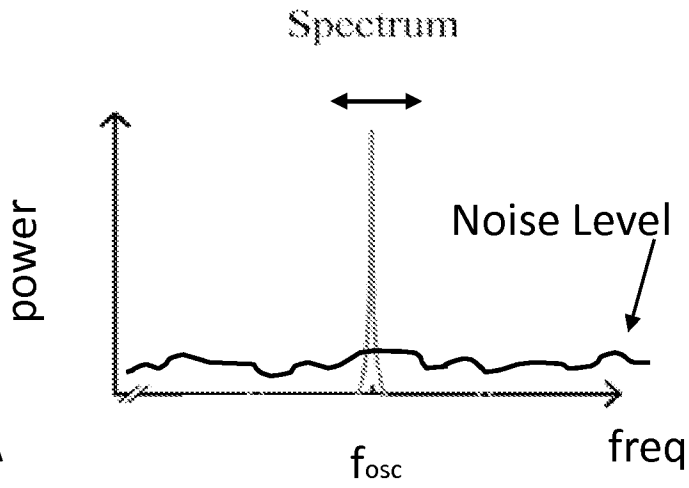


Fig. 8A

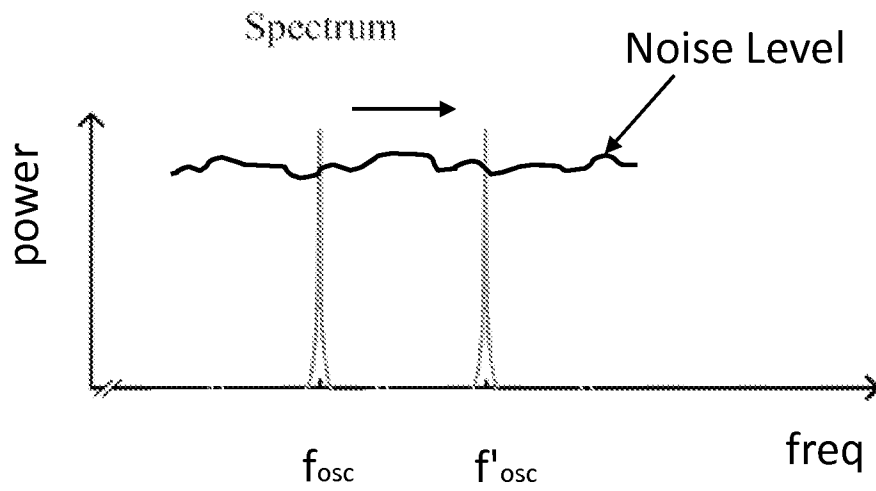


Fig. 8B

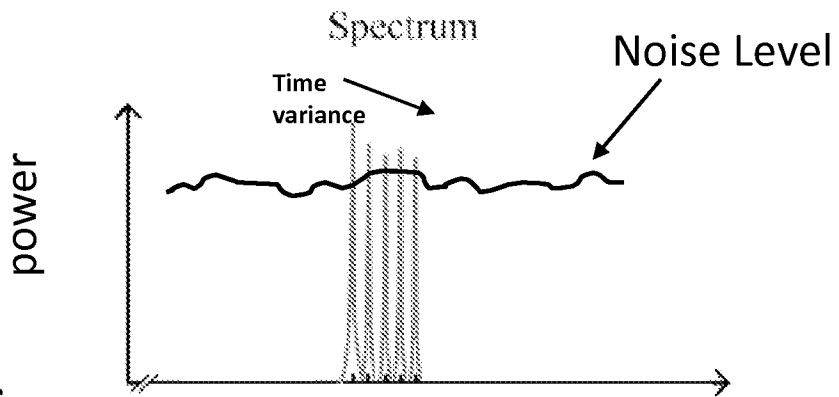


Fig. 8C

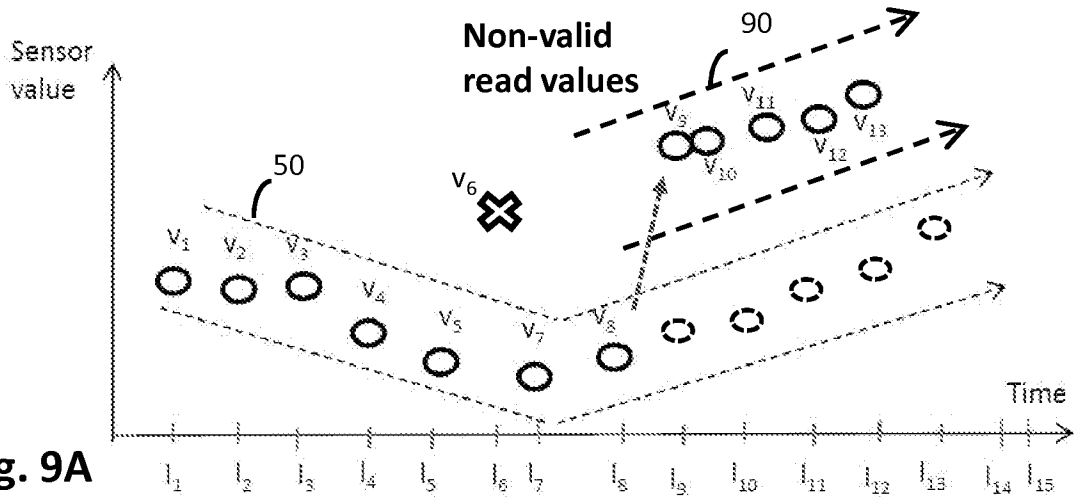


Fig. 9A

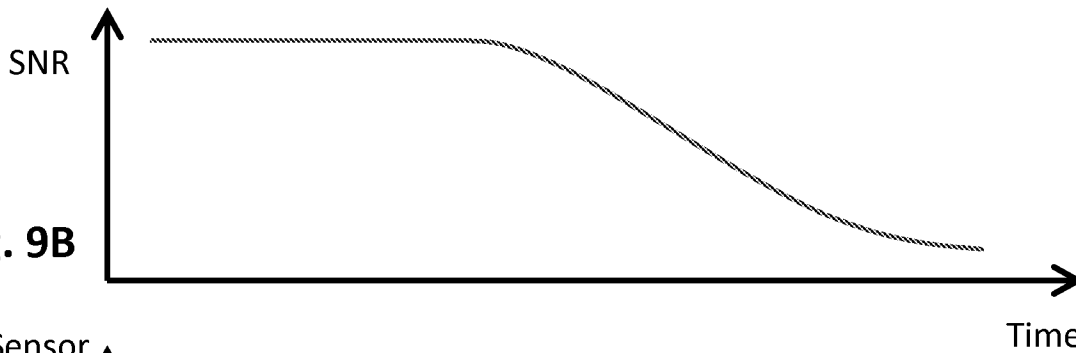


Fig. 9B

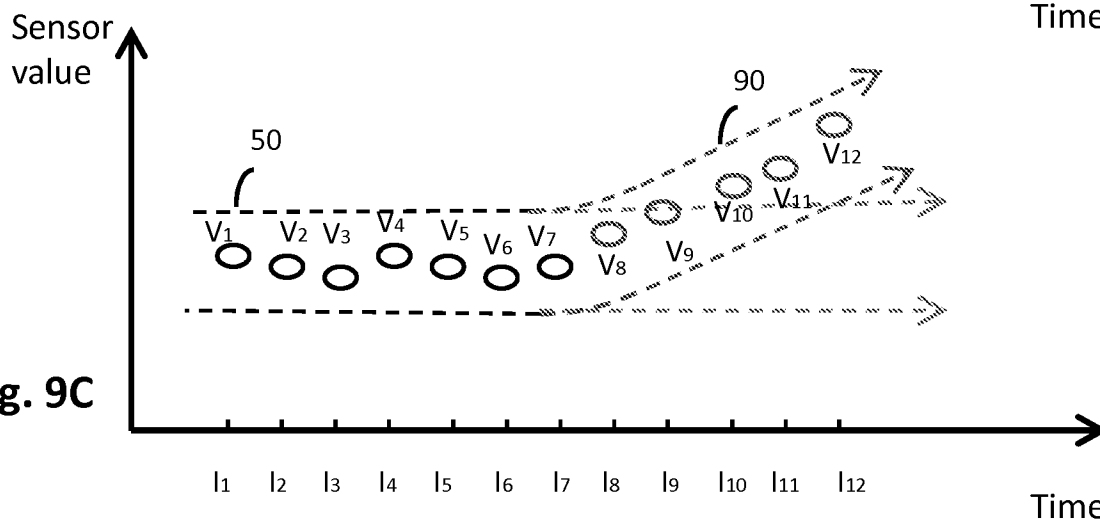


Fig. 9C

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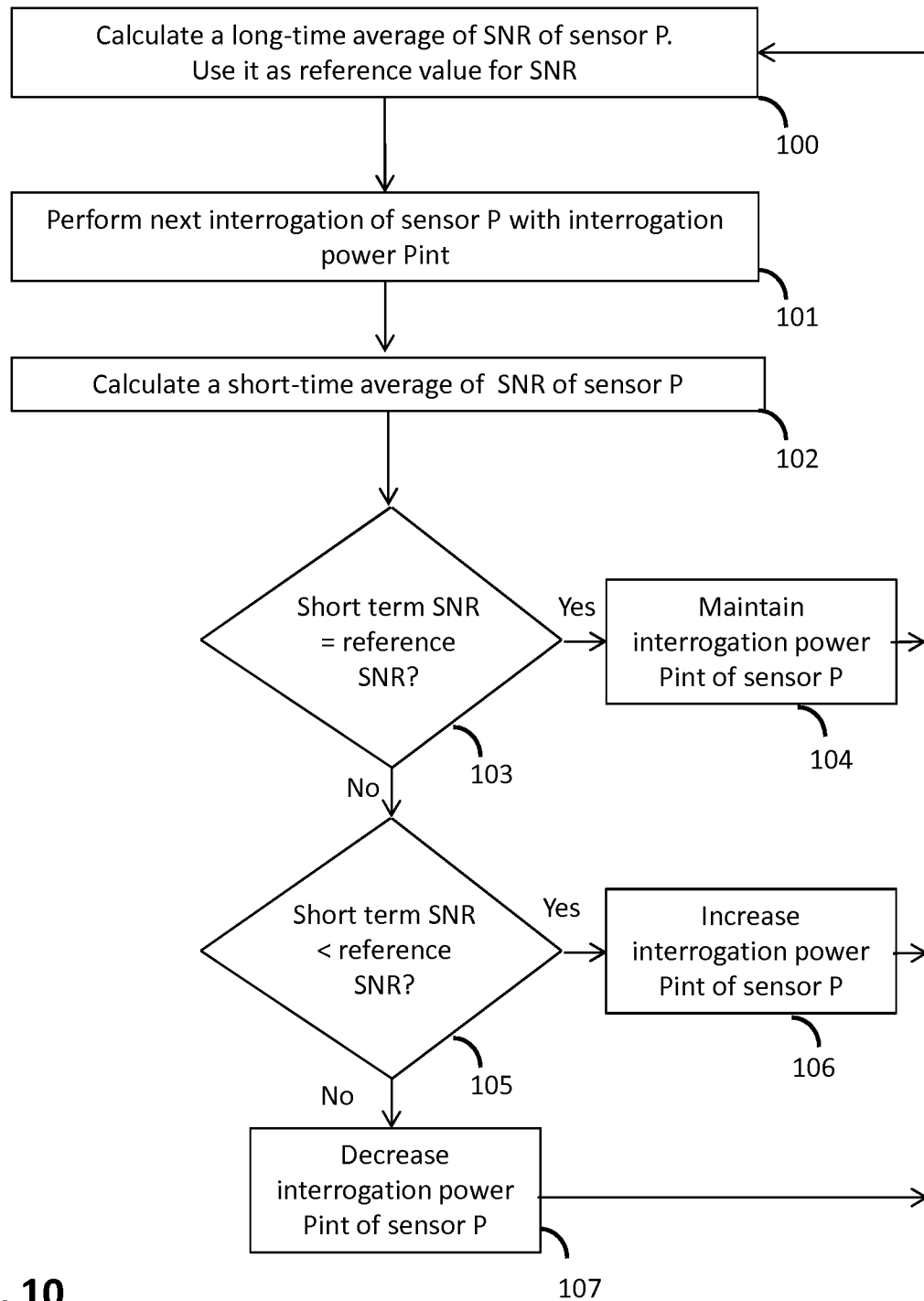


Fig. 10

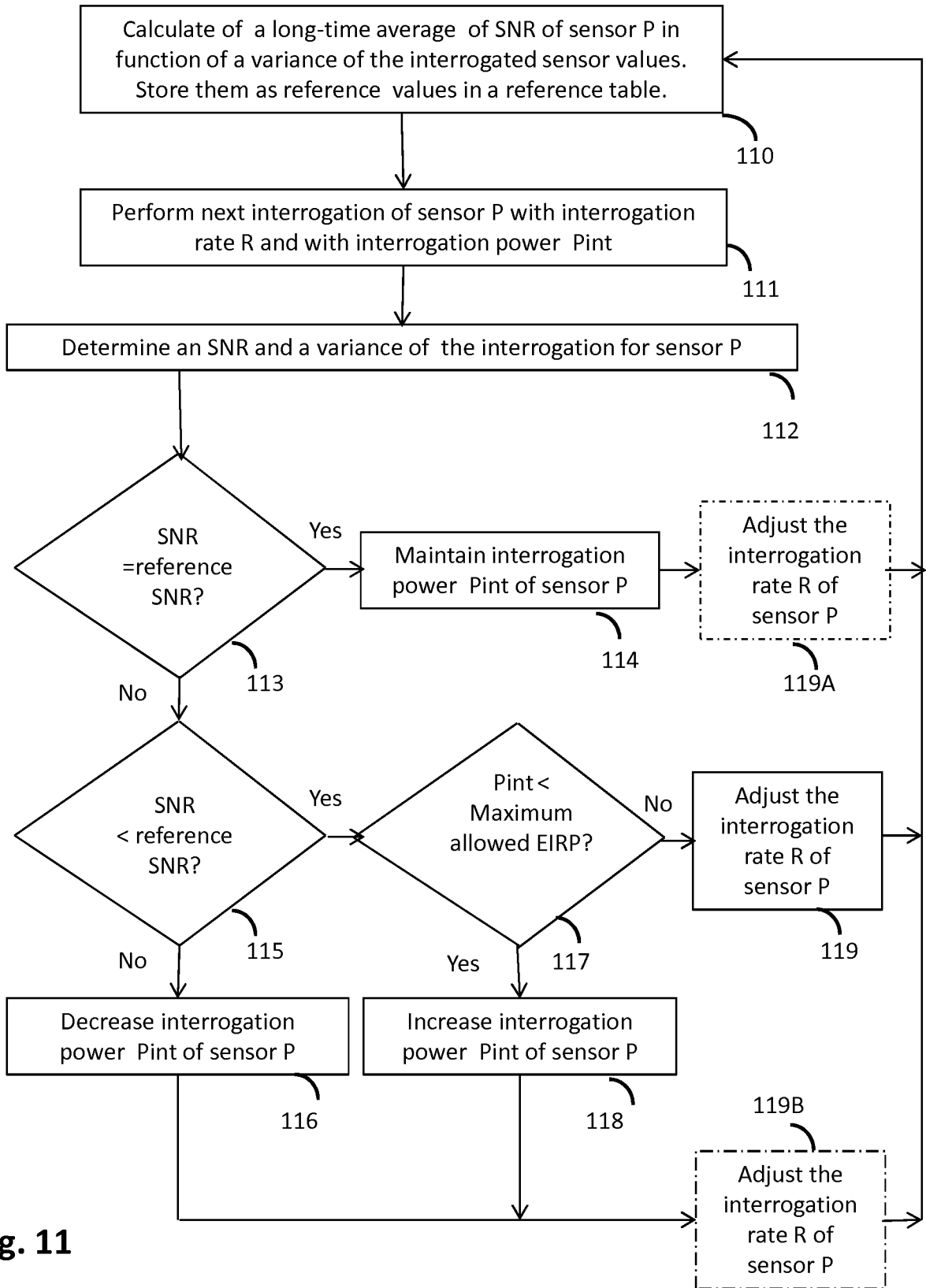


Fig. 11

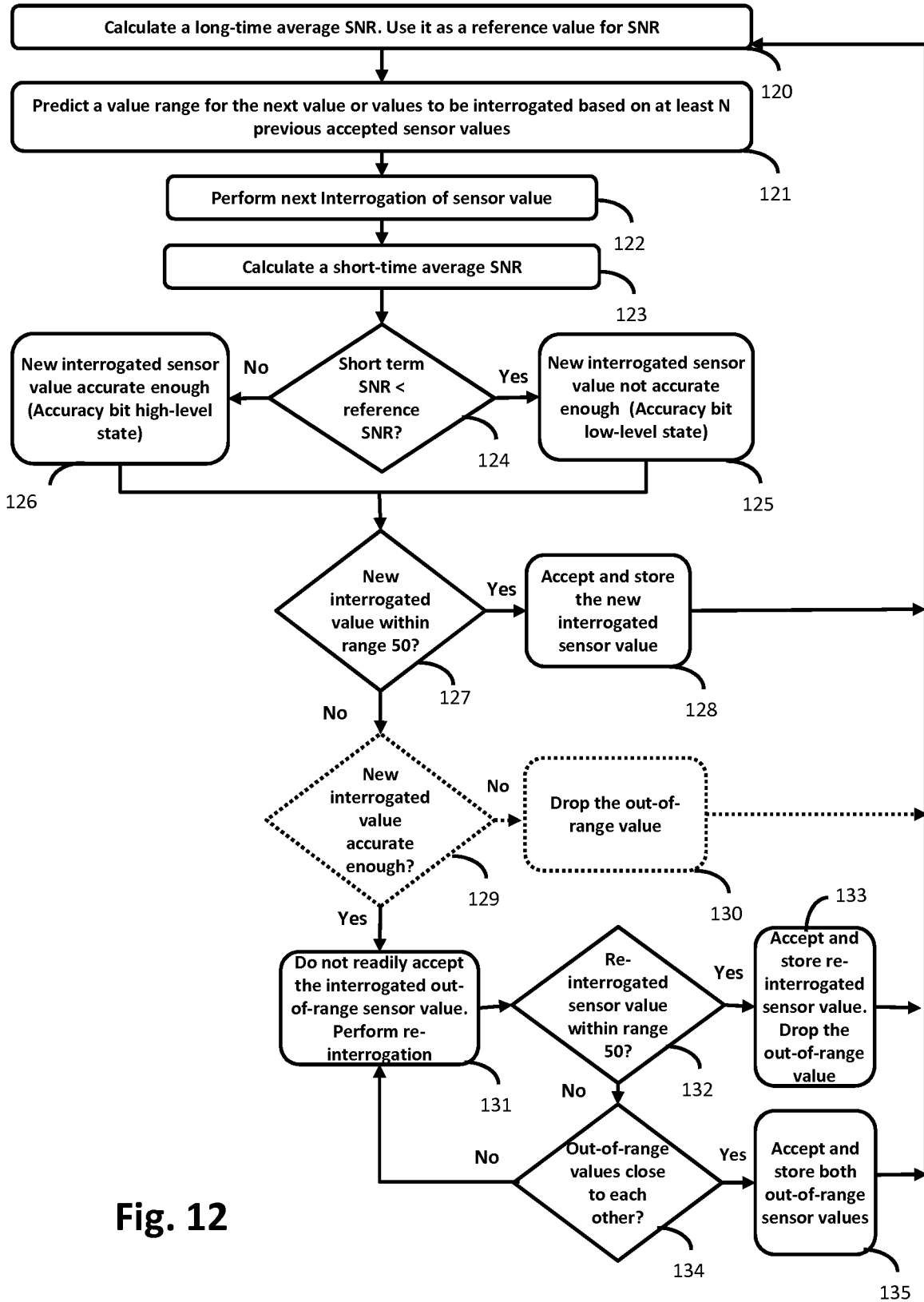


Fig. 12

10/12

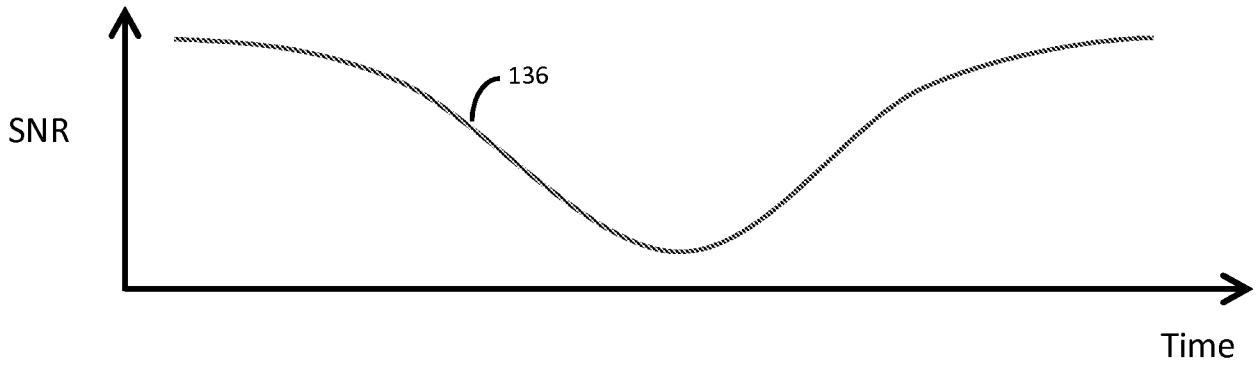


Fig. 13A

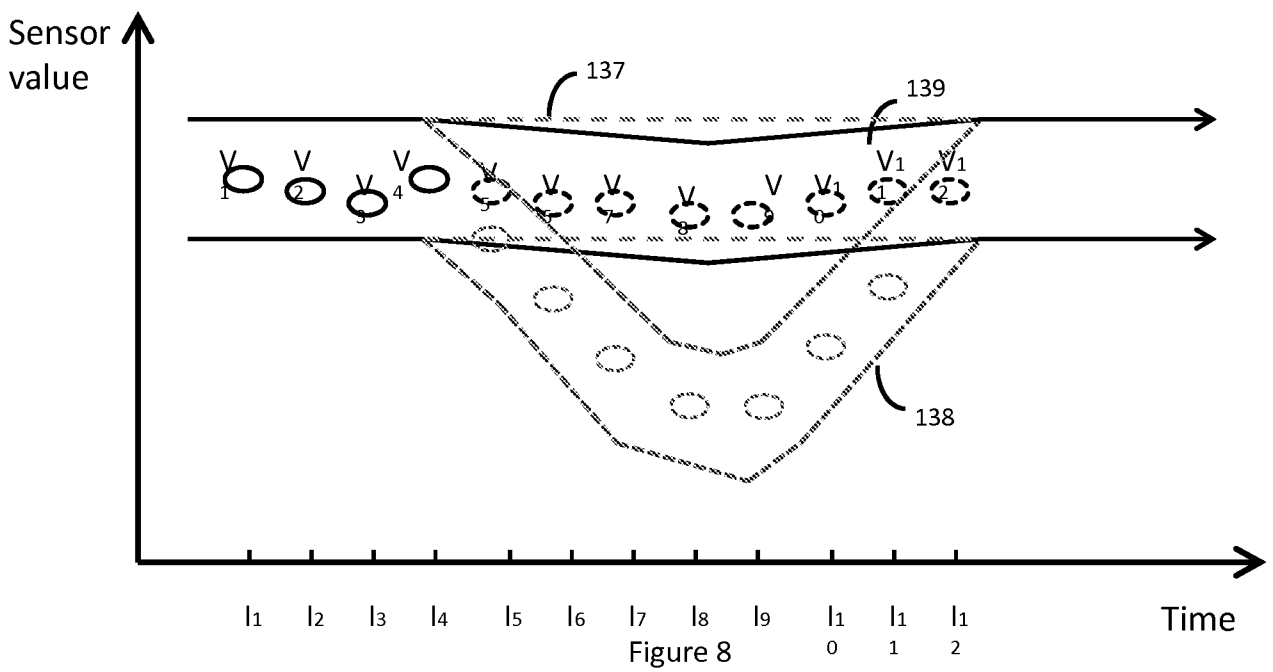


Fig. 13B

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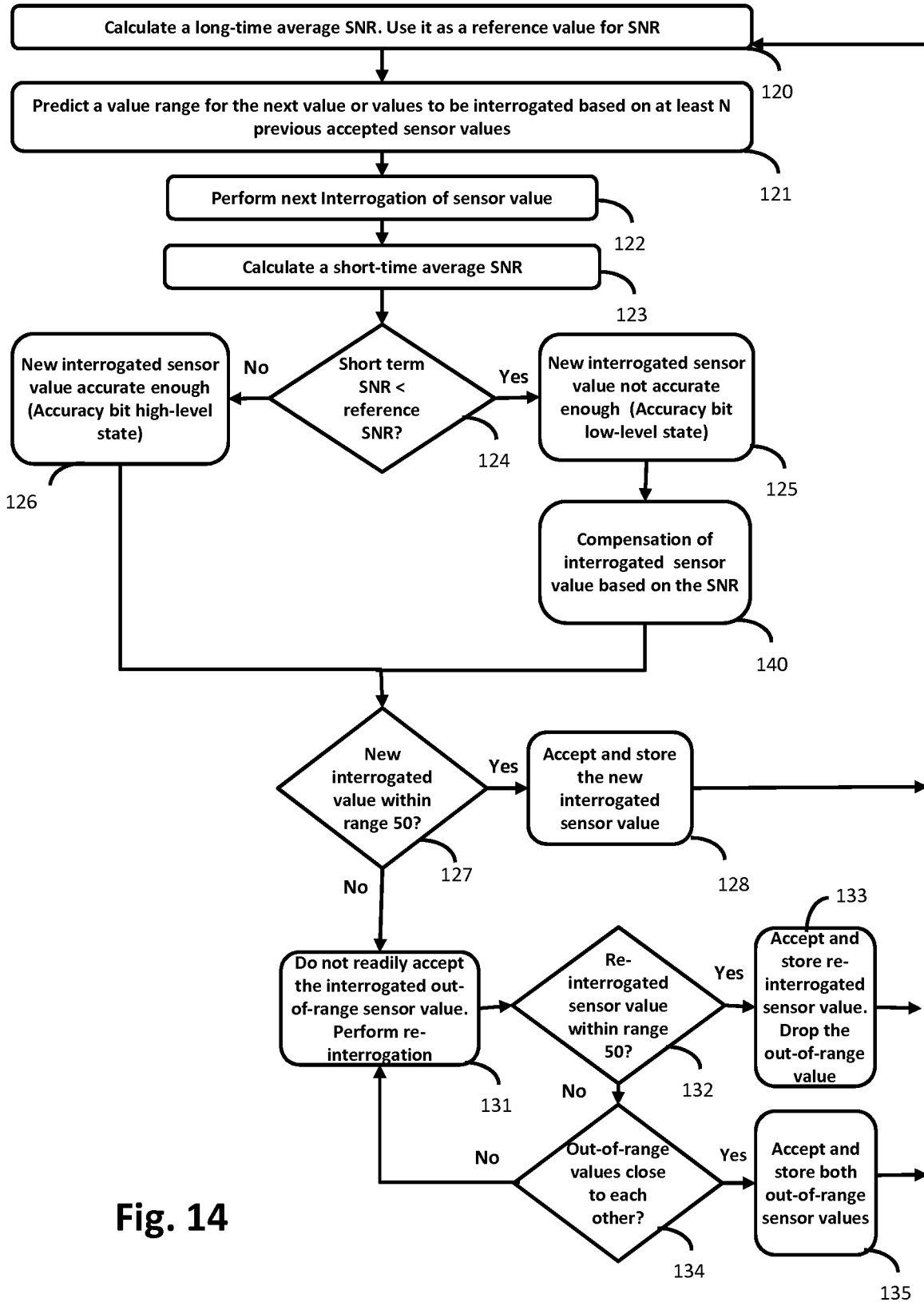


Fig. 14

12/12

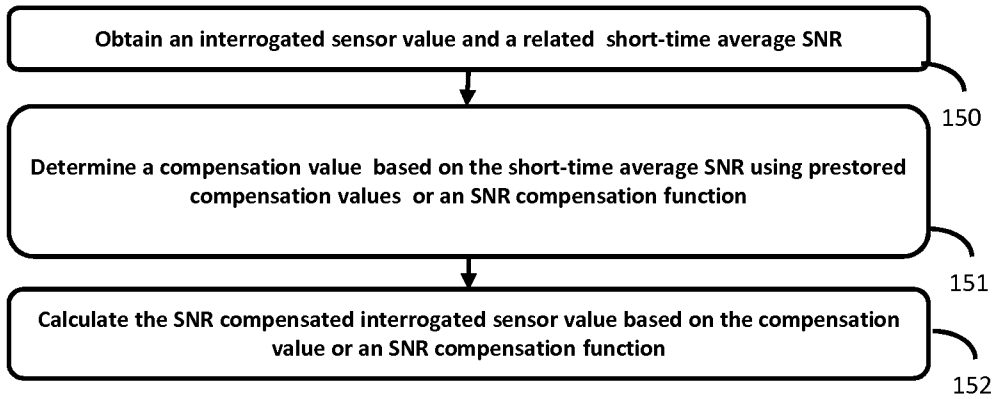


Fig. 15

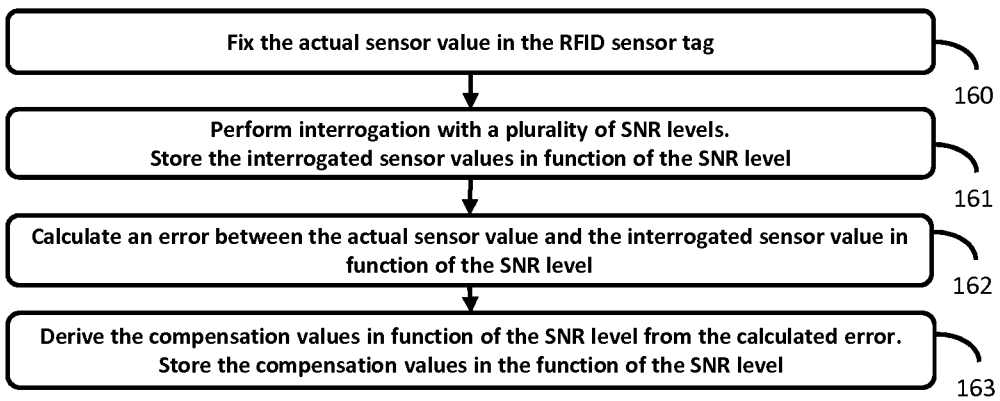


Fig. 16

INTERNATIONAL SEARCH REPORT

International application No.

PCT/FI2015/050487

A. CLASSIFICATION OF SUBJECT MATTER

See extra sheet

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

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

IPC: G06K, G08C

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

FI, SE, NO, DK

Electronic data base consulted during the international search (name of data base, and, where practicable, search terms used)

EPO-Internal, WPI, Google Scholar, IEEE Xplore

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 2006197652 A1 (HILD, S. et al.) 07 September 2006 (07.09.2006) abstract; Figs. 1-3; paragraphs [0026]-[0061]	1-3, 19-20
X	US 2013265139 A1 (NUMMILA, K. et al.) 10 October 2013 (10.10.2013) abstract; paragraphs [0036]-[0044], [0051]-[0055], [0059], [0106], [0109], [0121]-[0130], [0133]-[0134], [0140]-[0151], [0250]	1, 19-20
A	US 2012319862 A1 (NAGY, M. et al.) 20 December 2012 (20.12.2012) the whole document	1-20
A	US 8410906 B1 (DACUS, F. et al.) 02 April 2013 (02.04.2013) the whole document	1-20

 Further documents are listed in the continuation of Box C.
 See patent family annex.

* Special categories of cited documents:	"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
"A" document defining the general state of the art which is not considered to be of particular relevance	"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone
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"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)	"&" document member of the same patent family
"O" document referring to an oral disclosure, use, exhibition or other means	
"P" document published prior to the international filing date but later than the priority date claimed	

Date of the actual completion of the international search

23 September 2015 (23.09.2015)

Date of mailing of the international search report

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INTERNATIONAL SEARCH REPORT
Information on Patent Family Members

International application No.
PCT/FI2015/050487

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CLASSIFICATION OF SUBJECT MATTER

IPC
G06K 7/10 (2006.01)
G08C 17/02 (2006.01)
G06K 19/07 (2006.01)