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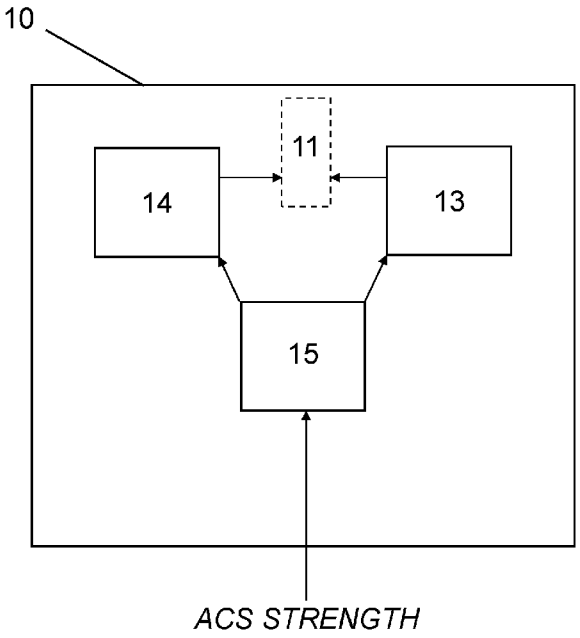
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(54) **Title:** RADIO FREQUENCY COMMUNICATION DEVICE FOR LOW POWER COMMUNICATION



(57) **Abstract:** Disclosed is a Radio Frequency communication device, RF communication device, (10) wherein said RF communication device (10) comprises a signal transmitting circuitry comprising tunnel diode oscillator circuitry, TDO circuitry, (13) and a Radio Frequency Switch Circuitry, RF switch circuitry (14); a detection and control unit (15) configured to detect the strength of an RF Ambient Carrier Signal, RF ACS. The RF communication device (10) is configured to selectively backscatter said ACS based on the strength of said detected ACS. Also disclosed is a Radio Frequency backscatter system, RF backscatter system, (1) that comprises an Ambient Carrier Signal Emitter, ACS emitter, (21), a tunnel diode oscillator circuitry, TDO circuitry, (22) and at least one Radio Frequency backscatter tag, RF backscatter tag, (23).

[Continued on next page]

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RADIO FREQUENCY COMMUNICATION DEVICE FOR LOW POWER COMMUNICATION

TECHNICAL FIELD

The proposed technology generally relates to a radio frequency communication device. More specifically it relates to a radio frequency communication device for low power communication. Even more specific it refers to a low power radio frequency communication device that selectively utilizes backscattering for transmissions.

BACKGROUND

Recent years have seen a rapid growth of sensing applications. These applications are commonly enabled through battery-powered devices. However, large-scale deployments with such devices suffer from high cost, i.e., tens to hundreds of USD per device, overhead of maintenance for replacing depleted batteries, and deployment inconvenience due to bulky form factor of devices. Thus, battery-powered sensor devices present a significant challenge to the vision of ubiquitous sensing. As a result, there has been a growing interest in battery-free sensor tags [4, 9]. Sensor tags are RF communication devices that operate without requiring batteries. Sensor tags may eliminate the need for batteries by operating on energy that is harvested from ambient sources such as light or wireless signals. It is, however, challenging to transmit on minuscule and intermittent energy using conventional wireless transmission mechanisms [4, 5, 9, 10].

Backscatter communication overcomes this limitation by enabling wireless transmissions at tens of uWs of power [4, 5, 9, 10]. Consequently, backscatter has emerged as the mechanism of choice to enable battery-free sensor tags.

Backscatter enables wireless transmissions by reflecting or absorbing ambient wireless signals [5, 7]. This process is realized by changing the impedance of the antenna, an operation that can be performed at sub-μW of power [7] which leads to very low power consumption of backscatter systems. Backscatter as a transmission mechanism is not new; one of the first systems was demonstrated more than half a

century ago. Backscatter mechanisms have also been used for decades in RFID systems. Although the underlying concept of backscatter communication has been known for decades, it is recently that backscatter systems have made significant progress. Recent systems are able to generate commodity wireless transmissions such as WiFi [5], ZigBee [4], BLE [3] and LoRa [9], or achieve a large (km) communication range [9, 10]. These advances in backscatter systems have also enabled novel applications.

Despite this success, limitations that hinder practical deployments remain. Backscatter systems require the presence of a strong ambient carrier signal, ACS. This requires the tag to be located in close proximity, e.g., 1m, of a strong ACS emitter, > 500 mW, to achieve the highest and often practical range [5, 10]. Even backscatter systems that leverage ambient signals instead of a dedicated ACS emitter encounter this problem. Ambient backscatter systems achieve a range that is sufficient to enable many applications when the backscatter tag is in proximity to a RF signal source, i.e., near a TV [7] or located near a WiFi or any other wireless device [4,11,12]. Furthermore, the strong ACS may also cause co-existence issues for other wireless devices that are sharing the spectrum.

The proposed technology aims to provide mechanisms and devices that at least alleviates the problems associated with some of the obstacles that lingers within the technical field.

SUMMARY

It is an object to provide a Radio Frequency communication device, RF communication device that improves low power communication.

It is in particular an object to provide a Radio Frequency communication device, RF communication device that enables transmission without requiring a strong ACS, or even in the absence of a ACS.

It is another object of the proposed technology to provide a Radio Frequency, RF, backscatter system that provides improved transmission characteristics even in cases with a weak ACS.

These and other objects are met by embodiments of the proposed technology.

According to a first aspect, there is provided a Radio Frequency communication device, RF communication device. The RF communication device comprises an antenna arrangement, a signal transmitting circuitry comprising tunnel diode oscillator circuitry, TDO circuitry, and a Radio Frequency Switch Circuitry, RF switch circuitry and a detection and control unit configured to detect the strength of an RF Ambient Carrier Signal, RF ACS. The detection and control unit is configured to control the RF communication device such that the RF switch circuitry backscatters the ACS when a detected ACS strength is above a first threshold strength and control the RF communication device such that the TDO circuitry generates a TDO RF signal when a detected ACS strength is below a second threshold strength, lower than said first threshold strength. The detection and control unit is also configured to otherwise controlling the TDO circuitry to backscatter the ACS.

According to a second aspect, there is provided a Radio Frequency backscatter system, RF backscatter system, that comprises an Ambient Carrier Signal Emitter, ACS emitter, a tunnel diode oscillator circuitry, TDO circuitry, and at least one Radio Frequency backscatter tag, RF backscatter tag.

The proposed technology enables a RF communication device to have a low power communication mode using backscattering even in cases where the ACS is weak or absent. This yields in turn a more flexible backscattering RF communication device that can also be used in environments without a dedicated ACS emitter.

Other advantages will be appreciated when reading the detailed description.

BRIEF DESCRIPTION OF THE DRAWINGS

The embodiments, together with further objects and advantages thereof, may best be understood by making reference to the following description taken together with the accompanying drawings, in which:

FIG. 1 is a schematic block diagram illustrating a RF communication device according to the proposed technology.

FIG. 2 is a schematic block diagram illustrating a particular embodiment of a RF communication device according to the proposed technology.

FIG. 3 is a is a schematic block diagram illustrating a particular embodiment of a RF communication device according to the proposed technology.

FIG. 4 is a is a schematic block diagram illustrating another particular embodiment of a RF communication device according to the proposed technology.

FIG. 5 is a is a schematic block diagram illustrating yet another particular embodiment of a RF communication device according to the proposed technology.

FIG. 6 is a is a schematic block diagram illustrating still another particular embodiment of a RF communication device according to the proposed technology.

FIG. 7 is a is a schematic block diagram illustrating a particular embodiment of a RF communication device according to the proposed technology that comprises an exemplary TDO circuitry.

FIG. 8 is a schematic illustration of a RF communication device according to an example of the proposed technology.

FIG. 9 is a schematic illustration of a RF communication device according to an example of the proposed technology.

FIG. 10 illustrates how a tunnel diode is biased within a subset of the region of negative resistance.

FIG. 11 is a graph illustrating the spectrum of a tunnel diode oscillator. It shows a signal generated in the 868 MHZ band with a peak biasing power of 57 μW.

FIG. 12 is a schematic diagram of a RF communication mechanism that comprises an antenna arrangement, TDO circuitry, RF switch, control and detection logic to select between TDO and RF switch, and a circuitry to detect the strength of the ACS.

FIG. 13 is a graph illustrating the phase noise of a tunnel diode oscillator.

FIG. 14 is an illustration of a particular indoor experiment of the proposed technology.

FIG. 15 is a graph illustrating the spectrum of a tunnel diode oscillator subject to injection locking.

FIG 16 is a graph illustrating how the resonant frequency of a tunnel diode changes with the bias voltage.

FIG. 17 is a graph illustrating how the frequency of a tunnel diode oscillator drifts over a period of six hours.

FIG. 18 illustrates the outcome of a through the wall experiment performed by using the proposed technology.

FIG. 19 is a graph illustrating a multi-floor experiment performed by utilizing the proposed technology.

FIG. 20 is a graph illustrating a through the wall backscattering experiment utilizing the proposed technology.

FIG. 21 illustrates a tunnel diode switch over mechanism.

FIG. 22 provides a block diagram illustration of a RF communication device according to the proposed technology.

FIG. 23 provides a schematic illustration of a back scatter system according to the proposed technology.

DETAILED DESCRIPTION

Throughout the drawings, the same reference designations are used for similar or corresponding elements.

Generally, all terms used herein are to be interpreted according to their ordinary meaning in the relevant technical field, unless a different meaning is clearly given and/or is implied from the context in which it is used. All references to a/an/the element, apparatus, component, means, step, etc. are to be interpreted openly as referring to at least one instance of the element, apparatus, component, means, step, etc., unless explicitly stated otherwise. The steps of any methods disclosed herein do not have to be performed in the exact order disclosed, unless a step is explicitly described as following or preceding another step and/or where it is implicit that a step must follow or precede another step. Any feature of any of the embodiments disclosed herein may be applied to any other embodiment, wherever appropriate. Likewise, any advantage of any of the embodiments may apply to any other embodiments, and vice versa. Other objectives, features and advantages of the enclosed embodiments will be apparent from the following description.

For a better understanding of the proposed technology, it may be useful to begin with a brief overview of the technical field and the contribution from the proposed technology.

There has been an ongoing interest in backscatter communication. Recent systems show the ability to generate WiFi [4, 5], Bluetooth [3], ZigBee [4], and LoRa [9] transmissions at tens of μWs of power consumption. Other efforts transmit over large distances, kilometres, [9, 10]. All of these systems need a strong ACS emitter and require that the tags are located in proximity to the ACS emitter to achieve the highest communication range. The constraint of proximity to a strong ACS emitter hinders potential application scenarios. In contrast, the proposed technology enables a large range even when the ACS is weak, for example, when the tag is not close to the ACS emitter.

The work presented herein is related to backscatter systems that reflect ambient

signals, and do not require a dedicated ACS emitter. Ambient backscatter reflects TV signals [7] and requires the vicinity of TV towers. Other systems such as Interscatter [4], HitchHike [11] can achieve sufficient range only in proximity to the ambient signal source e.g., a WiFi router or LoRa node. The proposed technology overcome these limitations and introduces a new modality that enables wireless transmissions for sensor tags without requiring any ambient signal.

Kimionis et al. design a reflection amplifier using a RF transistor with a gain as high as 10.2 dB in the 900 -930 MHz band at a power consumption of 325 μW [6]. Amatao et al. develop a reflection amplifier using a tunnel diode that achieves a gain as high as 40 dB in the 5.8 GHz band while consuming 45 uWs of power [1, 2]. Further, they demonstrate improvements in range using a signal analyzer as a receiver. We design the proposed technology on Amatao et al. [1,2] and obtain e.g., a reflection amplifier for the widely used 868MHz band. We experimentally demonstrate that as the carrier signal strength increases, a conventional backscatter tag designed using RF switch starts to outperform the tunnel diode reflection amplifier. Therefore, we design a low-power switchover mechanism to select between the reflection amplifier and the conventional tag depending on the strength of the ambient carrier signal. We are the first to demonstrate improvements in range using tunnel diodes with commodity radio transceivers as receivers, which enables a ubiquitous deployment of backscatter readers [3, 5, 10]. Finally, we also experimentally demonstrate the ability of the tunnel diode oscillator, TDO, to enable transmissions without requiring ACS for sensor tags.

Recent systems use commercial precision oscillators to support frequency shift backscatter [10]. The power consumption of these oscillators increases with frequency. This becomes prohibitively energy-expensive for sensor tags at higher frequencies; for example, they consume 2 mW at a frequency of 10 MHz [10]. Zhang et al. [12] overcome the energy limitations of commercial oscillators by trading off accuracy for power consumption. They design a ring oscillator that oscillates at a frequency of 20 MHz at 21 uW of power, to enable frequency- shift backscatter. However, all of these designs are unsuitable to support ACLT for sensor tags, as ACLT requires oscillators operating at hundreds of MHz at tens of uWs of power consumption. The proposed technology improves on this by using a TDO as part of the communication device.

The technology in the present disclosure is not the first to use tunnel diodes to improve the range of backscatter systems, and the presented technology build on existing works [1,2]. However, when compared to these existing works, there are significant differences as the proposed technology is the first to integrate a tunnel diode in a long-range backscatter system [10], and demonstrate orders of magnitude improvement in communication range when receiving with commodity radio transceivers. Also, we propose and design a mechanism to enable operation of tunnel diode based tag with ACS's of diverse strengths. Building on earlier works that use a tunnel diode as an oscillator [8], we demonstrate experimentally that tunnel diodes can function as an oscillator for sensor tags that can now communicate without an ACS.

Having described some of the background art and how the proposed technology improves them, we will now describe the communication device that is proposed in the present disclosure. The proposed communication device overcomes at least some of the problems that are highlighted above and it also addresses the fact that backscatter systems require in particular the presence of a strong ACS at the tag, a restriction that usually limits the application scenarios.

To achieve these purposes the proposed technology provides a Radio Frequency communication device, RF communication device, 10. The RF communication device 10 comprises a signal transmitting circuitry comprising tunnel diode oscillator circuitry, TDO circuitry, 13 and a Radio Frequency Switch Circuitry, RF switch circuitry 14. The RF communication device 10 also comprises a detection and control unit 15 configured to detect the strength of an RF Ambient Carrier Signal, RF ACS. The RF communication device 10 is also configured to selectively backscatter the ACS based on the strength of the detected ACS.

The RF communication device specified above is schematically illustrated in the block diagram of FIG. 1. The RF communication device 10 detects an ACS by means of the detection and control unit 15. Based on the outcome of the detected ACS, i.e., the strength of the same, the RF communication device is configured to selectively backscatter the ACS. If for example the detected ACS is weak, it may be backscattered by allowing the TDO circuitry 13 to generate a TDO RF signal to be transmitted by the antenna arrangement 11. This corresponds to an embodiment of

the proposed technology where the RF communication device 10 is further configured to selectively generate a TDO RF signal based on the strength of the detected ACS. If the ACS is deemed to be strong, the ACS may instead be backscattered by allowing the RF switch circuitry 14 to backscatter the ACS via the antenna arrangement 11.

Another particular embodiment of the proposed technology provides a Radio Frequency communication device, RF communication device 10 that comprises an antenna arrangement 11, a signal transmitting circuitry comprising tunnel diode oscillator circuitry, TDO circuitry, 13 and a Radio Frequency Switch Circuitry, RF switch circuitry 14. The RF communication device 10 also comprises a detection and control unit 15 that is configured to detect the strength of an RF Ambient Carrier Signal, RF ACS, and configured to control the RF communication device 10 such that:

• when a detected ACS strength is above a first threshold strength the RF switch circuitry 14 backscatters the ACS,

• when a detected ACS strength is below a second threshold strength, lower than the first threshold strength, the TDO circuitry 13 generates a TDO RF signal, and

• otherwise controlling the TDO circuitry 13 to backscatter the ACS.

The RF communication device specified above is schematically illustrated in the block diagram in FIG. 1. The RF communication device 10 detects an ACS by means of the detection and control unit 15. The detection and control unit 15 compares the detected ACS strength with a pre-determined pair of threshold strengths, a first and a second threshold strength, where the first threshold strength is larger than the second threshold strength. If the comparison yields that the detected ACS strength is above the first threshold strength the detection and control unit 15 controls the RF communication device so that the RF switch circuitry 14 backscatters the ACS via the antenna arrangement 11. If on the other hand the comparison yields that the detected ACS strength is below a second threshold strength, or even absent, that is to say no ACS was detected, the detection and control unit 15 controls the RF communication device so that the TDO circuitry 13 generates a TDO RF signal to be transmitted by the antenna arrangement 11. Finally, if the comparison yields that the detected ACS strength lies in between the first and second threshold strength the detection and control unit 15 controls the RF communication device so that the TDO circuitry 13

backscatter the ACS via the antenna arrangement 11. This procedure ensures that the RF communication device 10 may function when there is a strong ACS present, that is to say, when the ACS strength is above the first threshold strength, in which case either the RF switch circuitry 14 or the TDO circuitry 13 backscatters the ACS and when there is a weak ACS strength, that is to say, when the ACS is below the second threshold, in which case the TDO circuitry 13 generates a TDO RF signal to be transmitted by the antenna arrangement. The particular mechanism that is enabled by the proposed RF communication device ensures that a low power transmission mode can be used by a single device even in the presence of a weak ACS source or in the absence of such a source. It should be noted that the antenna arrangement 11 might be an antenna arrangement that is common for both the RF switch circuitry 14 and the TDO circuitry 13, that is, the RF switch circuitry 14 and the TDO circuitry 13 feeds the same antenna arrangement. It is however also possible that the different circuitries are provided with a dedicated antenna.

The first threshold may as an example be selected from the interval [-35, 0] dBm, and the second threshold may as an example be selected from the interval [-85, -34] dBm when decibel is used as a measure of signal strength. Other intervals are however possible. The second threshold should however be smaller than the first interval.

Here we provide an example of the above-mentioned embodiment. Consider a RF communication device in presence of the ACS source which device operates in backscatter mode. In such a case, the RF communication device is usually arranged some distance away from the ACS source. The ACS source generates a radio signal, referred to as an ACS above, which is incident on the RF communication device 10. Next, the RF communication device reflects or absorbs the ACS signal through the RF switch circuitry 14 or the TDO circuitry 13 together with the antenna arrangement 11. When the ACS signal incident at the RF communication device is strong, i.e., greater than first threshold, e.g. -30 dBm, the RF communication device backscatters the signal through RF switch circuitry 14. However, when the ACS signal incident at the RF communication device is weaker than the first threshold but larger than the second threshold, e.g. -80 dBm, the TDO circuitry backscatters the incident ACS.

Some of the embodiments contemplated herein will now be described more fully with reference to the accompanying drawings. Other embodiments, however, are

contained within the scope of the subject matter disclosed herein, the disclosed subject matter should not be construed as limited to only the embodiments set forth herein; rather, these embodiments are provided by way of example to convey the scope of the subject matter to those skilled in the art.

According to another embodiment of the proposed technology there is provided a RF communication device 10 that further comprises an optional energy harvesting circuitry 12 that is adapted to harvest energy from ambient energy sources. This embodiment is schematically illustrated in the block diagram of FIG. 2. The addition of an energy harvesting circuitry 12 to the RF communication device 10 provides an additional benefit since it can extract energy to be used for the operation of at least part of the device and, under beneficial circumstances, allow for a battery-free RF communication device.

A particular way to incorporate an energy harvesting circuitry 12 to the RF communication device 10 is to include it in a self-sustainable sensor circuitry together with a general sensor. According to a such an embodiment of the proposed technology there is provided a RF communication device 10 that further comprises self-sustainable sensor circuitry 16, where the self-sustainable sensor circuitry 16 comprises the energy harvesting circuitry 12 and a sensor that is configured to provide a sensor signal representative of at least one physical phenomenon. FIG. 3 provides a schematic block diagram illustration of such an RF communication device 10.

According to still another embodiment of the proposed technology there is provided a RF communication device 10 that further comprises a processing component 18 that is adapted to process and digitize the provided sensor signal. FIG. 4 provides a block diagram illustration of such RF communication device. In such a device the self-sustainable sensor circuitry 16 obtains a measure of a physical phenomenon. The sensor output is forwarded to the processing component 18 that digitizes the sensor output, and optionally also process the digitized signal based on some processing scheme relevant for the application at hand. The digitized signal is then forward to the detection and control unit for further preparation and subsequent transmission according to the proposed transmission mode with switched backscattering and TDO RF signals.

By way of example, the processing component 18 of the above embodiment may in certain applications be included in the detection and control unit 15. This yields a robust RF communication device with a reduced number of active components. The output of the self-sustainable sensor circuitry 16 would in such an embodiment be connected to a corresponding input on the detection and control unit 15. The detection and control unit 15 would have several functions in this embodiment, it should be able to provide a digitization of the sensor output, it should be able to detect ACS strength and it should be able to control the RF communication device to transmit according to the proposed transmission mode where backscattering is switched between a RF switch circuitry and a TDO circuitry depending on the strength of the ACS. It should be noted that the RF communication device 10 in these particular embodiments could act as a transmitting sensor where the transmission is done using batter-free low power transmissions. Such a sensor can find many applications where a continuous need for sensor readings are needed, for example with regard to devices connected to the Internet Of Things.

Yet another embodiment of the proposed technology provides a RF communication device 10 that further comprises modulation circuitry 17 that is configured to modulate the sensor signal and configured to provide a modulation signal to the TDO circuitry 13 and to the RF switch circuitry 14. There is in other words provided a RF communication device where the output of the modulation circuitry may be modulated by a sensor signal and provided to the TDO Circuitry 13 and the RF switch circuitry 14. A RF communication device 10 according to this embodiment is depicted schematically in the block diagram of FIGs. 5 and 6.

FIG. 22 provides an additional illustration of such a RF communication device but where the device is also provided with an antenna arrangement 11, a sensor 16 and an energy harvester.

The RF communication device 10 may be equipped with a self-sustainable sensor circuitry 16 that is configured to obtain a measure of a physical phenomenon, this is however optional.

By way of example, the proposed technology provides a RF communication device 10 wherein the modulation circuitry 17 is configured to provide Amplitude Shift Keying modulation, ASK modulation, or Frequency Shift Keying modulation, FSK modulation.

A particular embodiment of the proposed technology provides a RF communication device 10 wherein the TDO circuitry 13 comprises a tunnel diode 31, a biasing circuit 33 for configuring the tunnel diode into a region of negative resistance, RNR, and a matching network 35 for setting the resonant oscillating frequency. FIG. 7 provides a schematic block diagram of such a TDO circuitry where the TDO circuitry is connected to an antenna arrangement 11. The TDO circuitry 13 may in certain embodiments be provided with a dedicated antenna arrangement. A RF communication device 10 comprising such a TDO circuitry 13 is depicted in FIG. 7. A more detailed version of the RF communication device comprising also a modulation circuitry is depicted in FIG. 12. Here the various components comprised in the sub-circuitry of a possible TDO circuitry is depicted.

A particular example of the proposed technology, schematically shown in FIG. 1, provides a Radio frequency, RF, communication device 10 comprising an antenna arrangement 11, an energy harvesting circuitry 12, a tunnel diode oscillator, TDO, circuitry 13, a RF switch circuitry 14, and a detection and control circuitry 15. The detection and control circuitry is configured to detect an RF ambient carrier signal, ACS, strength and configured to control the communication device 10 such that:

- if the ACS strength is above a first threshold strength, the RF switch circuitry 14 backscatters the ACS signal,
- if the ACS strength is below a second threshold strength, the TDO circuitry 13 generates a TDO RF signal, and
- otherwise controlling the TDO circuitry 13 to backscatter the ACS signal.

This particular RF communication device may in addition comprise a self-sustaining sensor circuitry 16 that is configured to provide a sensor signal that is representative of at least one physical phenomenon and that comprises the energy harvesting circuitry 12, and modulation circuitry 17 that is configured to modulate the sensor signal and configured to provide a modulation signal to the TDO circuitry 13 and to the RF switch circuitry 14. That is to say, the proposed technology provides a RF communication device that comprises an energy harvesting circuitry 12 and where the output of the modulation circuitry may be modulated by the provided sensor signal and provide the modulation signal to the TDO Circuitry 13 and the RF switch circuitry 14.

The proposed technology also provides a Radio Frequency backscatter system, RF backscatter system that utilizes the proposed mechanisms to enable transmissions using Ambient Carrier Signals, ACSs. To this end there is provided a Radio Frequency backscatter system, RF backscatter system, 1 that comprises an Ambient Carrier Signal Emitter, ACS emitter, 21, a tunnel diode oscillator circuitry, TDO circuitry, 22 and at least one Radio Frequency backscatter tag, RF backscatter tag, 23. The backscatter tag 23 may in particular comprise a RF communication device 10 according to what has been described above. A backscatter system according to the proposed technology is schematically illustrated in FIG. 23.

For the purpose of this disclosure not that an ACS emitter in a backscatter system usually consists of a dedicated radio communication device such as RFID reader, software defined radio, or other wireless devices like WiFi routers that provide necessary ACS signal. An ACS signal is a sinusoidal high frequency radio signal generated through a circuitry comprising of components including high frequency oscillators. In a backscatter system, the ACS signal is generated from the emitter device. This signal is incident at a RF scatter tag. At the scattering tag, based on the information to be transmitted, the properties, e.g., the impedance, of the antenna is altered through the use of the RF switch. In the simplest case, the antenna either reflects or absorbs the incident ACS signal, thus generating changes in the reflected signal corresponding to the information that are to be transferred.

Based on what has been described above a general system suitable to utilize the proposed technology can generally be divided into three components: a generic battery-free sensor tag that we call TunnelTag that transmits using the TunnelScatter mechanism, an edge device comprising one or more RF receivers to receive and interpret sensor readings, and an optional ACS emitter. As the sensor tag referred to as TunnelTag, and in particular the mechanism referred to as TunnelScatter are our key contributions, they will be discussed in detail in the example section provided below. In the following sections the term TunnelTag refers to a sensor device comprising a RF communication device which may also be called TunnelScatter, a control and digitization unit, modulating element, and sensor and energy harvesting element. The term TunnelScatter on the other hand refers to a RF communication mechanism that comprises the antenna arrangement, TDO circuitry, RF switch,

control and detection logic to select between TDO and RF switch, and a circuitry to detect the strength of the ACS.

EXAMPLES AND EVALUATION

In order to significantly improve the communication range of backscatter systems when the ACS is weak or even when it is absent, the disclosed technology present a specific mechanism and communication device that is designed using a semiconductor device tunnel diode which shows a region of negative resistance, RNR [8]. The presence of RNR enables the use of tunnel diodes in a variety of RF applications, for example, as oscillators [8], amplifiers [2], and as will be described herein, to enhance backscatter systems.

At a high level, our system performs a series of steps as follows: First, the TunnelTag using a self-sustaining sensor harvests energy from an ambient source and charges s supercapacitor. TunnelTag uses this energy to support the operation of the tag. Next, when there is an event of interest such as a temperature change, the polymorphic processing pipeline, PPP, depending on the energy harvesting condition, processes and digitizes the sensor readings at a high or a low resolution. Finally, the digitized sensor readings are transmitted using the TunnelScatter mechanism and received and interpreted by an edge device.

Summary of results. We focus on the results obtained using TunnelScatter, the key component of the system.

•TunnelScatter, unlike backscatter, enables transmissions without requiring an ACS. It enables us to communicate through several walls covering a distance of 18 m.

•When backscattering, TunnelScatter adapts to strength of the ACS: with a weak carrier signal, it backscatters with amplification achieving multi-floor communication. In comparison, a tag based on state-of-the-art LoRea [10] under similar conditions achieves a range of 3 m.

Tunnel Diodes. A tunnel diode is a two-terminal device with a p-n junction that has

an order of magnitude higher doping concentration than the junctions of conventional diodes. Therefore, tunnel diodes have a very thin depletion region at the junction. Due to the thin depletion region, tunnel diodes demonstrate an effect called quantum tunneling effect [8]. This effect causes a region of negative resistance, i.e., as we increase the voltage beyond the peak voltage, the current through the device decreases, as we show in FIG 10. FIG 10 illustrates tunnel diode characterization upon biasing and operating the tunnel diode within a subset of the region of negative resistance, which we call region of interest**.** The region of negative resistance makes it possible to design tunnel diode-based RF amplifiers and oscillators, as we demonstrate in this paper. In this paper, we use a tunnel diode GE 1N3712, due to its low peak voltage (0.65 mV), and current consumption (1 mA). We bias the tunnel diode to a voltage between 65 mV and 150 mV to keep it within the region of interest (RNR).

Ambient carrier signal emitter. In the presence of an ACS, TunnelScatter operates in ABT mode, and transmits sensor readings using backscatter communication. To generate the ambient carrier signal, we use a software-defined radio (SDR), USRP B200 , as ACS emitter. We use an SDR to generate the ACS, as it allows us to control the strength of the ACS at the tag. This, in turn, enables us to perform controlled experiments with weak ACS strengths where amplification using tunnel diodes is important. However, our system can also employ commodity and low-cost radio transceivers to generate the ACS, which enables commodity devices to act as ACS emitters. To support the use of commodity radio transceivers for ACS generation, we can either build on LoRea [10] or Interscatter [4].

Battery free Tags and Applications. We employ TunnelScatter on battery-free sensor tags that we call TunnelTags. TunnelTags can communicate even without an ACS. Therefore, the ACS emitter is an optional component to our tag. A complete system also includes an edge device to receive and process the transmitted signals.

To sense physical phenomena, we design a sensing component that we call self-sustaining sensor. Many sensing phenomena can also be the source of energy. We design the self-sustaining sensor by coupling an energy harvester with a sensor. This supports battery-free operation due to low power consumption of sensors.

TUNNELTAG We show an overview of TunnelTag in FIG 8, it is divided into three components; self-sustaining sensor, PPP, and TunnelScatter mechanism.

In this section, we describe TunnelTag's components with a greater emphasis on the TunnelScatter mechanism.

Self-sustaining Sensor TunnelTags' main task is to sense physical phenomena. We couple the sensing and harvesting components to design what we call a self-sustaining sensor. It can track different physical phenomena, while operating by harvesting energy from ambient energy sources. Coupling the sensing and harvesting components has the advantage that some phenomena can also be a source of energy. Thus, by enabling the sensor to both harvest energy and sense, we reduce the complexity and cost of its design.

Sensors. TunnelTag supports diverse sensors to sense different phenomena such as temperature and vibrations. As the next step in the operation of the TunnelTag, i.e., processing sensor readings through the PPP, requires an analog signal, we restrict ourselves to sensors with analog outputs. To support operations on harvested energy, we look for sensors that sense at a low power consumption. We list such sensors in Table 1.

Table 1: Examples of low power sensors that can be integrated with self-sustaining sensors.

SENSOR TYPE	NAME	POWER
ACCELEROMETER	ADXL 377	540 μW
MICROPHONE	ADMP801	17 μW
TEMPERATURE	LM94021	13.5 μW

Before sensor readings can be transmitted, they need to be digitized. The energy harvesting conditions can vary significantly during a deployment. However, digitization using high resolution ADCs can be prohibitively energy expensive under poor energy

harvesting conditions.

Tunnel diode oscillator. In ACLT mode, TunnelScatter locally generates a signal using a tunnel diode oscillator. The signal is then modulated using amplitude shift keying (ASK). We design the TDO to operate at a frequency band of 868 MHz, a license-free band for communication in major parts of the world. The TDO can also be tuned to operate at other bands. We design the TDO taking advantage of the fact that RNR enables tunnel diodes to oscillate at high RF frequencies. In fact, tunnel diodes were used to design RF oscillators more than half a century back [8]. However, they are not widely used due to their limited peak current which restricts the output power. We use the limited power consumption to our advantage to design RF oscillators for battery-free sensor tags.

We show the schematic of the TDO in the top right part of FIG 12. The TDO is designed using a tunnel diode, a biasing circuit, a matching network, and an antenna. The matching network (CM1 and LM1) sets the resonant oscillating frequency. The biasing circuit configures the tunnel diode into the RNR which is essential to enable oscillations.

To support operation without an ACS, we design the ambient carrier-less transmissions, ACLT, mode of the TunnelScatter mechanism. This mode uses a tunnel diode as an RF oscillator to generate a signal at a frequency band of 868 MHz. This signal is then modulated using amplitude shift keying, ASK, to encode sensor readings. To perform this operation, we have to maintain the tunnel diode in RNR, for which we consume a peak biasing power of 57 μW. The ACLT mode enables sensor tags to communicate without the ACS, which existing backscatter systems require.

TunnelScatter operates with enhanced capabilities in the presence of an ACS. We observe that in the presence of an ACS, the tunnel diode oscillator, TDO, latches onto the ACS through a process called injection locking [8] and behaves as a reflection amplifier [2]. This results in a significant gain while backscattering. Based upon this concept, we design a long-range mode we call amplified backscatter transmissions, ABT. This mode encodes sensor readings using frequency shift keying, FSK, and shows orders of magnitude improvement in communication range as compared to LoRea [10], when backscattering a weak ACS. However, when the ACS is strong, we

observe that the reflection amplifier performs poorly compared to a conventional backscatter tag. Hence, we also design a mechanism that senses the ACS' strength and uses the tunnel diode only when the ACS is weak. This ensures that TunnelScatter exploits the full range of the ACS strengths that an application may encounter.

Edge device. In our system, at the edge device, we do not use SDRs or RFID readers to receive backscatter transmissions, as is commonly done. Instead, we leverage a low-cost radio transceiver (< 10 USD), the Texas Instruments CC1310 with a high sensitivity (-124 dBm), as a receiver. Reception using low cost transceivers enables ubiquitous deployments of backscatter readers [10]. The transceiver can be used to receive FSK backscatter transmissions when TunnelScatter operates in ABT mode, or to function as an energy detector to receive amplitude-modulated transmissions when TunnelScatter operates in ACLT mode. Hence, we equip the edge device with two CC1310 receivers, to receive transmissions from TunnelScatter operating in either ABT or ACLT mode.

To receive the amplitude-modulated transmissions, we continuously gather the energy measurements by performing Received Signal Strength, RSS, sampling at the frequency of the transmissions from the TunnelTag. We reconstruct the sensor readings from the received samples by first determining the average noise floor, and then by approximating all values above it to binary ones, and below it to binary zeroes. The bitrate in the ACLT mode is restricted by the RSS sampling rate of the CC1310 receiver, which we found in our implementation to be 10 kHz restricting bitrate to 1 kbps. We believe this is an engineering constraint, as FS-Backscatter [12] demonstrates a bitrate of 50 kbps, using ASK and RSS sampling. On the other hand, to receive backscatter transmissions, we build on LoRea, and demonstrate a bitrate of 2.9 kbps in this paper, while we can also support bitrates as high as 100 kbps, as reported by LoRea [10]. Once the sensor readings are received, the edge device can process them according to the target application.

If any other backscatter modulator such as WiFi, LoRa, Zig- Bee or Bluetooth are used, the edge device can be equipped with respective transceiver.

Low Power Transmissions using TunnelScatter As the last step in the operation of TunnelTag, the digitized sensor readings are transmitted to an edge device for further processing using the TunnelScatter mechanism.

Overview. The TunnelScatter mechanism uses tunnel diodes to significantly enhance the design of existing backscatter tags [5, 10, 11]. At a high level, the mechanism works as follows: TunnelScatter passively senses and adapts to the strength of the ACS. In the presence of a strong ACS, TunnelScatter backscatters the signal using a conventional RF-switch similar to LoRea [10]. When the ACS is weaker, for example, when the tag is not close to the ACS emitter, the mechanism backscatters the weak ACS with a no- table gain using a tunnel diode as a reflection amplifier [1,2], thereby achieving a significant improvement in communication range. Finally, in the absence of an ACS, the mechanism generates a signal locally using tunnel diodes, modulates the signal with sensor readings, and transmits it. Thus, TunnelScatter enables communication in diverse ACS conditions. We show the TunnelScatter hardware prototype in FIG 9. Before discussing the detailed design of TunnelScatter, we provide a brief background on tunnel diodes.

Ambient Carrier-less Transmissions. As discussed earlier, a major obstacle that hinders the deployment of backscatter systems is the requirement of a strong ACS. Conventional transceivers do not encounter this problem, as they generate the carrier signal locally. However, these transceivers are too energy expensive for battery-free sensor tags since they consume mWs of peak power [3, 5] due to the use of active analog components such as RF oscillators. Hence, to transmit without an ACS, TunnelScatter requires a low-power oscillator operating at hundreds of MHz while consuming μWs of power. Operation at hundreds of MHz ensures that we can communicate in the commonly used ISM bands. On the other hand, as discussed earlier state- of-the-art backscatter systems design or use μWs oscillators operating at tens of MHz [12]. TunnelScatter tackles this challenge through a tunnel diode-based RF oscillator.

TDO performance. We evaluate the TDO, as it dictates the communication ability of the TunnelScatter mechanism. Like any wireless system, the TDO can be affected by ambient noise or interfering signals, and hence we perform the measurements in an anechoic chamber. First, we connect the TDO to a Keithley 2810 RF signal analyzer

through a cable and capture the spectrum plot. FIG 11 provides a graph that shows the result of the experiment. It shows that most of the energy is contained within the resonant frequency of the TDO, i.e, 867.4 MHz. We note that the resonant frequency itself can change with bias voltage or can drift slightly over time, as we evaluate in Section 5.1. The peak strength of the signal generated by TDO was -19 dBm.

Phase noise is commonly used to characterize the performance of oscillators. We investigate the phase noise using the RF signal analyzer. In FIG 13, we observe that we have a higher phase noise as compared to precision oscillators,

Amplified Backscatter Transmissions. In many scenarios, an ACS might be present. State-of-the-art backscatter systems [5, 9, 10, 11, 12] achieve a large range only when the ACS is sufficiently strong. TunnelScatter overcomes this limitation through the amplified backscatter transmitter (ABT) mode. The ABT mode takes advantage of the fact that in the presence of an ACS, the TDO demonstrates a behavior called injection locking [1,2, 8]. This allows the TDO to backscatter the ACS and achieve a significant gain also with a weak ACS.

Injection locking. This is a phenomenon where an oscillator is influenced by a signal from another oscillator operating in the vicinity of the resonant frequency of the first oscillator. Injection locking as a phenomenon was discovered in the late 16th century by Christiaan Huygens, who observed two pendulum clocks on the wall synchronizing with each other.

We use the TDO's injection locking to backscatter a weak ACS with significant gain which makes the tunnel diode act as a reflection amplifier [1,2]. In this mode, the TDO uses some energy to bias the diode to amplify, modulate and reflect back the ACS. To demonstrate this phenomenon, we set up TunnelTag approximately 1 m away from an ACS emitter (SDR), and co-locate an RF spectrum analyzer. First, we observe the signal generated from the TDO in absence of an ACS. Next, we generate a carrier signal using the SDR. Fig- ure 8 shows that the TDO latches onto the impinging signal and is influenced by the ACS. In fact, this also enhances the harmonics produced by the backscatter process. Injection locking also reduces the phase noise of the oscillator. In our experiments, we have also observed that the injection locking ability of the TDO is influenced by the strength of

the ACS, and the offset of the ACS from the resonant frequency of the TDO. We observe that the stronger the external signal is, the further it can be from the resonant frequency of TDO, and yet result in injection locking. Due to space constraints, we do not present this result.

Amplified Backscatter Transmitter. We design the ABT mode by building on the injection locking of TDO and the FSK modulator presented by LoRea [10]. Since the tunnel diode acts as a reflection amplifier, this mode can achieve a significant range improvement over LoRea when reflecting a weak ACS. We show our high-level circuit design in Figure 5. It works as follows: we generate the two frequencies to enable FSK transmissions, using low-power oscillators, LTC 6906. One of these signals is selected using a multiplexer according to the bit being transmitted. Next, this signal is fed to the biasing network which tunes the tunnel diode into the negative resistance region. In the presence of an ACS, it gets modulated and reflected back with a gain. We have measured the gain using a vector network analyzer (VNA) and found it to be as high as 35 dB at -60 dBm of input power. We note that the FSK modulator can also be replaced by other modulators such as those to support generation of WiFi, Bluetooth, ZigBee and LoRa signals. of the tunnel diode. The impedance of the tunnel diode is a function [2] of frequency (f), the bias voltage (V), RF input power (PRF), and temperature (T), i.e., Zi(f, R, PRF, T). This means, as we increase the strength of the incident carrier signal, PRF increases, which causes the impedance of the tunnel diode to change, which we, and Amato et al. [2] have also observed. On the other hand, the matching network (CMI and LMI) of the circuit is configured for a specific impedance value of the tunnel diode. Hence, there is a mismatch which contributes to the poor performance of the tunnel diode at higher ACS strength, which makes a conventional tag perform better when the ACS is stronger.

We overcome the above challenge with a switchover mechanism. We build this mechanism using a passive envelope detector that is also used on backscatter tags, We use a passive envelope detector to sense the ACS' strength, and based on the ACS strength, we switch in a range of conditions. The key highlights are: TunnelScatter enables communication through several walls in a non-line-of-sight environment in ACLT mode, using the tunnel diode oscillator. TunnelScatter allows communication through several floors of a building while backscattering (ABT mode)

a weak ACS. In a similar setting, a tag similar to LoRea [10] achieves a range of only 3 m. 5.1 Ambient Carrier-less Transmitter In this section, we evaluate the ability of TunnelScatter to communicate using the ACLT mode, i.e., in the absence of an ACS. Our experiments focus on the stability of the signal generated by the TDO, and the range achieved in a challenging non-line-of-sight (NLOS) scenario, between tunnel diode or the standard RF-switch (HMC190BMS8 **).**

In designing this mechanism, we take advantage of a limitation of envelope detectors, which is their poor sensitivity. Envelope detectors are designed using discrete components, and commonly have a sensitivity of approximately -40dBm. The poor sensitivity of envelope detectors ensures that they only output a signal when the ACS signal is sufficiently strong, which activates the conventional backscatter tag. On the other hand, when the ACS is weak, the mechanism selects the tunnel diode. We design the switchover mechanism using an ultra-low power multiplexer and comparator (TS 881).

EVALUATION OF THE PRESENTATION

In this section we evaluate different aspects of our system in a range of conditions. The key highlights are:

•TunnelScatter enables communication through several walls in a non-line-of-sight environment in ACLT mode, using the tunnel diode oscillator.

•TunnelScatter allows communication through several floors of a building while backscattering, ABT mode, a weak ACS. In a similar setting, a tag similar to LoRea [10] achieves a range of only 3 m.

Ambient Carrier-less Transmitter

In this section, we evaluate the ability of TunnelScatter to communicate using the ACLT mode, i.e., in the absence of an ACS. Our experiments focus on the stability of the signal generated by the TDO, and the range achieved in a challenging non-line-of-sight scenario, NLOS scenario.

Setup

To measure the stability of the TDO, we connect the TunnelScatter to a RF spectrum analyzer; Keithley 2810. We have seen that the TDO can be influenced by ambient RF noise, and hence we perform these measurements in an anechoic chamber. The ACLT mode transmits amplitude- modulated transmissions. To receive the transmissions, a CC1310 radio acts as energy detector, RSS sampling, similar to FS-backscatter [12]. We perform the experiment in an office, as shown in FIG 14. The walls between the rooms consist of insulated gypsum and are approximately 16 cm thick. The rooms are equipped with standard office equipment such as chairs, tables with drawers, and monitors.

Oscillator stability with bias voltage

To enable oscillations, the tunnel diode has to be biased to the negative resistance region, as shown in FIG 16. However, within this region, we observe that the frequency of the TDO is influenced by the bias voltage. To investigate this closer, we connect the biasing network of the TunnelScatter mechanism to an external waveform generator, Digilent Analog Discovery 2, which enables us to control the bias voltage. We change the bias voltage and observe the frequency of the TDO. We plot the results as the change in the bias voltage, and corresponding changes observed in the frequency of the TDO in FIG 11. Our results show that the frequency of the TDO changes linearly with the bias voltage. To counter this drift, we maintain a constant bias voltage on TunnelTag using an ultra-low power regulator (S-1313).

Oscillator stability over time

In this experiment, we look at the long-term stability of the TDO. As we consume significantly lower power compared to commercially available precision oscillators, we expect the TDO to be less stable. We provide a constant bias voltage to the TDO using a low- power regulator. We keep track of the frequency of the TDO at an interval of 6 s. We run the experiment for a duration of 6h. Figure 10 demonstrates the result of the experiment. Throughout the experiment, the frequency of the TDO varies slightly, but remains within 80 kHz of the initial frequency, with a standard deviation of 19 kHz. This is not a problem for our system, as we receive transmissions using ASK

and energy detectors, which are less impacted by small shifts in the frequency of the carrier signal. Further, in our experiments, we have noticed that under injection locking in ABT mode, the backscatter signal remains stable with little deviation, which enables reliable reception.

Through the wall communication. In this experiment, we investigate the ability of TunnelScatter to support communication without an ACS. Due to space constraints, we present only a range experiment. The receiver is placed at different distances from the tag. Our results in Figure 11 show that we are able to communicate through three walls despite the NLOS environment, at bitrates of 100 bps and 1 kbps. We cover a distance of 18 m. We observe slightly anomalous behavior around the second wall, which might be caused by the presence of metallic equipment in this location. As we had seen earlier, the TDO's output power is restricted to approx. -19 dBm. Yet, we are able to communicate through the wall due to the high sensitivity of the CC1310 receiver.

Amplified Backscatter Transmitter

We evaluate the ability of TunnelScatter to support backscatter transmissions. A line-of-sight (LoS) environment significantly improves the range of backscatter systems [10] and our system is no exception. Hence, we focus on challenging NLoS environments. We perform experiments indoors within our university building.

Setup

We use an SDR, USRP B200, as an ACS emitter. We equip both the SDR and the TunnelTag with a VERT900 antenna. For receiving the transmissions, we use the FSK mode on the CC1310, with parameters similar to those used by LoRea [10]. We use a frequency shift of 100 kHz to avoid self-interference [10], and bitrate of 2.9 kbps. We compare the ABT results with a tag similar to LoRea. We have verified that this tag achieves a communication range similar to the one reported for LoRea.

Multifloor communication

We evaluate the range improvement of TunnelScatter when backscattering with amplification with an ACS incident on the tag of a very low strength. We place the tag

at a distance of 1m from the ACS emitter (SDR) but configure the SDR to generate an ACS of strength of -27 dBm, which represents orders of magnitude lower strength compared to existing long-range systems [9, 10]. First, we measure range and reliability with a LoRea tag. Then we replace it with a TunnelTag.

FIG 19 demonstrates the result of the experiment. With the TunnelTag, we can communicate easily through four floors of the university building, while under similar settings, the LoRea tag achieves a range of only three meters. The experiment demonstrates that the TunnelScatter mechanism achieves a significant range improvement over the state-of- the-art backscatter LoRea tag [10].

Through the wall communication

Next, we evaluate the ability of TunnelScatter to operate in a challenging NLOS environment. We set up a carrier generator transmitting with a signal of strength 16 dBm, located 30 m away, separated by seven walls from the tag as shown in FIG 14. We experiment in a manner similar to the multifloor experiment described above.

FIG 20 demonstrates the result. FIG 20 illustrates through the wall backscatter, and shows that even when the ACS emitter is placed several walls away (30 m), the TunnelScatter enables the tag to communicate 15 m, going through several walls.

The LoRea tag is able to communicate only a few meters, and cannot communicate through the wall while the TunnelTag communicates through three walls covering a distance of 15 m.

Switchover mechanism

We evaluate the advantage of switching between a tunnel diode and a conventional RF switch for backscatter transmissions. This switchover happens depending on the strength of the ambient carrier signal incident on the tag. In the experiment, we place the TunnelTag at a distance of 1 m from the ACS emitter. We co-locate the tag with a spectrum analyzer to keep track of the incident ACS strength. We position a CC1310 receiver about 4 m from the tag. We keep track of the signal strength of the received transmissions at the CC1310 receiver.

FIG 21 demonstrates the results of the experiment. The figure depicts that the strength of the backscattered signal from the conventional tag increases with the strength of the ACS, similar to other backscatter systems [10]. The figure shows that the strength of the backscattered signal remains constant with the tunnel diode-based tag. At an ACS strength between -30 dBm and -40 dBm, the conventional tag starts to outperform the tunnel diode-based tag. These values of ACS strength provides a particular example of the first and second threshold disclosed herein.

As described in the earlier section with title Amplified Backscatter Transmissions, using the input from the passive envelope detector, TunnelScatter switches between tunnel diode and the standard RF switch. This makes certain that TunnelScatter adapts to the strength of the ambient carrier signal and ensures that the SNR of the backscattered signal is maximized at the receiver.

Power Consumption

We evaluate the power consumption of our system. As the ACS emitter and the edge device would be powered externally, we do not evaluate their power consumption.

Experiment setup

To measure the power consumption, we operate using a 2 V supply, as it decreases with the operating voltage [12]. We measure the power consumption by connecting a Fluke multimeter in series to the circuit to measure the current draw. To measure the power consumption of the TunnelScatter mechanism, we use a highly sensitive Keysight E36300 voltage supply.

TunnelScatter

Due to the low biasing voltage required by the tunnel diode, we measure the power consumption through the highly sensitive Keysight voltage supply. We observe that the tunnel diode consumes a peak biasing power of 57 μW, as we show in the Figure 3. This low power consumption for biasing is similar to other works that have used a tunnel diode as reflection amplifier operating at 5 GHz band [1,2]. The very low power consumption facilitates battery-free operation, while significantly improving the ability

to operate at a distance far away from the ACS emitter. The comparator, and standard RF-backscatter switch, each consume sub-μW of power. The envelope detector consumes no additional power. On the contrary, it can be used to harvest energy.

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CLAIMS

1. A Radio Frequency communication device, RF communication device, (10) wherein said RF communication device (10) comprises:
   - a signal transmitting circuitry comprising tunnel diode oscillator circuitry, TDO circuitry, (13) and a Radio Frequency Switch Circuitry, RF switch circuitry (14);
   - a detection and control unit (15) configured to detect the strength of an RF Ambient Carrier Signal, RF ACS;

   said RF communication device (10) being configured to selectively backscatter said ACS based on the strength of said detected ACS.

2. The RF communication device (10) according to claim 1, wherein said RF communication device is further configured to selectively generate a TDO RF signal based on the strength of said detected ACS.

3. The RF communication device (10) according to claim 2, wherein said detection unit further comprises a control unit (15) configured to control the RF communication device (10) such that:
   - when a detected ACS strength is above a first threshold strength the RF switch circuitry (14) backscatters the ACS;
   - when a detected ACS strength is below a second threshold strength, lower than said first threshold strength, the TDO circuitry (13) generates a TDO RF signal, and
   - otherwise controlling the TDO circuitry (13) to backscatter the ACS.

4. The RF communication device (10) according to any of the claims 1-3, further comprising an antenna arrangement (11).

5. The RF communication device (10) according to any of the claims 1-4, further comprising an energy harvesting circuitry (12) adapted to harvest energy from ambient energy sources.

6. The RF communication device (10) according to claim 5, further comprising self-sustainable sensor circuitry (16), said self-sustainable sensor circuitry (16) comprising said energy harvesting circuitry (12) and a sensor configured to provide a sensor signal representative of at least one physical phenomenon.

7. The RF communication device (10) according to claim 6, further comprising a processing component adapted to process and digitize said provided sensor signal.

8. The RF communication device (10) according to claim 7, wherein said processing component is included in said detection and control unit (15).

9. The RF communication device (10) according to claim 7 or 8, further comprising modulation circuitry (17) configured to modulate said sensor signal and configured to provide a modulation signal to said TDO circuitry (13) and to said RF switch circuitry (14).

10. The RF communication device (10) according to claim 9, wherein said modulation circuitry (17) is configured to provide ASK modulation and/or FSK modulation.

11. The RF communication device (10) according to any of the claims 1-10, wherein said TDO circuitry (13) comprises a tunnel diode, a biasing circuit for configuring the tunnel diode into a region of negative resistance, RNR, an antenna (11) and a matching network for setting the resonant oscillating frequency.

12. A Radio Frequency backscatter system, RF backscatter system, (1) comprising:
    - an Ambient Carrier Signal Emitter, ACS emitter, (21);
    - a tunnel diode oscillator circuitry, TDO circuitry, (22), and
    - at least one Radio Frequency backscatter tag, RF backscatter tag, (23).

13. The RF backscatter system (1) according to claim 12, wherein said RF backscatter tag (23) comprises a RF communication device (10) according to any of the claims 1-11.

1. A Radio Frequency communication device, RF communication device, (10) wherein said RF communication device (10) comprises:
   - a signal transmitting circuitry comprising tunnel diode oscillator circuitry, TDO circuitry, (13) and a Radio Frequency Switch Circuitry, RF switch circuitry (14);
   - a detection and control unit (15) configured to detect the strength of an RF Ambient Carrier Signal, RF ACS;

   said RF communication device (10) being configured to selectively backscatter said ACS based on the strength of said detected ACS,

   wherein said RF communication device is further configured to selectively generate a TDO RF signal based on the strength of said detected ACS, and

   wherein said detection unit and control unit (15) further comprises a control unit (15) configured to control the RF communication device (10) such that:
   - when a detected ACS strength is above a first threshold strength the RF switch circuitry (14) backscatters the ACS;
   - when a detected ACS strength is below a second threshold strength, lower than said first threshold strength, the TDO circuitry (13) generates a TDO RF signal, and
   - otherwise controlling the TDO circuitry (13) to backscatter the ACS.

2. The RF communication device (10) according to claim 1, further comprising an antenna arrangement (11).

3. The RF communication device (10) according to any of the claims 1-2, further comprising an energy harvesting circuitry (12) adapted to harvest energy from ambient energy sources.

4. The RF communication device (10) according to claim 3, further comprising self-sustainable sensor circuitry (16), said self-sustainable sensor circuitry (16) comprising said energy harvesting circuitry (12) and a sensor configured to provide a sensor signal representative of at least one physical phenomenon.

5. The RF communication device (10) according to claim 4, further comprising a processing component adapted to process and digitize said provided sensor signal.

6. The RF communication device (10) according to claim 5, wherein said processing component is included in said detection and control unit (15).

7. The RF communication device (10) according to claim 5 or 6, further comprising modulation circuitry (17) configured to modulate said sensor signal and configured to provide a modulation signal to said TDO circuitry (13) and to said RF switch circuitry (14).

8. The RF communication device (10) according to claim 7, wherein said modulation circuitry (17) is configured to provide ASK modulation and/or FSK modulation.

9. The RF communication device (10) according to any of the claims 1-8, wherein said TDO circuitry (13) comprises a tunnel diode, a biasing circuit for configuring the tunnel diode into a region of negative resistance, RNR, an antenna (11) and a matching network for setting the resonant oscillating frequency.

10. A Radio Frequency backscatter system, RF backscatter system, (1) comprising:
    - an Ambient Carrier Signal Emitter, ACS emitter, (21);
    - a tunnel diode oscillator circuitry, TDO circuitry, (22), and
    - at least one Radio Frequency backscatter tag, RF backscatter tag, (23),

    wherein said RF backscatter tag (23) comprises a RF communication device (10) according to any of the claims 1-9.

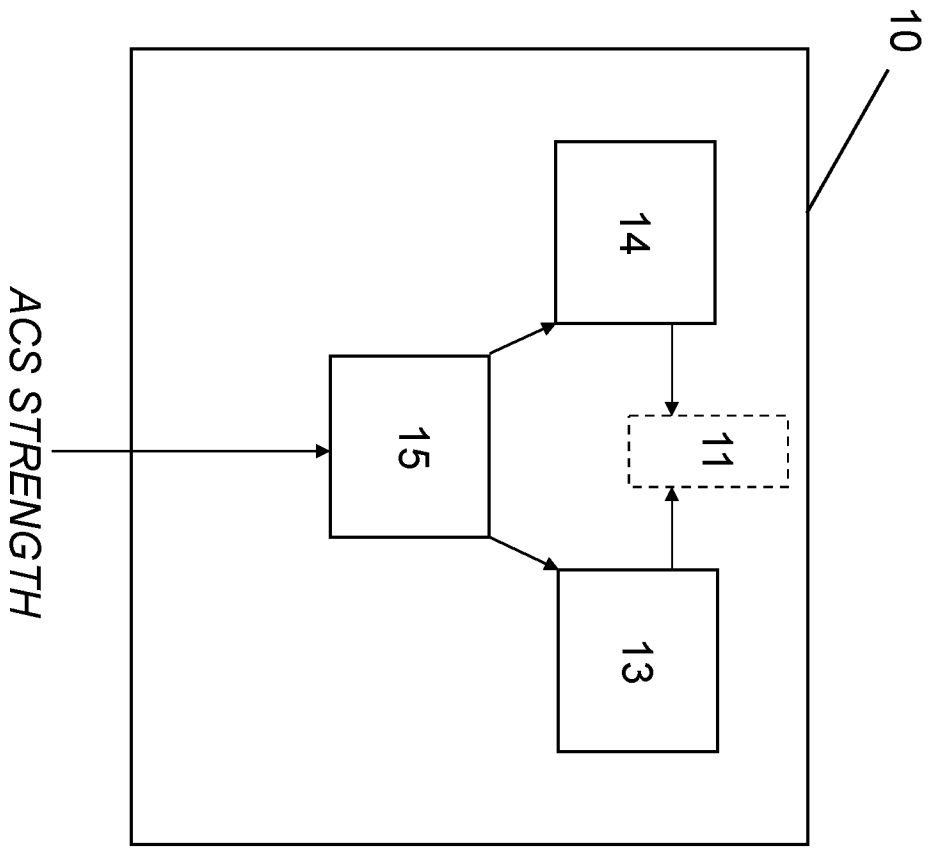


Fig. 1

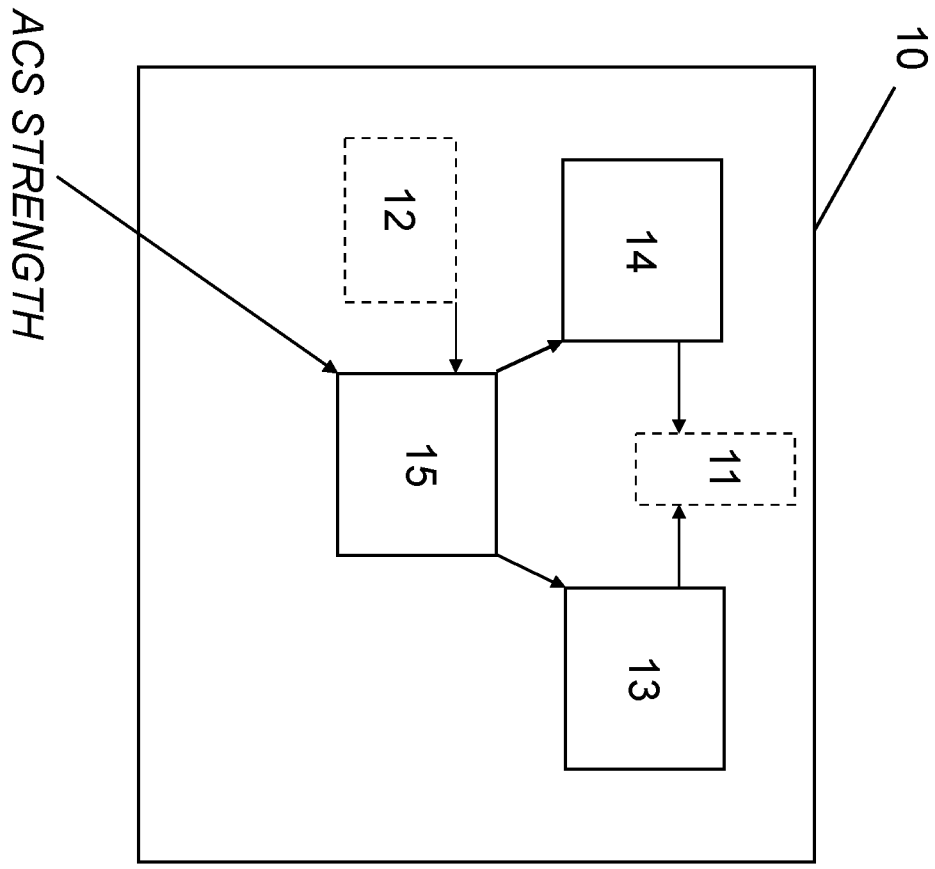


Fig.2

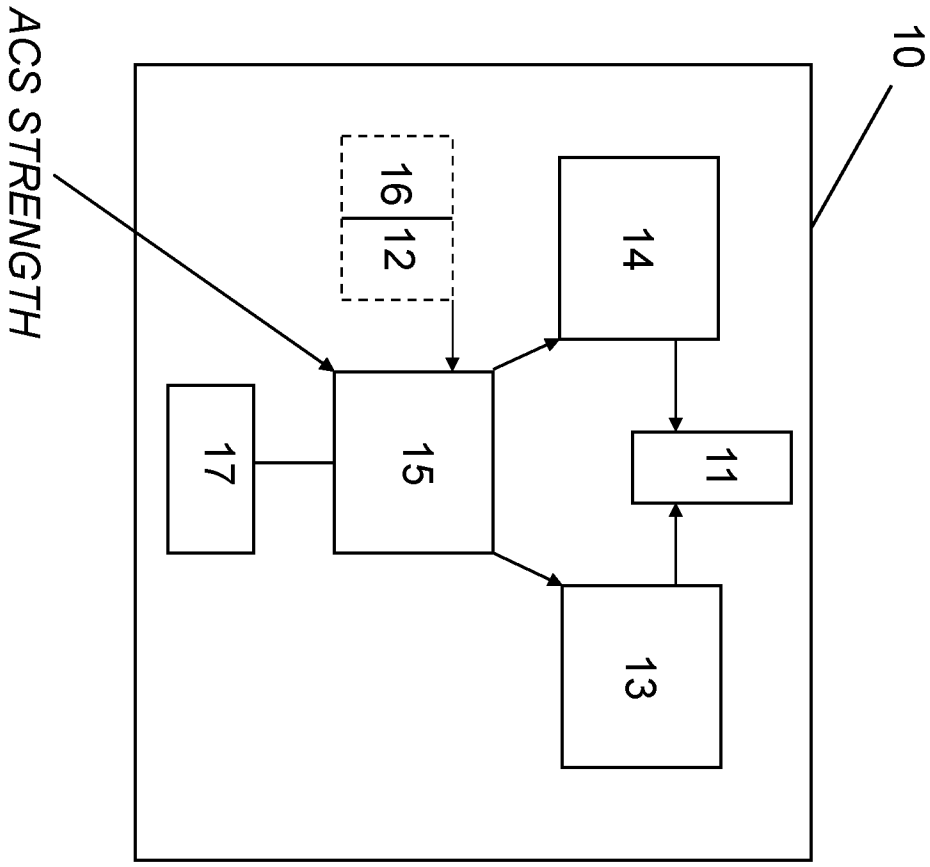


Fig.3

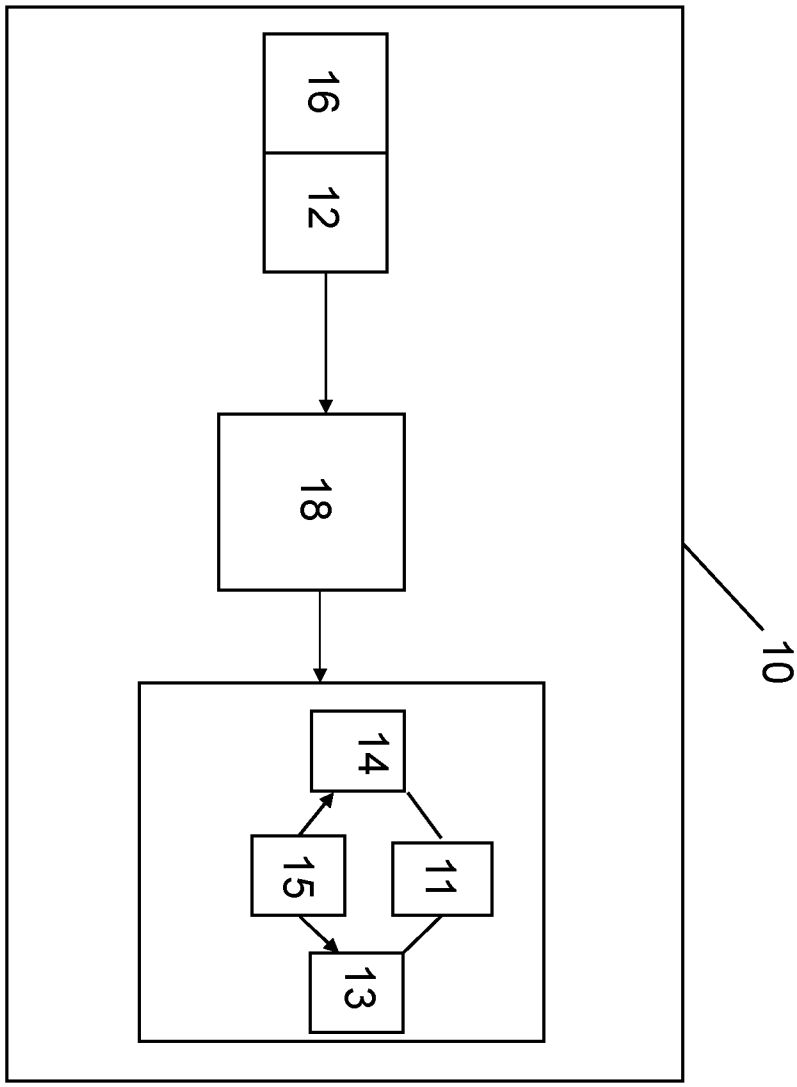


Fig.4

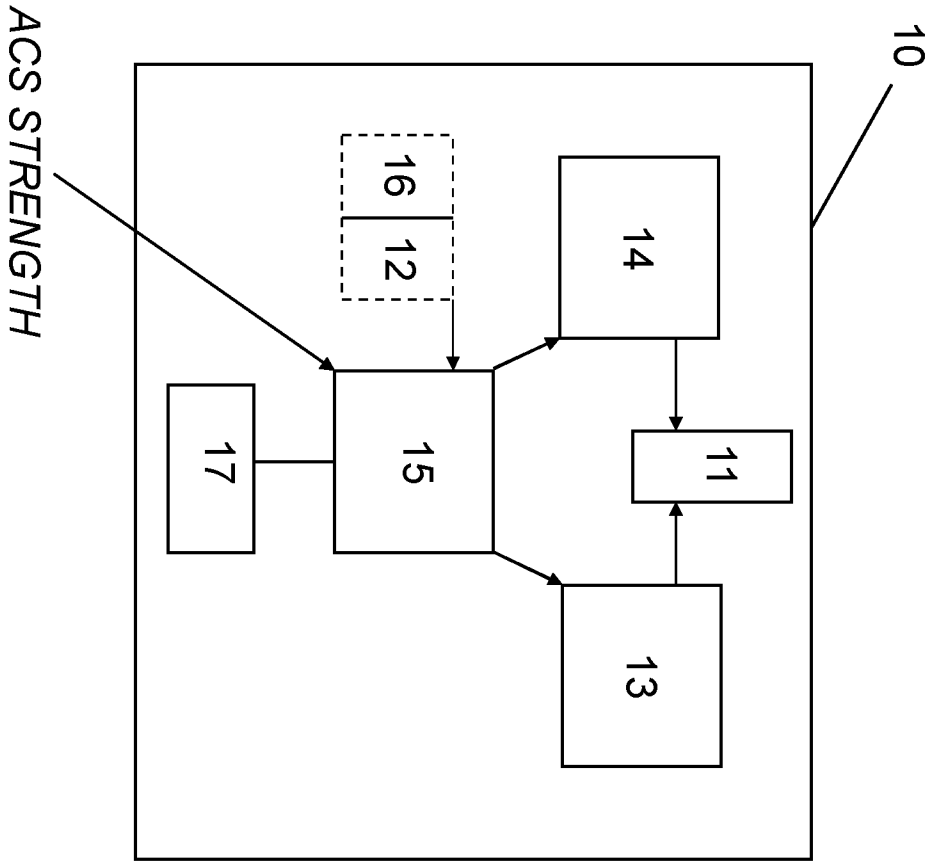


Fig.5

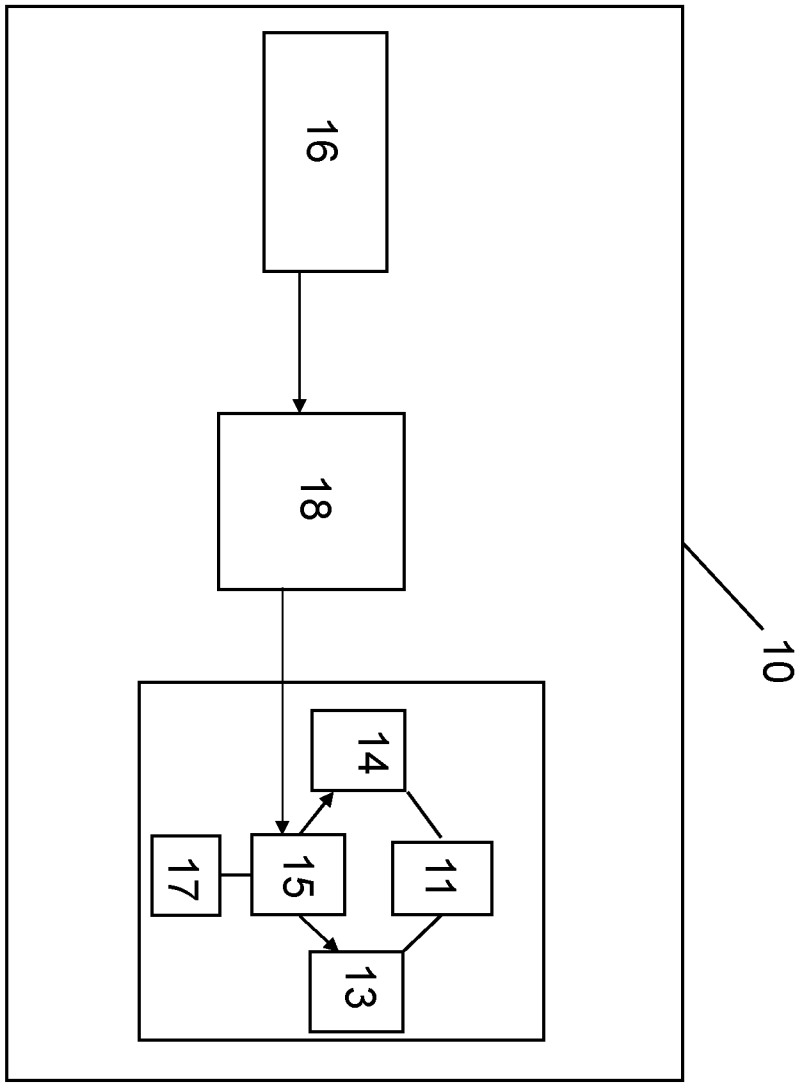


Fig.6

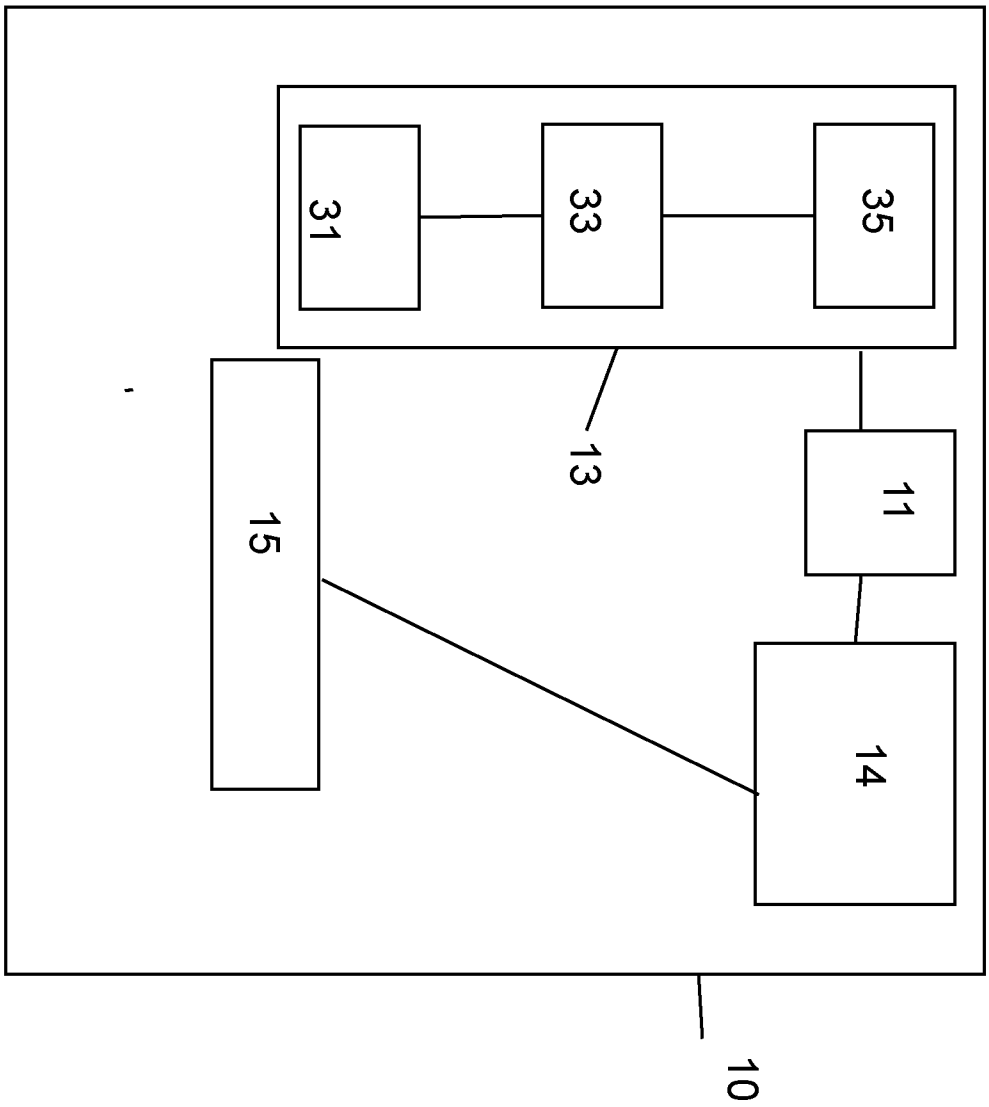


Fig.7

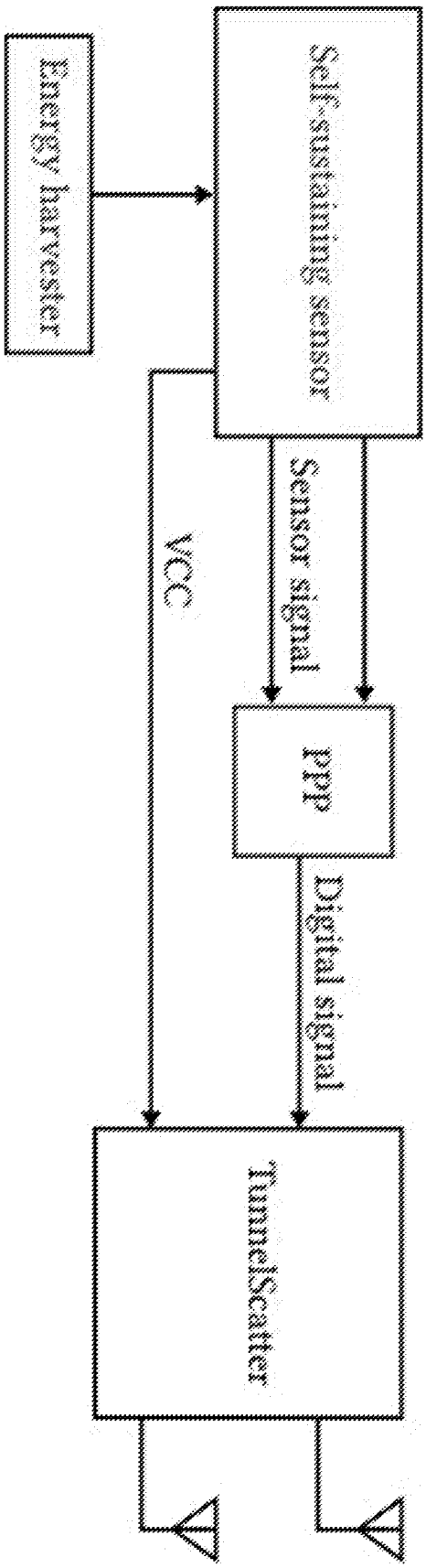

Energy harvester
Self-sustaining sensor
VCC
Sensor signal
PPP
Digital signal
TunneScatter

Fig.8

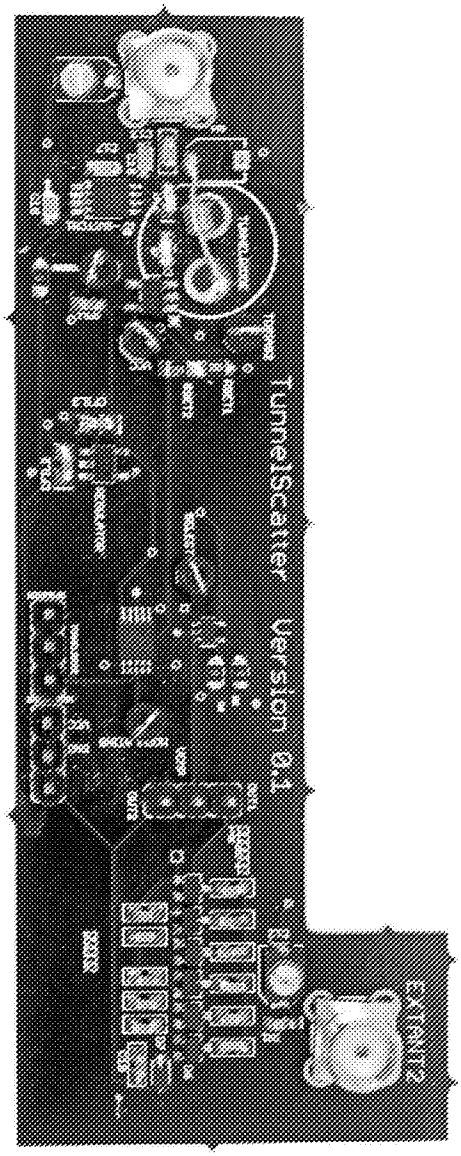


Fig. 9

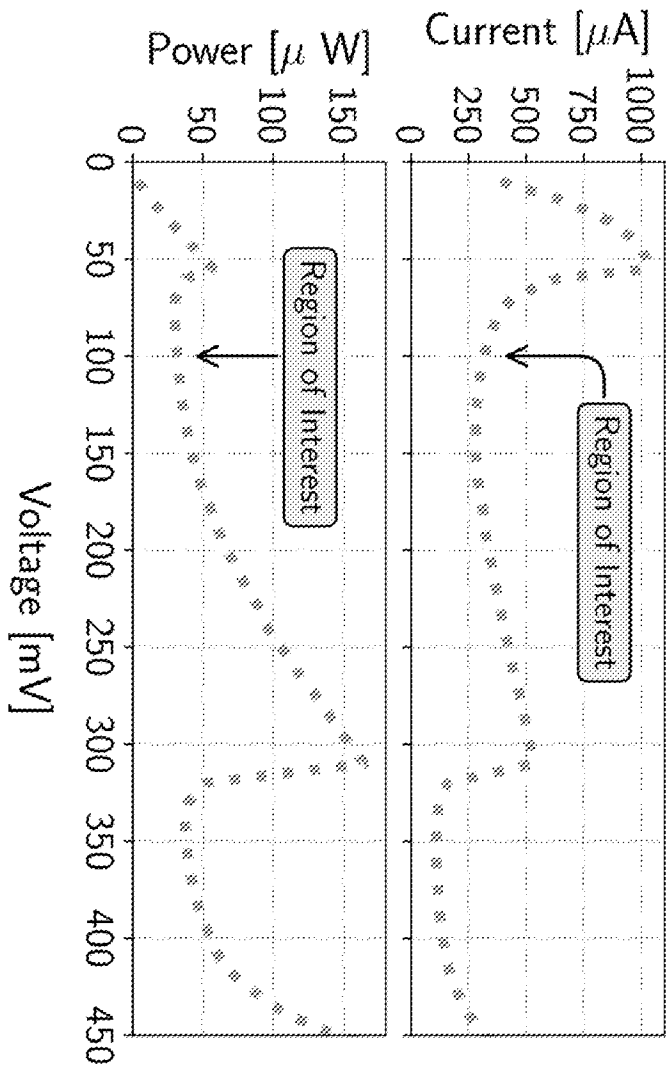

Power [μ W]
Current [μA]
Region of Interest
Region of Interest
Voltage [mV]
0
50
100
150
200
250
300
350
400
450
0
50
100
150
0
250
500
750
1000

Fig. 10

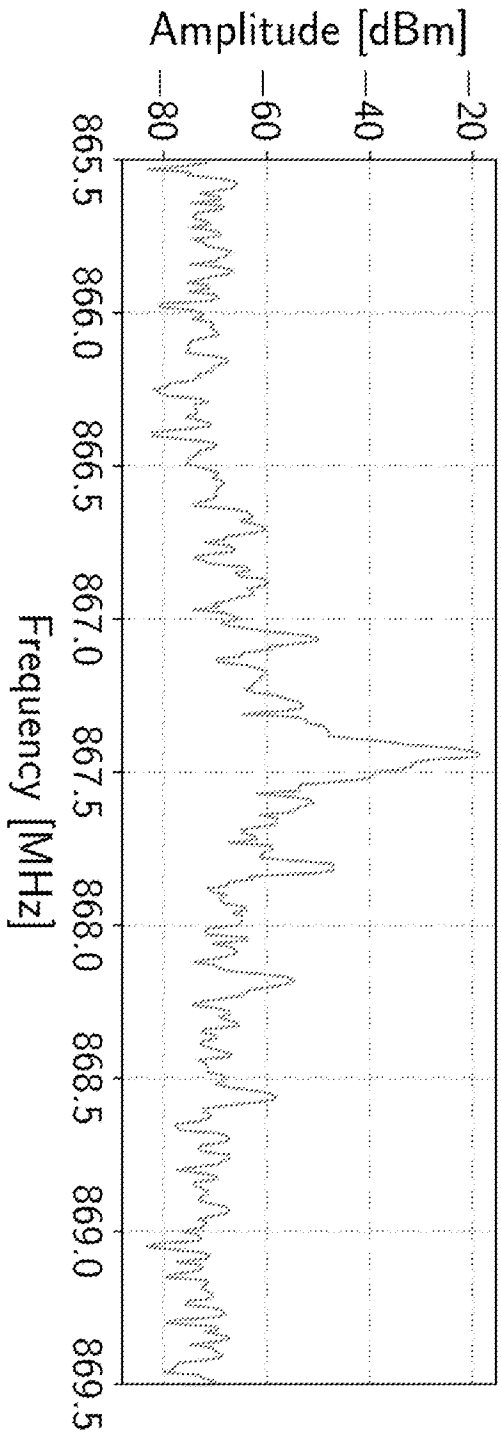

Amplitude [dBm]
−80
−60
−40
−20
Frequency [MHz]
865.5
866.0
866.5
867.0
867.5
868.0
868.5
869.0
869.5

Fig. 11

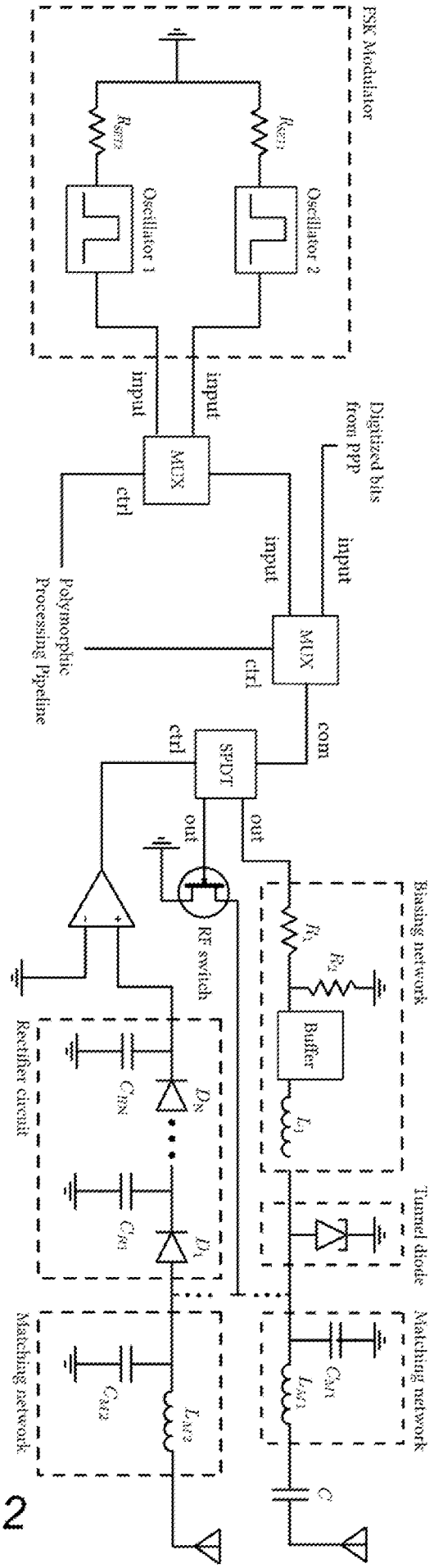

FSK Modulator
Oscillator 1
Oscillator 2
input
input
MUX
ctrl
Digitized bits from PEP
input
Polymorphic Processing Pipeline
input
MUX
ctrl
com
SPDT
ctrl
out
out
RF switch
Biasing network
Buffer
Rectifier circuit
Tunnel diode
Matching network
Matching network

Fig. 12

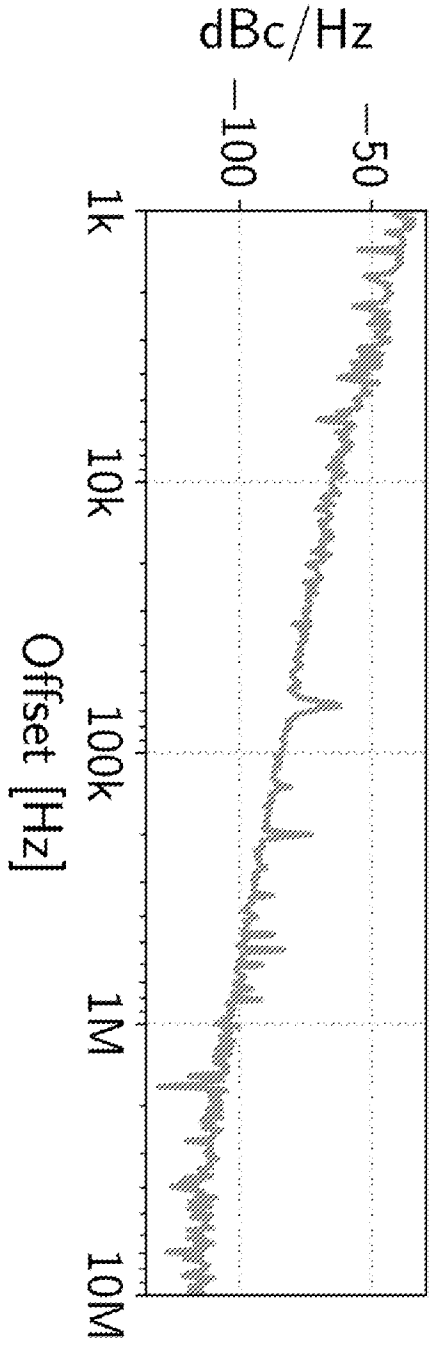


Fig. 13

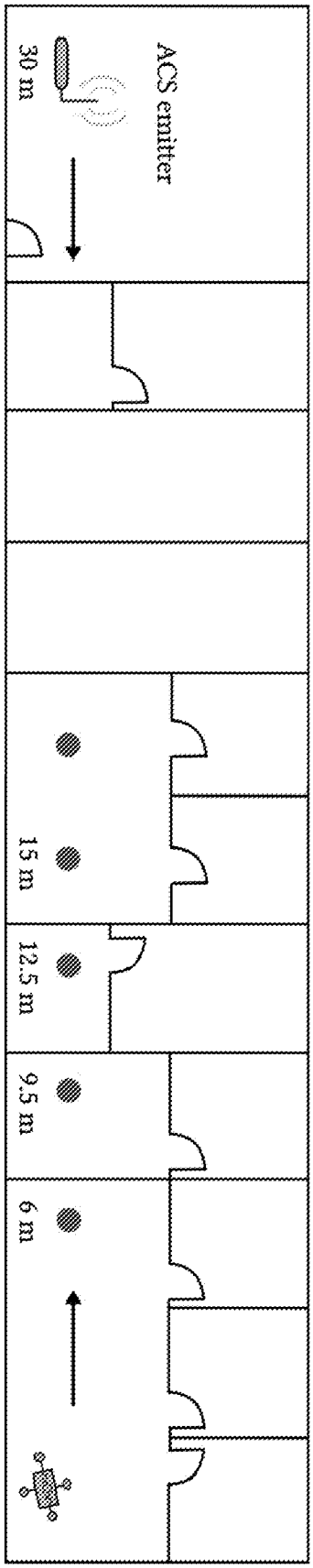


Fig. 14

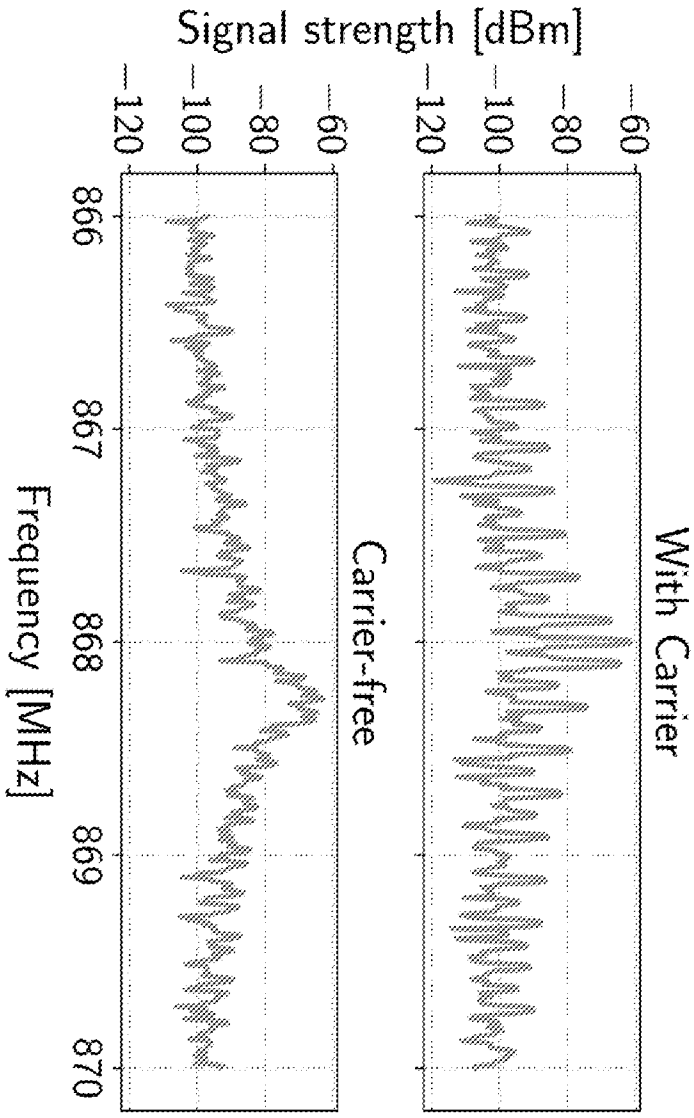

Signal strength [dBm]
−120
−100
−80
−60
866
867
868
869
870
Frequency [MHz]
Carrier-free
With Carrier

Fig. 15

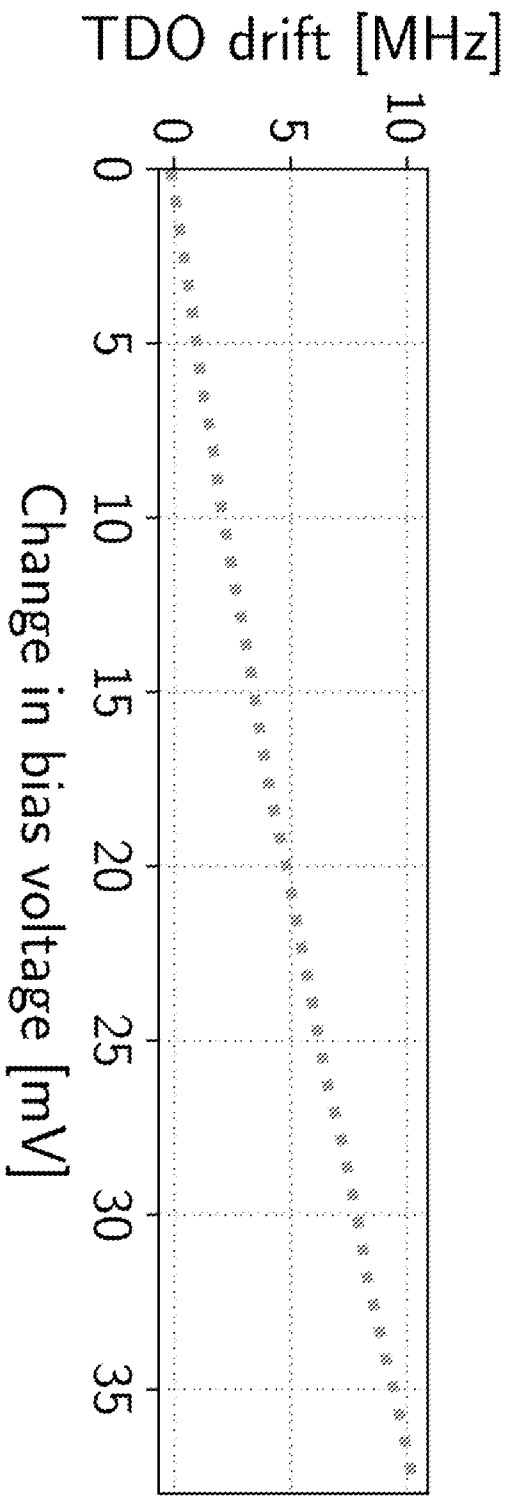

TDO drift [MHz]
0
5
10
Change in bias voltage [mV]
0
5
10
15
20
25
30
35

Fig. 16

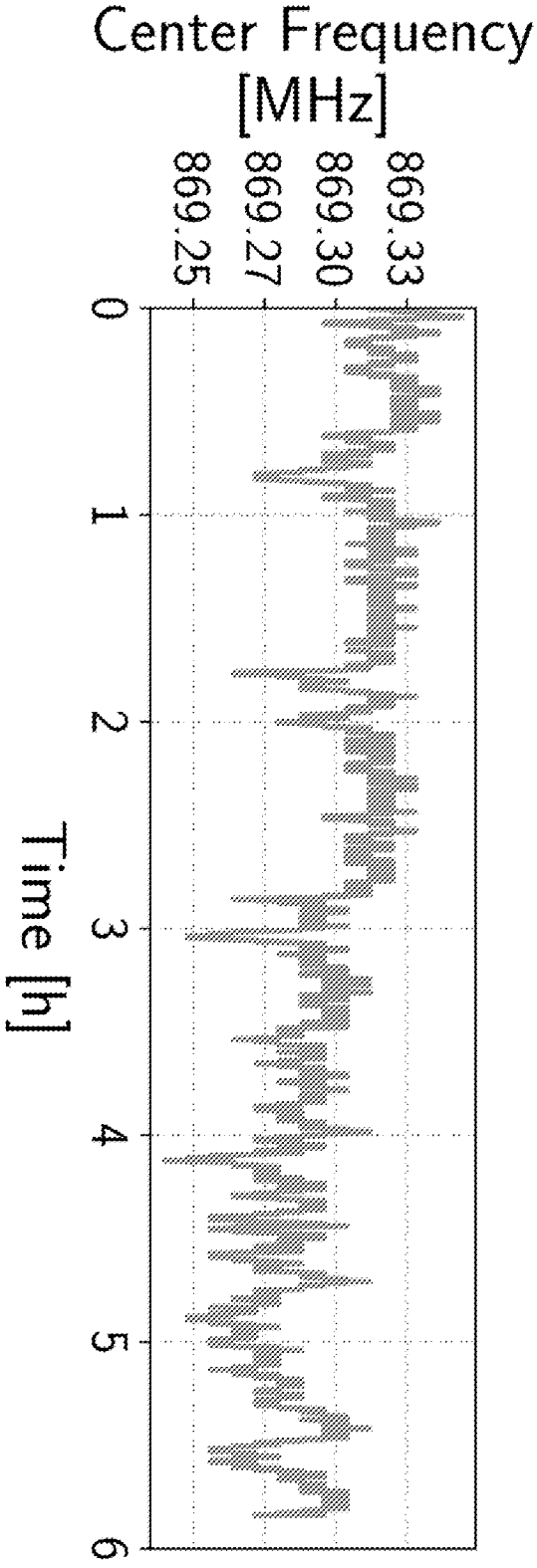

Center Frequency
[MHz]
869.25
869.27
869.30
869.33
Time [h]
0
1
2
3
4
5
6

Fig. 17

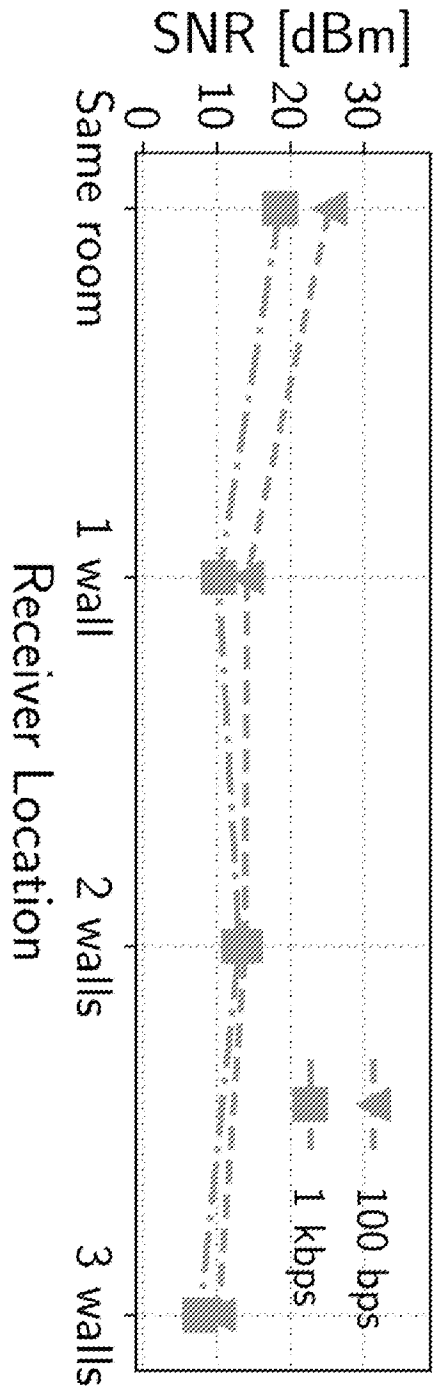

SNR [dBm]
0
10
20
30
Same room
1 wall
2 walls
3 walls
Receiver Location
100 bps
1 kbps

Fig. 18

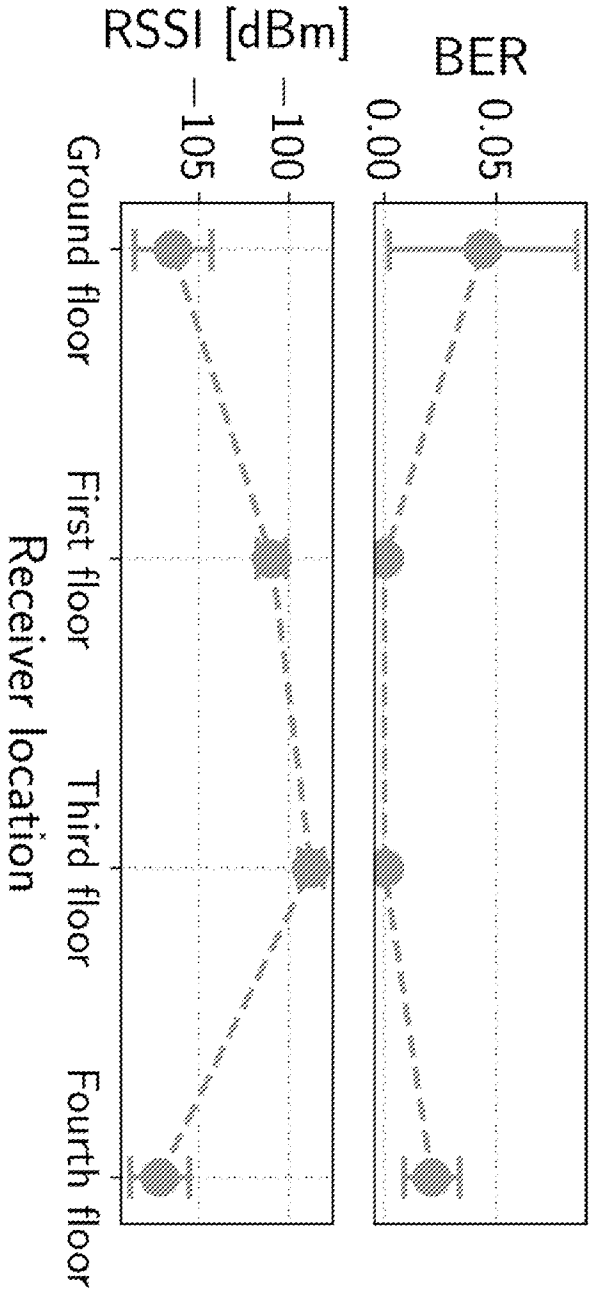

RSSI [dBm]
−105
−100
BER
0.00
0.05
Ground floor
First floor
Third floor
Fourth floor
Receiver location

Fig. 19

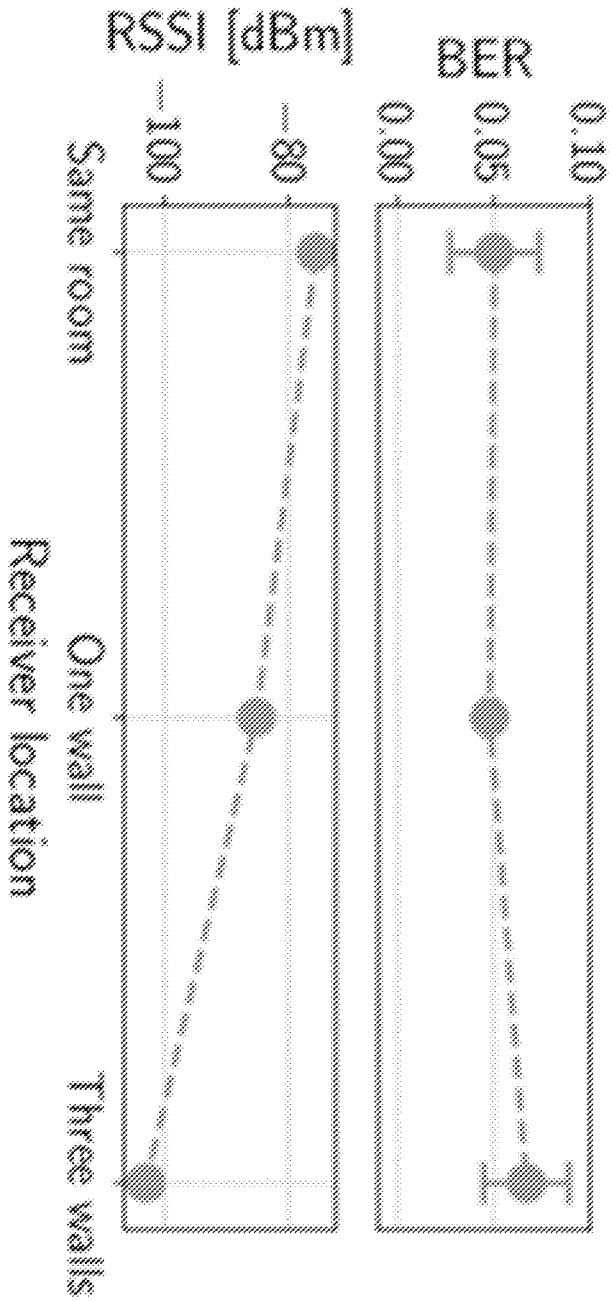

RSSI [dBm]
BER
-100
-80
0.00
0.05
0.10
Same room
One wall
Three walls
Receiver location

Fig. 20

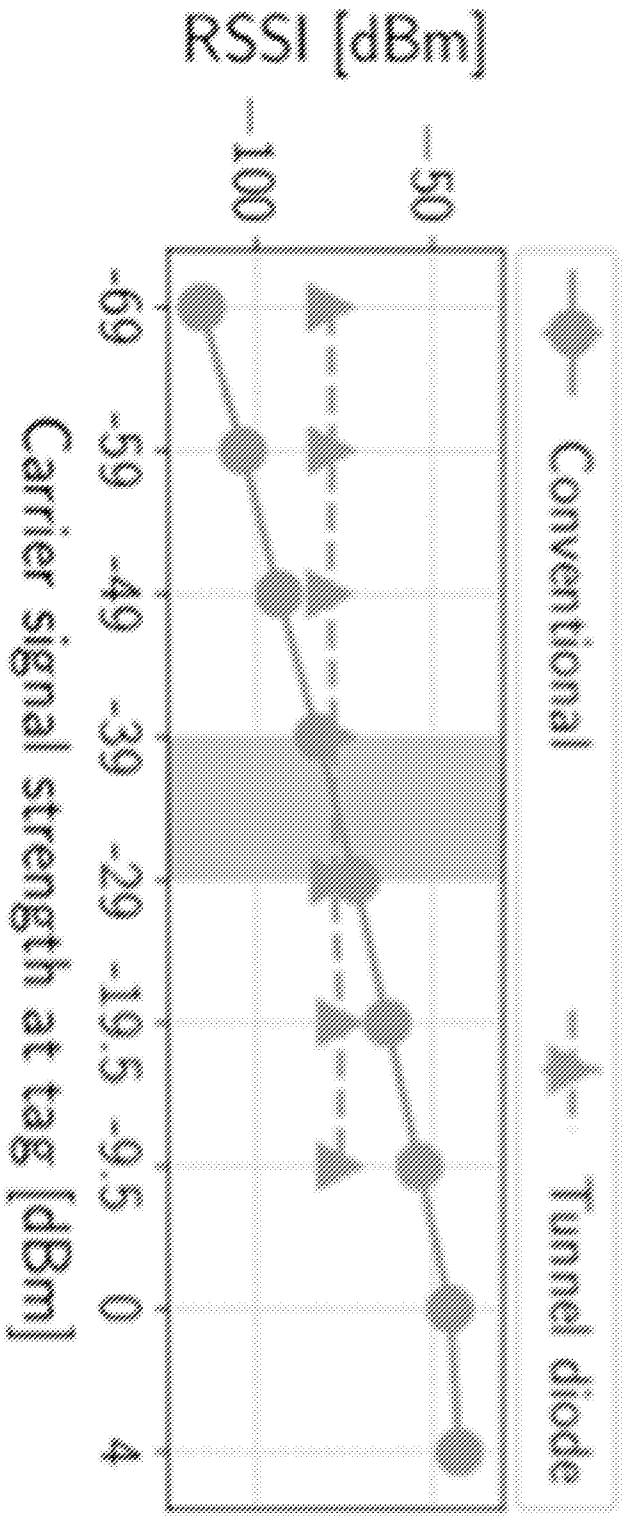

RSSI [dBm]
-100
-50
Carrier signal strength at tag [dBm]
-69
-59
-49
-39
-29
-19.5
-9.5
0
4
Conventional
Tuned diode

Fig. 21

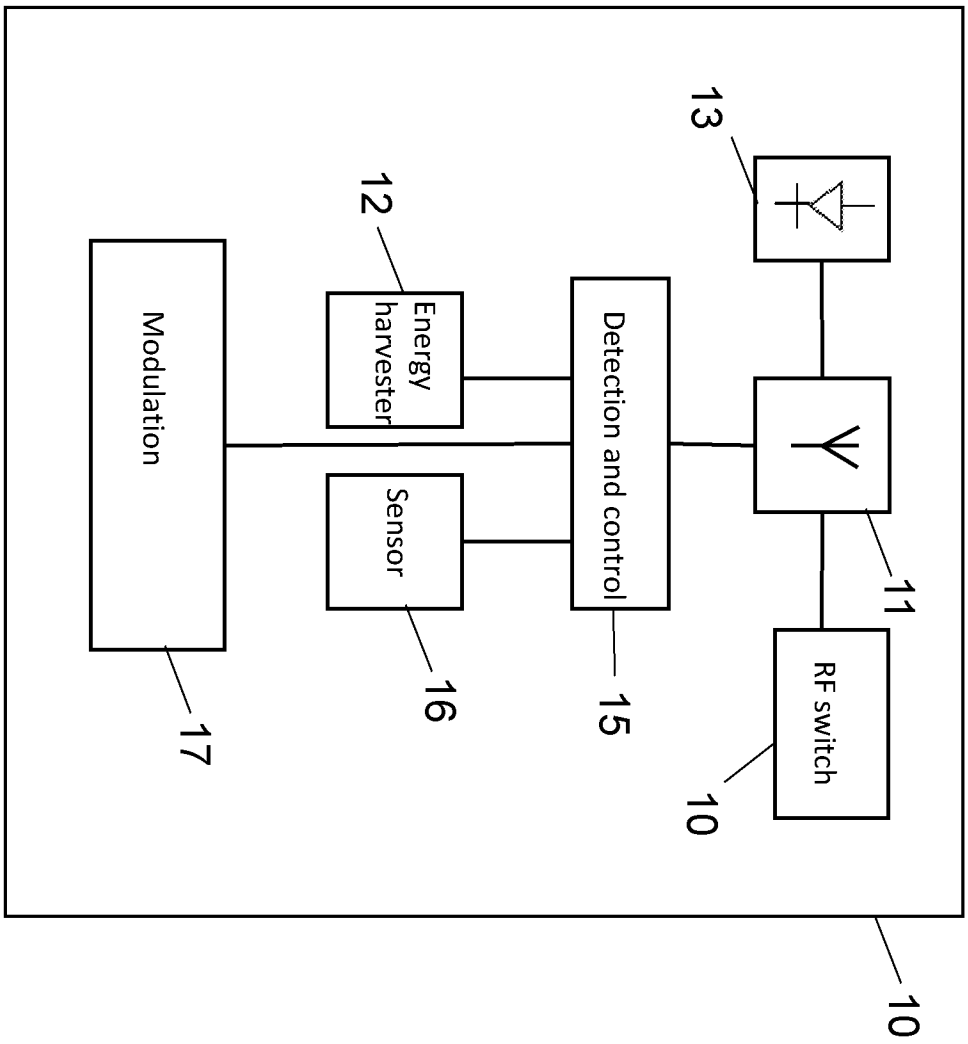

13
12
Modulation
Energy harvester
Detection and control
Sensor
RF switch
11
16
15
17
10
10

Fig. 22

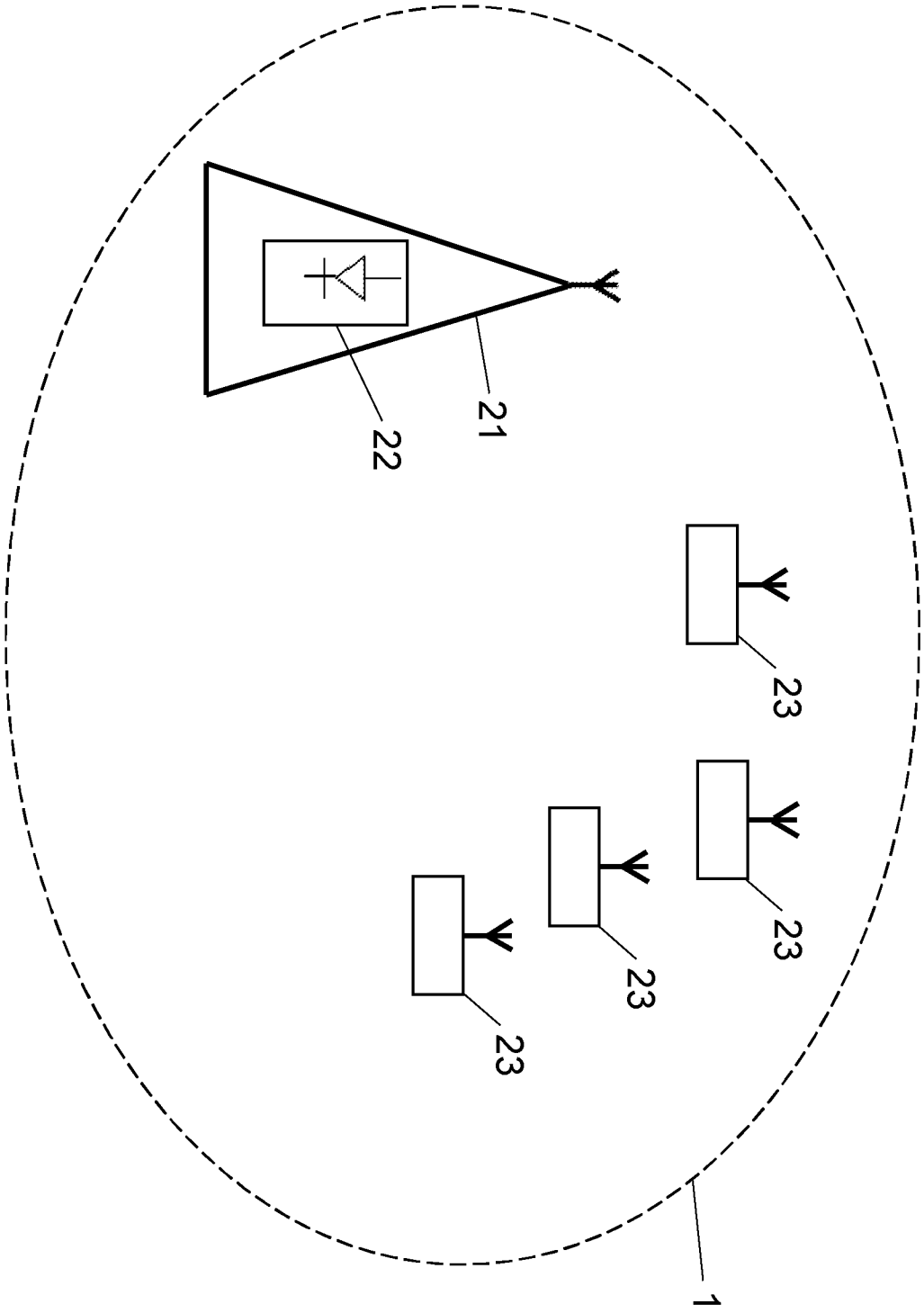


Fig. 23

INTERNATIONAL SEARCH REPORT

International application No.
PCT/SE2020/050577

A. CLASSIFICATION OF SUBJECT MATTER

IPC: 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: G01S, G06K, H01L, H02J, H03K, H04B, H04W

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

SE, DK, FI, NO classes as above

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

EPO-Internal, PAJ, WPI data, COMPENDEX, INSPEC, IBM-TDB

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	Xiao Lu et al., "Wireless-Powered Device-to-Device Communications With Ambient Backscattering: Performance Modeling and Analysis", in: IEEE Transactions on Wireless Communications, Vol. 17, No. 3, March 2018, pp. 1528 - 1544, ISSN 1536-1276, DOI: 10.1109/TWC.2017.2779857; pages 1530, 1533; figure 1	1-2, 4-13
A	--	3
Y	US 20110148580 A1 (BROMMER KARL D ET AL), 23 June 2011 (2011-06-23); paragraphs [0001], [0005]-[0008], [0025], [0036]; figures 1-2,12	1-2, 4-13
A	--	3

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

* Special categories of cited documents:

"A" document defining the general state of the art which is not considered to be of particular relevance

"D" document cited by the applicant in the international application

"E" earlier application or patent but published on or after the international filing date

"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)

"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

"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

"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

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
31-07-2020	31-07-2020

Name and mailing address of the ISA/SE	Authorized officer
Patent- och registreringsverket Box 5055 S-102 42 STOCKHOLM Facsimile No. + 46 8 666 02 86	Jonas Holmqvist Telephone No. + 46 8 782 28 00

INTERNATIONAL SEARCH REPORT

International application No.
PCT/SE2020/050577

C (Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	Eriksson, G., "Towards Long-Range Backscatter Communication with Tunnel Diode Reflection Amplifiers", Student thesis, Uppsala University, Department of Engineering Sciences, Solid State Electronics, 25 June 2018, ISSN 1401-5757, URN: urn:nbn:se:uu:diva-354901; pages 16-17, 25-27; figures 20-22	12
A	--	1-11, 13
P, X	Varshney, A. et al., "TunnelScatter: Low Power Communication for Sensor Tags using Tunnel Diodes", in: Proceedings Of The 25th Annual International Conference On Mobile Computing And Networking, Los Cabos, Mexico, Oct 21-25, 2019; Sections 4.3 and 5.1	1-13
A	--	
	US 20180269909 A1 (REYNOLDS MATTHEW S), 20 September 2018 (2018-09-20); paragraphs [0004], [0028]-[0030], [0033]-[0037], [0044]; figures 4,5	1-13
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	Sung Hoon Kim et al., "Hybrid backscatter communication for wireless powered communication networks", in: 2016 International Symposium on Wireless Communication Systems (ISWCS), Poznan, Poland, 20-23 Sept. 2016, ISBN 978-1-5090-2061-4, DOI: 10.1109/ISWCS.2016.7600912; figure 1; Section II - SYSTEM MODEL	1-13
D, A	--	
	Amato, F. et al., "Tunneling RFID Tags for Long-Range and Low-Power Microwave Applications", in: IEEE Journal of Radio Frequency Identification, Vol. 2, No. 2, June 2018, pp. 93 - 103, ISSN 2469-7281, DOI: 10.1109/JRFID.2018.2852498; whole document	1-13
D, A	--	
	Amato, F. et al., "Long range and low powered RFID tags with tunnel diode", in: 2015 IEEE International Conference on RFID Technology and Applications (RFID-TA), Tokyo, Japan, 16-18 Sept. 2015, ISBN 978-1-4799-7990-5, DOI: 10.1109/RFID-TA.2015.7379815; whole document	1-13
	--	

International application No.
PCT/SE2020/050577

Continuation of: second sheet

International Patent Classification (IPC)

H04B 1/401 (2015.01)
G01S 13/75 (2006.01)
G06K 19/07 (2006.01)
H02J 50/20 (2016.01)
H03K 3/315 (2006.01)
H04B 5/00 (2006.01)
H04W 88/06 (2009.01)
H01L 29/88 (2006.01)

US	20110148580	A1	23/06/2011	US	8373543	B2	12/02/2013
US	20180269909	A1	20/09/2018	US	10461783	B2	29/10/2019