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AN5320
Application note

Wake-up mode for ST25R3916/16B, ST25R3917/17B, ST25R3918, ST25R3919B, and ST25R3920/20B devices

Introduction

This document describes the Wake-up mode of the ST25R3916, ST25R3916B, ST25R3917, ST25R3917B, ST25R3918, ST25R3919B, ST25R3920, and ST25R3920B devices, which feature different low-power modes to detect the presence of a card.

Three wake-up sources are available, namely capacitive sensing, amplitude measurement and phase measurement. Each source is individually configurable, and can generate an interrupt to the MCU.

The document is based on the ST25R3916 device, but its content applies to ST25R3916B, ST25R3917/17B, ST25R3918, ST25R3919B, and ST25R3920/20B as well.

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1 Terms and acronyms

Table 1. Terms and acronyms

Acronym	Description
AAT	Automatic antenna tuning
ADC	Analog to digital converter
CSO	Capacitance sense output
CSI	Capacitance sense input
DAC	Digital to analog converter
EMC	Electromagnetic compatibility
HW	Hardware
IRQ	Interrupt request
MCU	Microcontroller
PCB	Printed circuit board
RC	Resistive-capacitive
RF	Radio frequency
SW	Software

2 Wake-up mode

The Wake-up mode is used to perform the low-power detection of card presence. It is implemented on the devices addressed in this document, according to *Table 2*.

Table 2. Wake-up mode capability

Device	Capacitive sensing (see *Section 2.3*)	Amplitude sensing (see *Section 2.4*)	Phase sensing (see *Section 2.5*)
ST25R3916	Yes	Yes	Yes
ST25R3916B	No	Yes	Yes
ST25R3917	No	Yes	Yes
ST25R3917B	No	Yes	Yes
ST25R3918	No	Yes	Yes
ST25R3919B	No	Yes	Yes
ST25R3920	Yes	Yes	Yes
ST25R3920B	No	Yes	Yes

Usually the card detection is performed by a polling loop, which requires the device to periodically turn its field on, wait for a certain period to fulfill the card guard time (typically 5 to 20 ms), and then send a poll request.

As this procedure is inefficient in terms of power consumption and detection time, the ST25R family offers a low-power Wake-up mode.

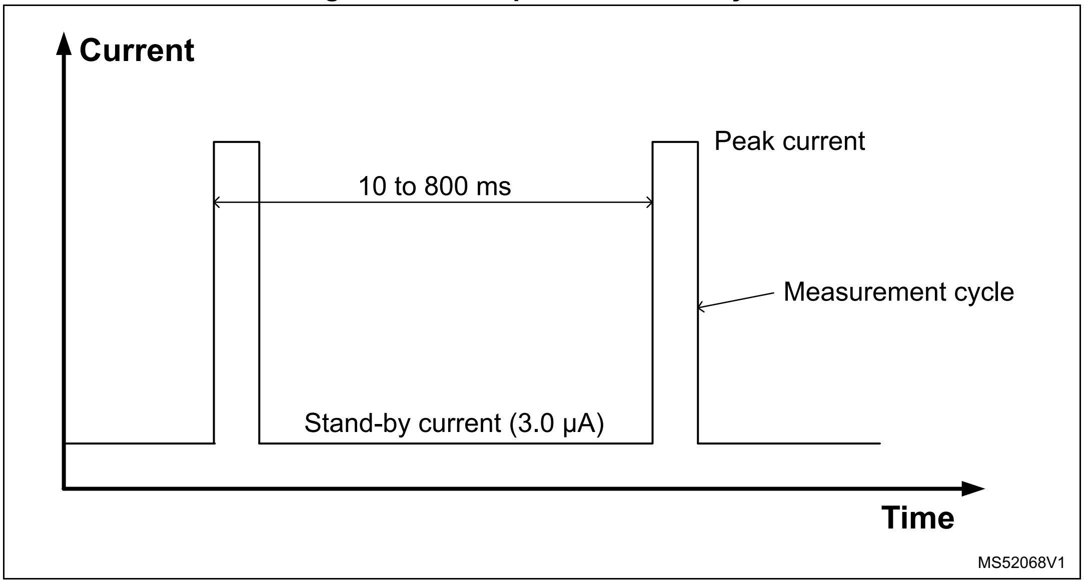
Once in this mode, the devices operate on an internal low-power RC oscillator while performing measurements. The periodically measured values are internally compared against the ones preset by the user. An interrupt is triggered if the measured value is outside the limits. This allows the MCU to sleep while the device autonomously detects approaching tags. The MCU can then be woken up by the interrupt pin, and start normal polling for cards.

2.1 Low-power wake-up generator

The low-power wake-up generator is always active. The device consumes typically 3.0 µA in this mode.

The wake-up generator can be programmed in 16 steps between 10 and 800 ms to trigger a measurement, and compare it to the preset limits.

Figure 1. Wake-up measurement cycle



2.2 Auto averaging

The auto averaging is a method to adapt dynamically the reference value on slow varying environment conditions (such as temperature, voltage) using a weighted moving average.

The higher the weight, the longer the reference takes to adapt, as more measurements are required. The values for the weight are 4, 8, 16, and 32.

Each time a new ADC value is measured, the weighted difference between the new and the stored value is added to the stored value:

NewAverage = OldAverage + ((MeasuredValue - OldAverage) / Weight)

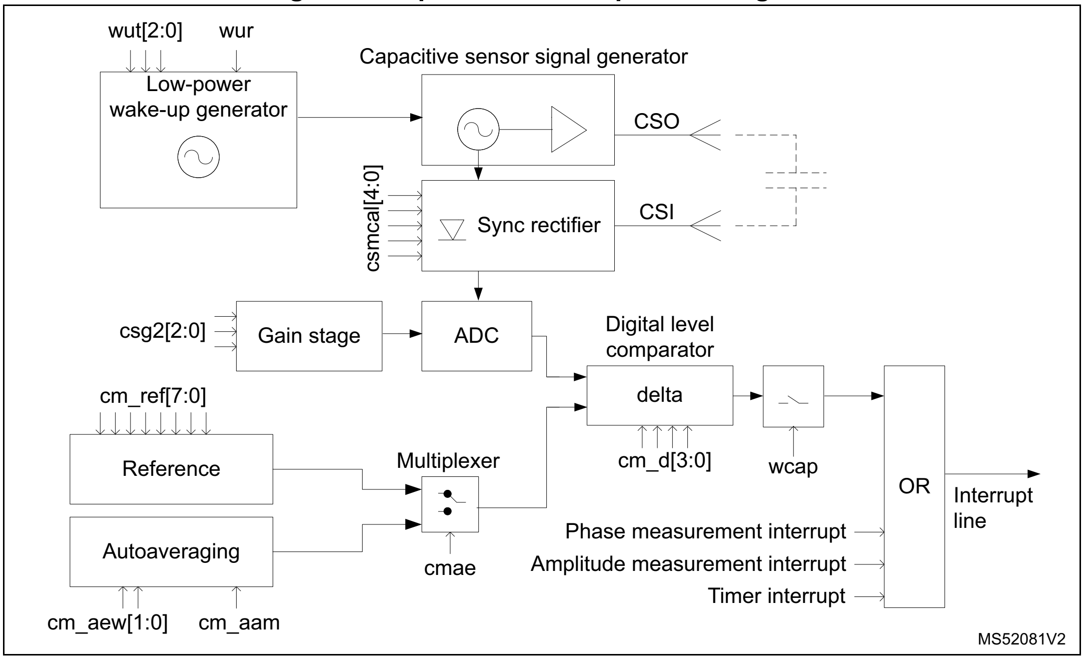
When the auto averaging is enabled, the reference evolves automatically to adapt to the new environment conditions. This reference is stored internally and it persists even if the Wake-up mode is exited and then restarted. The direct command Set default resets the stored reference.

2.3 Capacitive sensing

Figure 2 shows the capacitive wake-up system, composed by two electrodes, a 500 kHz signal generator, a synchronous rectifier with the calibration unit, and the ADC of the device.

The capacitive wake-up is achieved using a different procedure, explained in the next section.

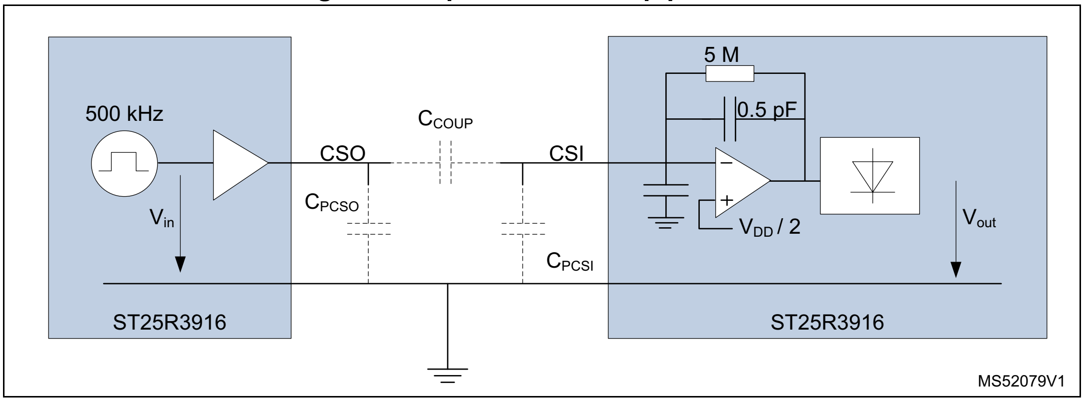
Figure 2. Capacitive wake-up block diagram



2.3.1 Measurement principle

The system includes two electrodes, CSO, and CSI. Each pin is connected to an electrode, which is made out of a solid area on the PCB. On the CSO output, a 500 kHz rectangular carrier voltage is applied for a short period (300 µs), and coupled via the parasitic capacitance C_{COUP} to the electrode on the CSI input.

Figure 3. Capacitive wake-up parasitics



Each electrode has a parasitic capacitance to ground. Assuming a strong driver and low parasitic capacitance between CSO and ground, the voltage on CSO pin is not significantly impacted by C_{PSO}.

The CSI input comprises a charge to voltage amplifier. This amplifier keeps the voltage on CSI input constant by using an internal feedback capacitor. As a consequence, the parasitic capacitance C_{PSI} does not have any effect.

When an object approaches the electrical field of the electrodes, two things can happen:

- If the object is conductive and not grounded, C_{COUP} increases as the object gets influenced by the emitting electrode, and the receiving electrode sees a higher electrical field.
- If the object is conductive and grounded (or has high capacitance to ground), it acts as a shield between the emitting and receiving electrode, thus reducing C_{COUP}, and the receiving electrode sees a lower electrical field.

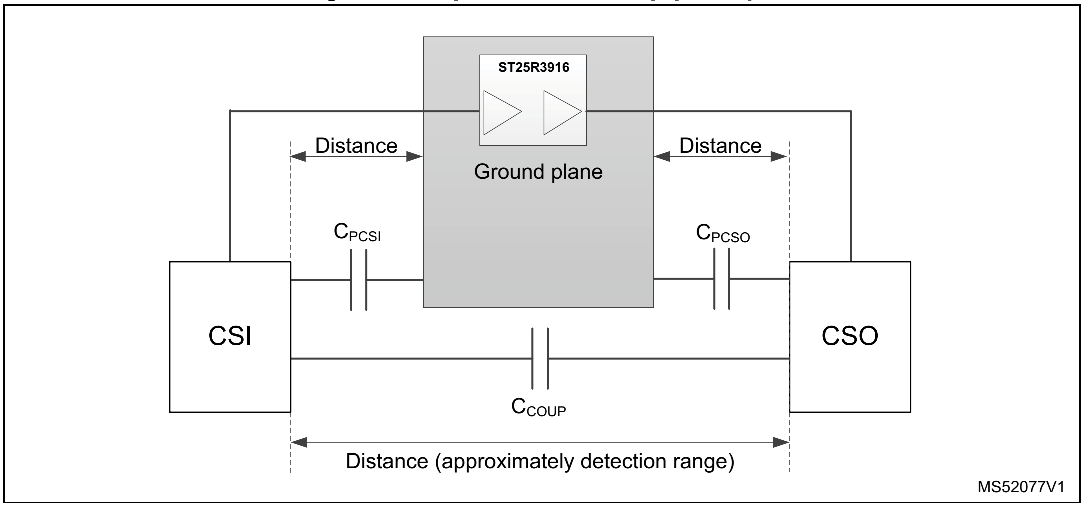
In both cases, there is a change of the C_{COUP} capacitance from CSO to CSI, detected by the device.

2.3.2 Optimization layout for C_{COUP}

The parasitic capacitance to ground has to be as small as possible. This can be done by moving the capacitive plates away from any GND reference or GND plane.

To increase the measurement range or measurement precision, the device can perform an offset calibration of the capacitance sensor. The capacitance measurement offset value can be chosen manually (up to 3.1 pF), or determined by the device with a built-in self-calibration procedure. To get some margin on the self-calibration, it is recommended to use a coupling capacitor up to 2.7 pF.

Figure 4. Capacitive wake-up principle



2.3.3 Influence of materials

The normal use case is a card carried by a human hand. The hand contains water, which changes the field propagation. The measurements show a reduction of the capacitance when a human hand is in proximity of the reader.

2.3.4 Shape of the electrodes

The shaping can be done either with a solid plane, a grid plane, or stripped lines.

A solid plane gives the best area/capacitance ratio, but must be not too close to the RFID antenna, as eddy currents generated in the wake-up electrode dampen the field.

The distance between the RF antenna and the electrodes must be at least 5 mm.

2.3.5 Setup of the wake-up system

The minimum resolution of the capacitive measurement is 1.2 fF. To configure the capacitance wake-up, the device provides a calibration system that suppresses the initial capacitance caused by pin pads, and has a configurable threshold level at which the change of capacitance is reported to the microcontroller. The calibration procedure is described in *Section 4.1*.

2.3.6 Digital capacitor sensing unit

The capacitive sensor system consists of a frequency generator, which delivers a signal onto an electrode (CSO pin). The signal is received across the coupling capacitance on the input electrode (CSI pin).

To minimize the noise in the system, an embedded synchronous rectifier generates a DC signal. To reject the effect of parasitic capacitances, calibration bits cs_mcal adjusts the DC voltage. The resulting DC signal is then amplified in a programmable gain stage (bit cs_g configures the gain), and fed to the ADC. The ADC converts the DC value into the digital domain, and delivers a digital value to the level comparator.

The level comparator has two inputs, one from the ADC and another from the reference.

There are two options to set the reference:

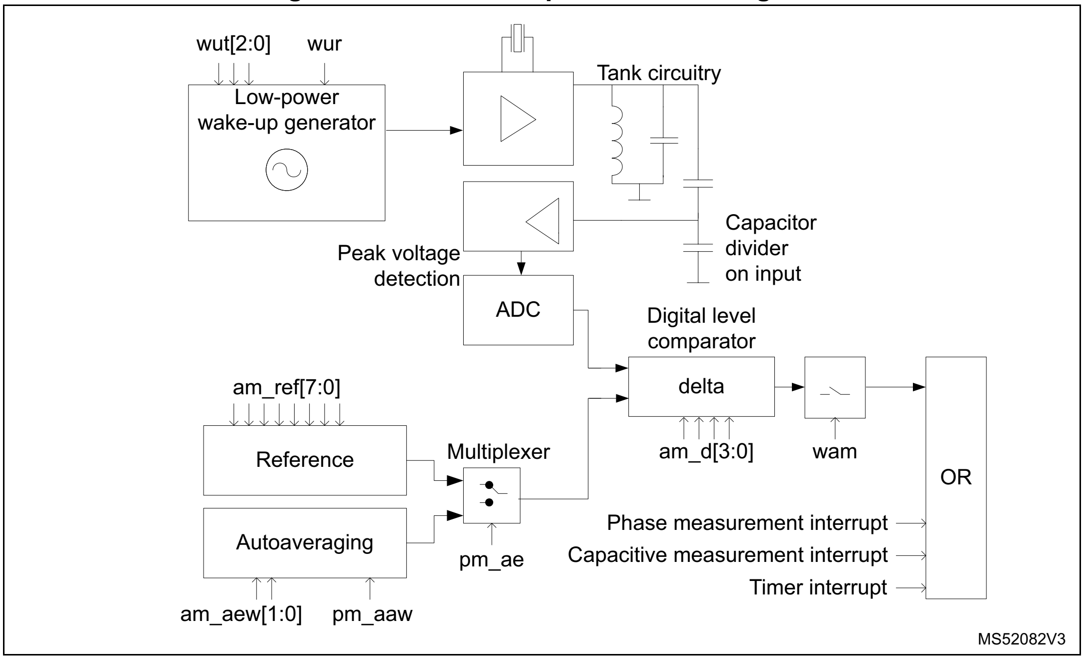
- fixed value inside a register
- floating average generated by a digital averaging circuitry.

2.4 Amplitude sensing

Inductive wake-up uses the detuning of the antenna caused by an approaching tag. This method requires a running crystal oscillator and an RF field, hence the average current consumption is higher compared to the capacitive wake-up. To decrease the current during transmission, the driver output resistance can be changed to a higher value, using the RFO normal level definition register.

The measurement and interrupt trigger procedure is similar to that of the capacitive wake-up, the difference lies in the generation of the ADC value.

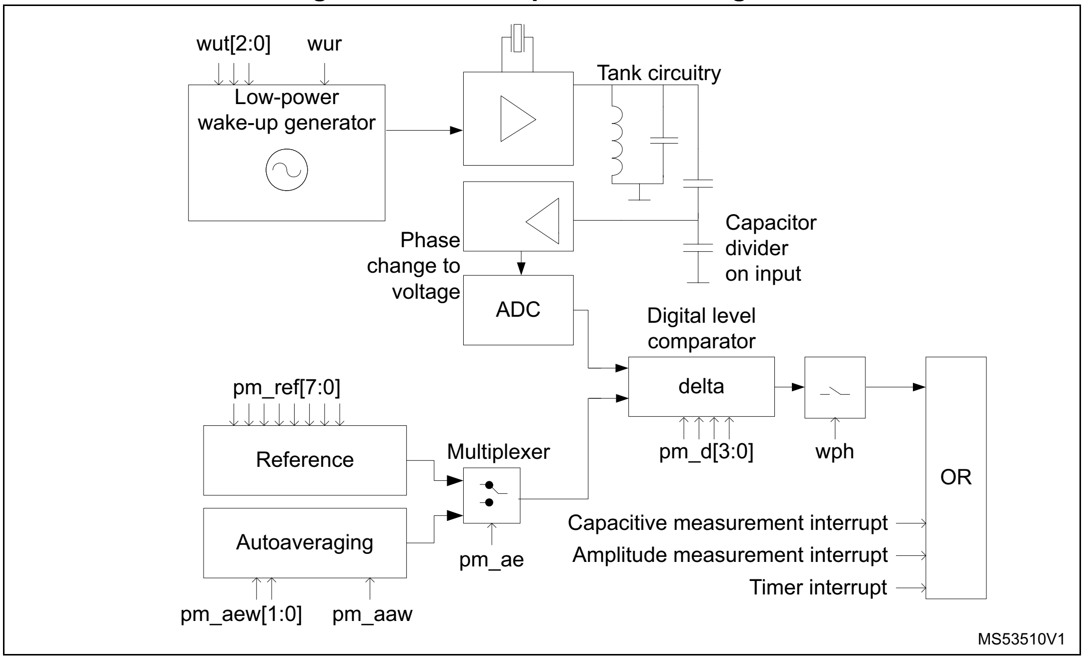
Figure 5. Inductive amplitude block diagram



2.5 Phase sensing

The inductive wake-up with a phase change is similar to the inductive wake-up with amplitude change, but the measurement value is taken from the phase measurement.

Figure 6. Inductive phase block diagram



3 Wake-up configuration

The Wake-up mode can be configured to perform either capacitive or inductive measurements. The amplitude measurement can be combined with phase measurement if desired for the wake-up, but the capacitive measurement must always be configured without any other.

Table 3. Relevant registers for Wake-up mode

Address (hex)	Name	Description
02	Operation control	Wake-up mode enable
32	Wake-up timer control	Wake-up configuration
33	Amplitude measurement configuration	Amplitude measurement configuration and display
34	Amplitude measurement reference	
35	Amplitude measurement auto-averaging display	
36	Amplitude measurement display	
37	Phase measurement configuration	Phase measurement configuration and display
38	Phase measurement reference	
39	Phase measurement auto-averaging display	
3A	Phase measurement display	
3B	Capacitance measurement configuration	Capacitance measurement configuration and display
3C	Capacitance measurement reference	
3D	Capacitance measurement auto-averaging display	
3E	Capacitance measurement display	

To set up the Wake-up mode, a common configuration must be applied, together with measurement specific configuration.

3.1 Common configuration

Register 32h contains the generic configuration for the Wake-up mode, with the following bits:

- wur and wut configure the interval at which the Wake-up mode performs the defined measurement(s)
- wto defines if the host controller gets an interrupt on every timeout (regardless from the detection of a card)
- wam, wph, and wcap specify which measurements are performed periodically.

3.2 Measurement specific configuration

Each type of measurement has its own set of registers, which configure the behavior of the individual measurement. The available configurations are identical for the three measurements.

For simplicity purposes, similar bits for the individual measurement are explained together.

For this reason, the letter x is used instead of a, p, or c for, respectively, amplitude, phase, and capacitance.

Measurement configuration registers (33h, 37h, and 3Bh) configure the individual measurement specifics with the following bits:

- xm_d sets the difference from the reference value to the measured one, which triggers a wake-up interrupt when reached
- xm_aam makes it possible to include or exclude the measurement that caused the IRQ when using auto-averaging feature
  - when included, the auto-averaging reference evolves into the new environment conditions after signaling the IRQ
  - when excluded, the auto-average reference stays at the old value continuing to signal IRQs.
- xm_ae enables or disables the auto-averaging feature.

Figure 7 and *Figure 8* show how bit xm_aam causes the reference (blue line) to evolve or not, and how it affects the triggered wake-up interrupts (red dots).

Figure 7. Auto-averaging with xm_aam enabled

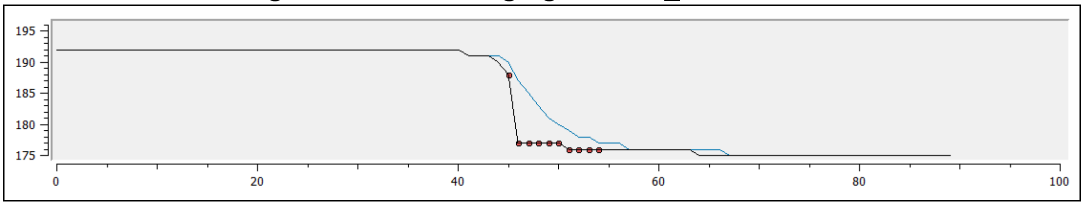
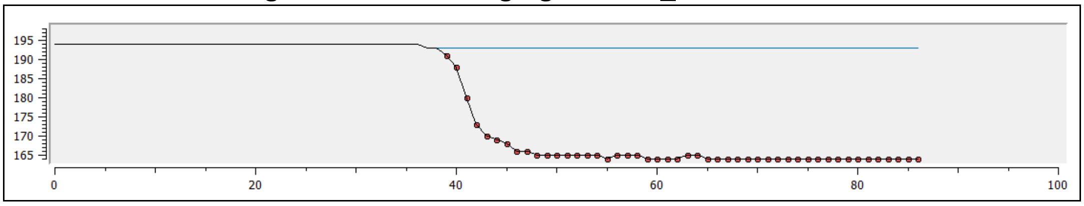


Figure 8. Auto-averaging with xm_aam disabled



Measurement reference registers (34h, 38h, and 3Ch) define the reference value for each individual measurement. These reference values are compared periodically against the measured ones, and a difference greater than or equal to xm_d triggers a wake-up interrupt.

Measurement auto-averaging display registers (35h, 39h, and 3Dh) show the current reference when the auto-averaging feature is enabled.

Measurement display registers (36h, 3Ah, and 3Eh) show the result of the last performed measurement.

4 Wake-up flow

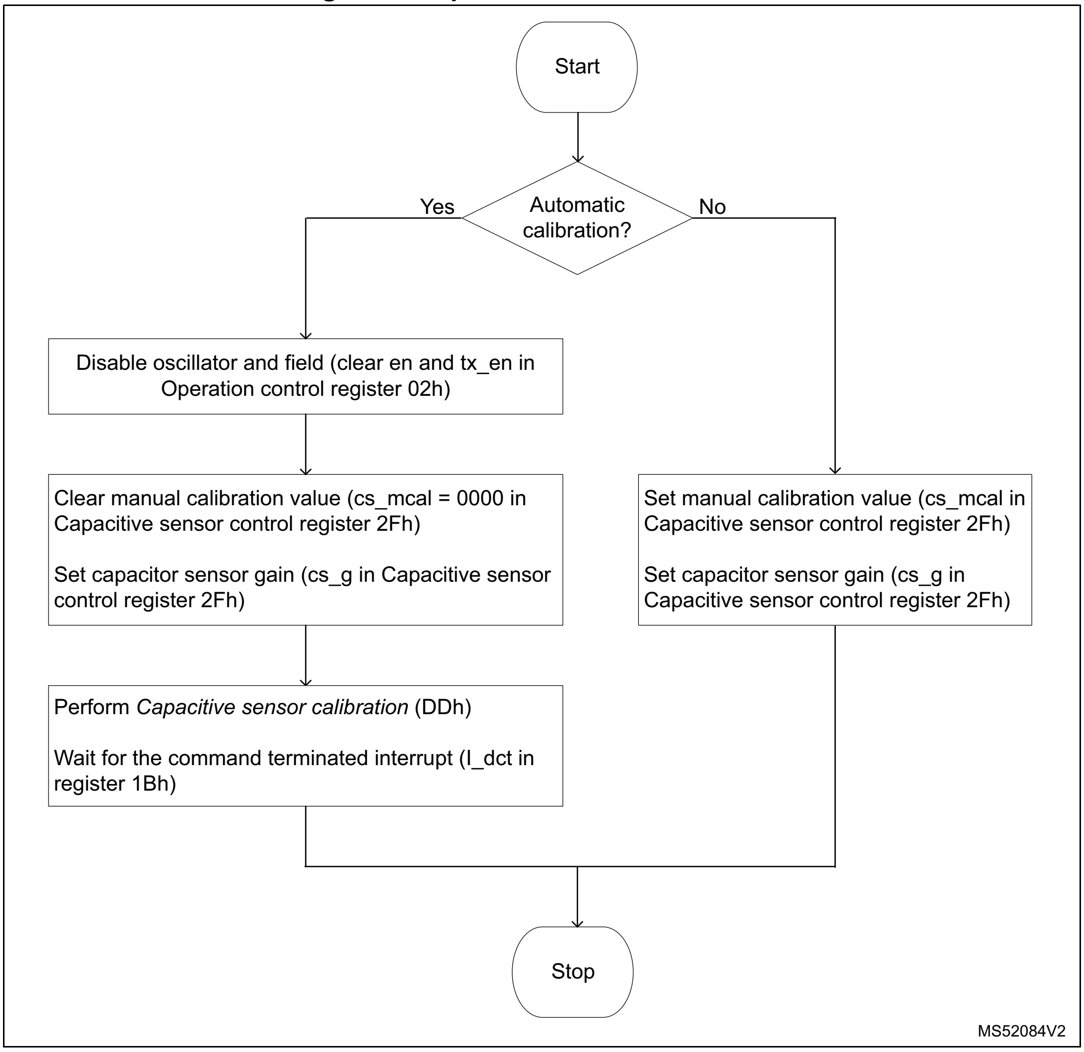
A specific sequence must be executed to enter and exit the Wake-up mode.

The procedure is similar for each wake-up measurement, with one additional step if the capacitance measurement is used (requires up-front calibration).

4.1 Capacitive sensor calibration

Two options (detailed in *Figure 9*) are available to calibrate the capacitive sensor, namely manual or automatic calibration.

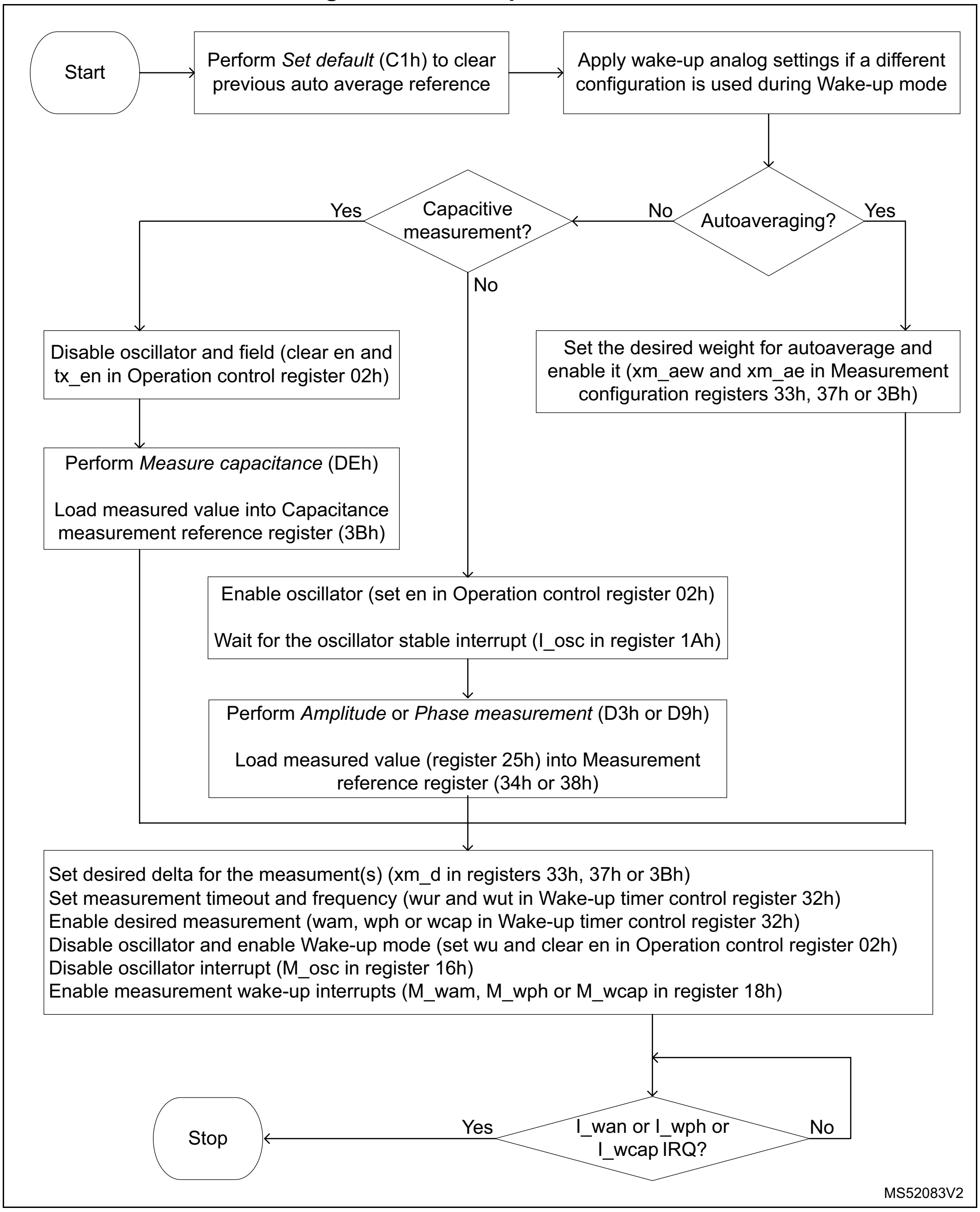
Figure 9. Capacitive sensor calibration



4.2 Entering Wake-up mode

Figure 10 illustrates the sequence to configure and enable the Wake-up mode.

Figure 10. Wake-up mode enable



Initially, execute a Set default command to reset the auto-averaging reference value. The Set default is required only when the auto-averaging is used, but it is recommended to run it anyway, as it ensures a defined state.

After setting the default values on the device, a known good analog setting for wake-up must be applied.

Some systems require to have different analog settings for Wake-up and normal modes, to optimize power consumption and maximize range.

If the auto-averaging feature must be used, configure and enable it for each measurement.

Without auto-averaging a reference measurement must be obtained by executing the corresponding measurement command. Afterwards, the measured value must be set as a reference for each measurement type used.

There is a difference between performing capacitive or inductive (phase and amplitude) measurements:

- for capacitive measurements the sensor must be calibrated (as described before) and the device must be in Power-down mode (field and oscillator disabled), to avoid interferences
- for inductive measurements the oscillator must be enabled and stable, to perform the reference measurements.

Once the reference measurement is complete, the value must be loaded into the corresponding measurement reference register(s).

At this stage it is important to ensure that the measured value is within an expected valid range.

Unexpected/invalid values indicate that something is wrong with the measurement, typically a mis-configured antenna or a measurement triggered without waiting for a stable oscillator.

Values close to the edges can lead to a configuration that never wakes-up the system, so, if delta is the difference that triggers an interrupt, the reference value must always satisfy the following conditions:

- reference - delta > 0
- reference + delta < 255.

Afterwards the wake-up can be configured by defining the measurement(s) interval, the measurement(s) to be performed, and then placing the device in Wake-up mode.

Note: It is known that having the field enabled for long periods may increase the temperature of the matching components, such as wire wound EMC inductors.
While entering the Wake-up mode a reference measurement is taken, and it has been observed in some systems that the increased temperature of the matching components leads to a deviated reference value. This situation causes the device to trigger a wake-up IRQ as soon as the components cool down.
The reference measurement must be carried out in conditions similar to those where the Wake-up mode runs. Therefore, in some system designs, it is recommended to ensure a certain period of time with field off before executing the Wake-up mode enable procedure, so that the components can get back to the environment temperature.

4.3 Exiting Wake-up mode

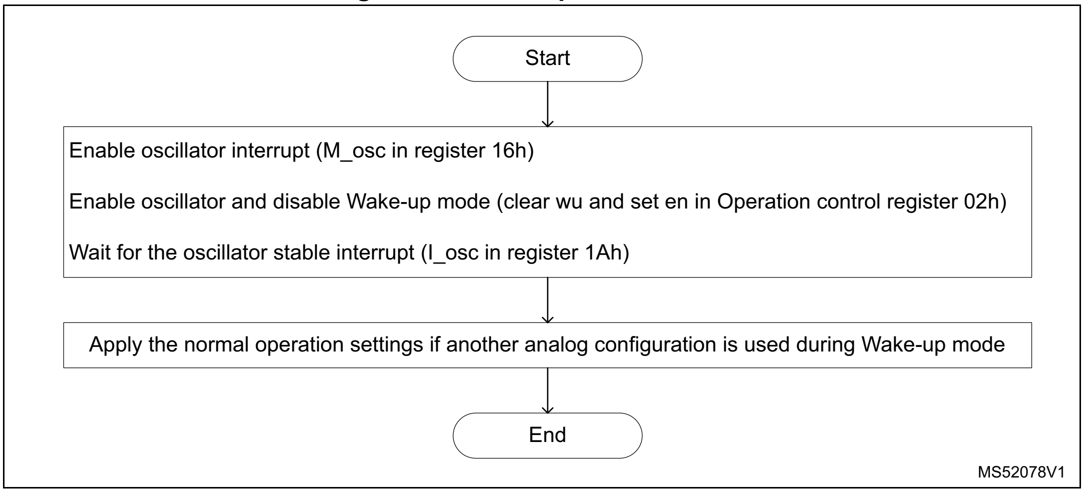
Once the Wake-up mode is enabled the host MCU can go to low-power mode to minimize power consumption.

As soon as the device detects a change on the measured value bigger than the defined difference it will trigger an IRQ.

The host MCU then reacts by disabling the ST25R3916 Wake-up mode, and executing the normal polling cycle.

Figure 11 shows the sequence to exit from the Wake-up mode.

Figure 11. Wake-up mode disable



To return to normal mode, the Wake-up mode must be disabled and the oscillator enabled.

If a different analog setting is used during Wake-up mode, the normal operation setting has to be applied.

5 Wake-up mode power calculation

While in Wake-up mode, the ST25R3916 performs the enabled measurements (inductive and/or capacitive), more frequent measurements result in higher power consumption.

Unlike the capacitive measurement, the power consumption of the inductive measurements is dependent on the target matching impedance.

Each measurement has a different duration and therefore different power consumption. The duration of each measurement type is shown in the following figures, where yellow is for the RF field and green for V_{SP_RF}.

Figure 12. Amplitude measurement

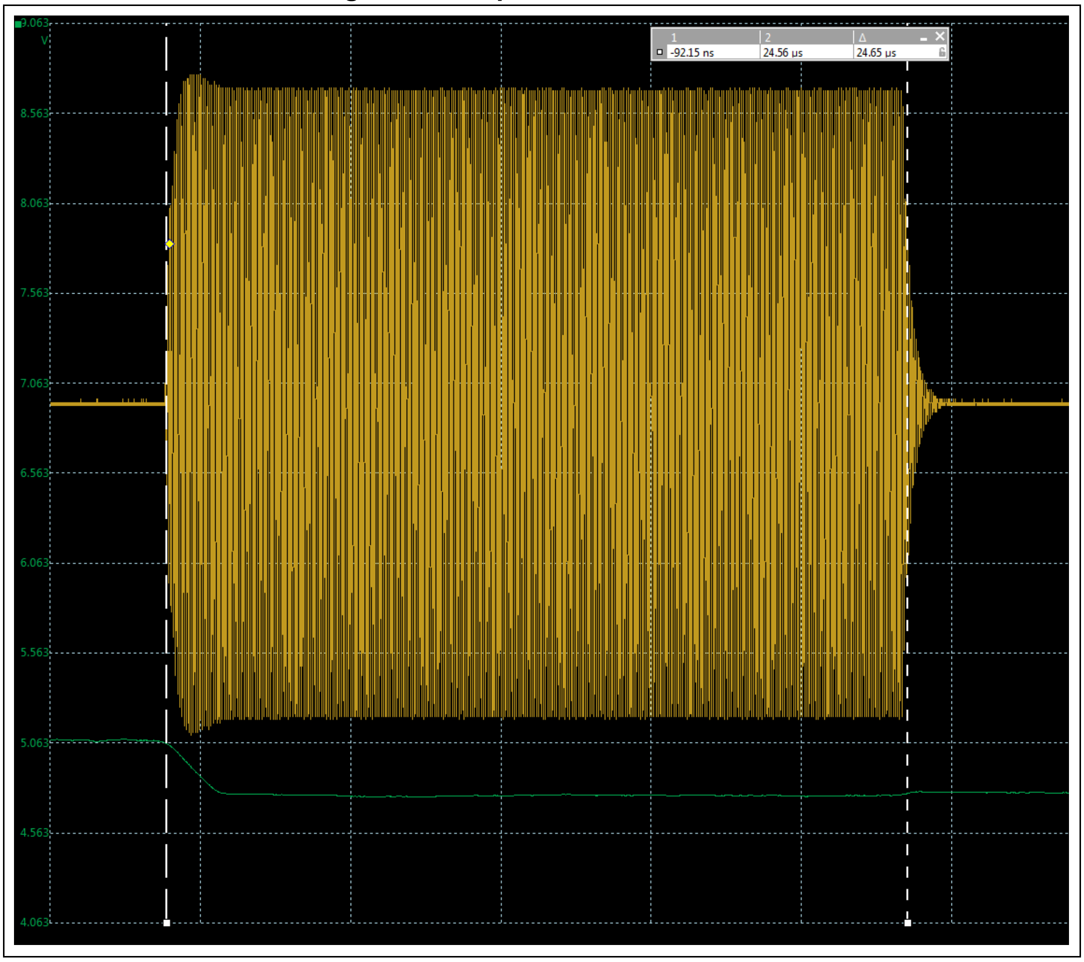


Figure 13. Phase measurement

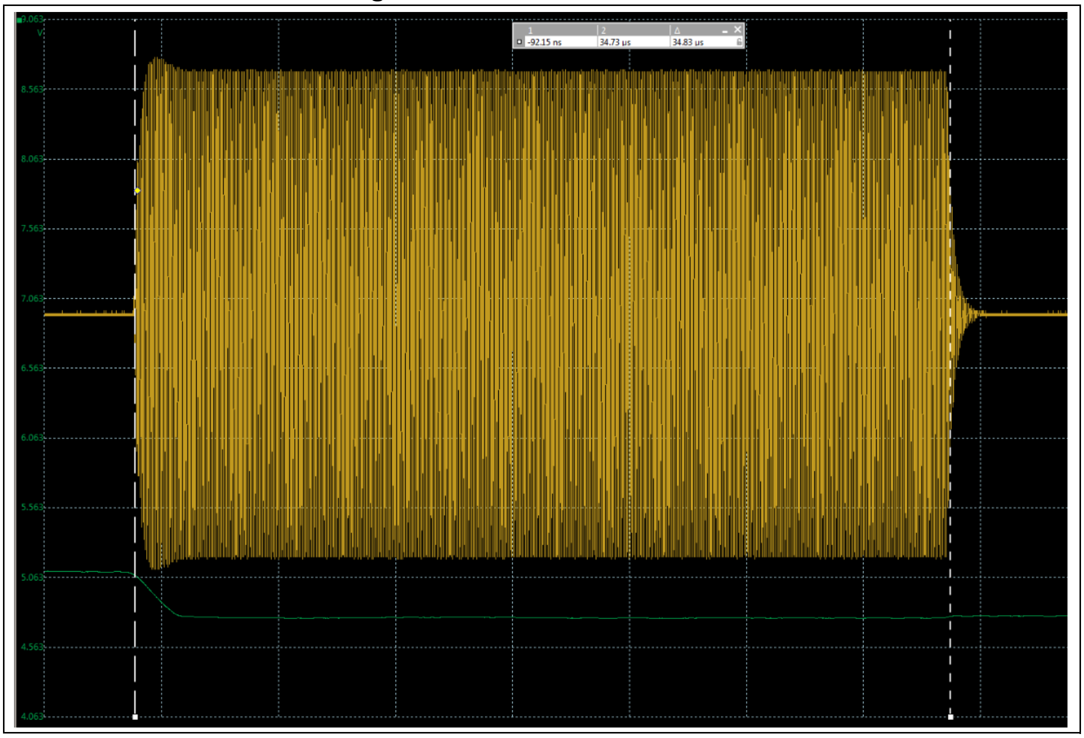
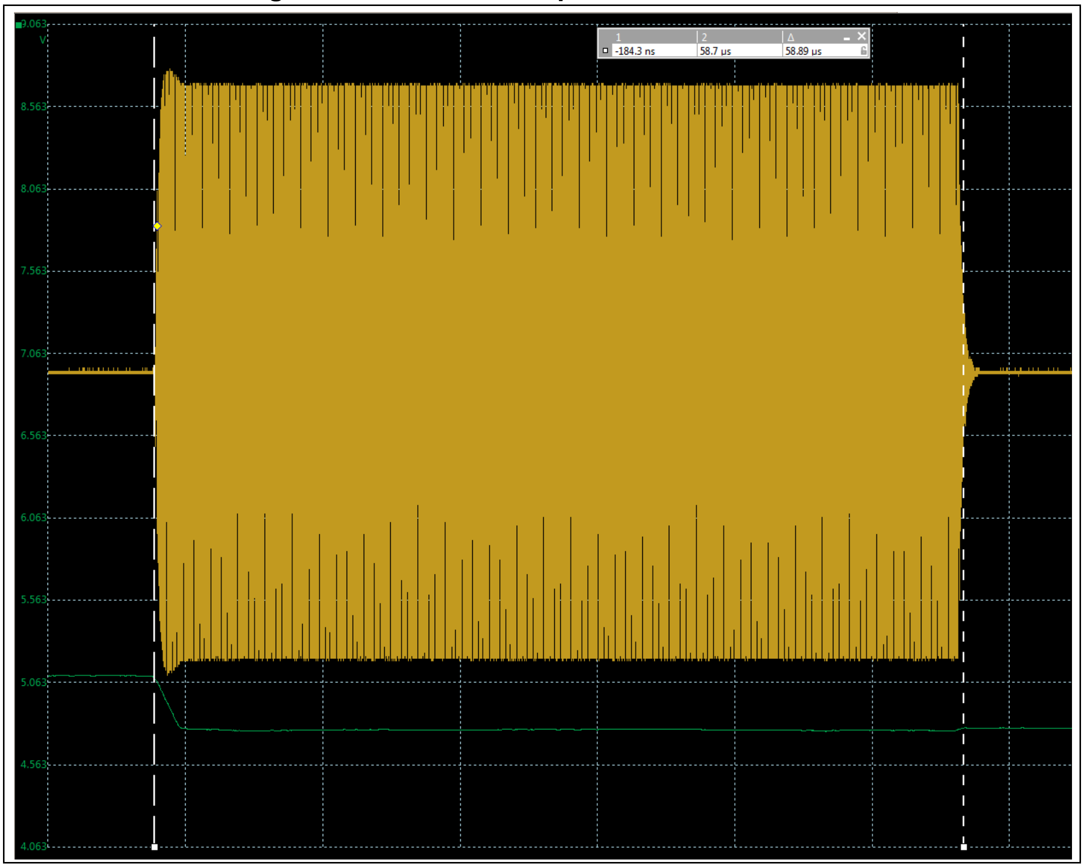


Figure 14. Phase and amplitude measurements



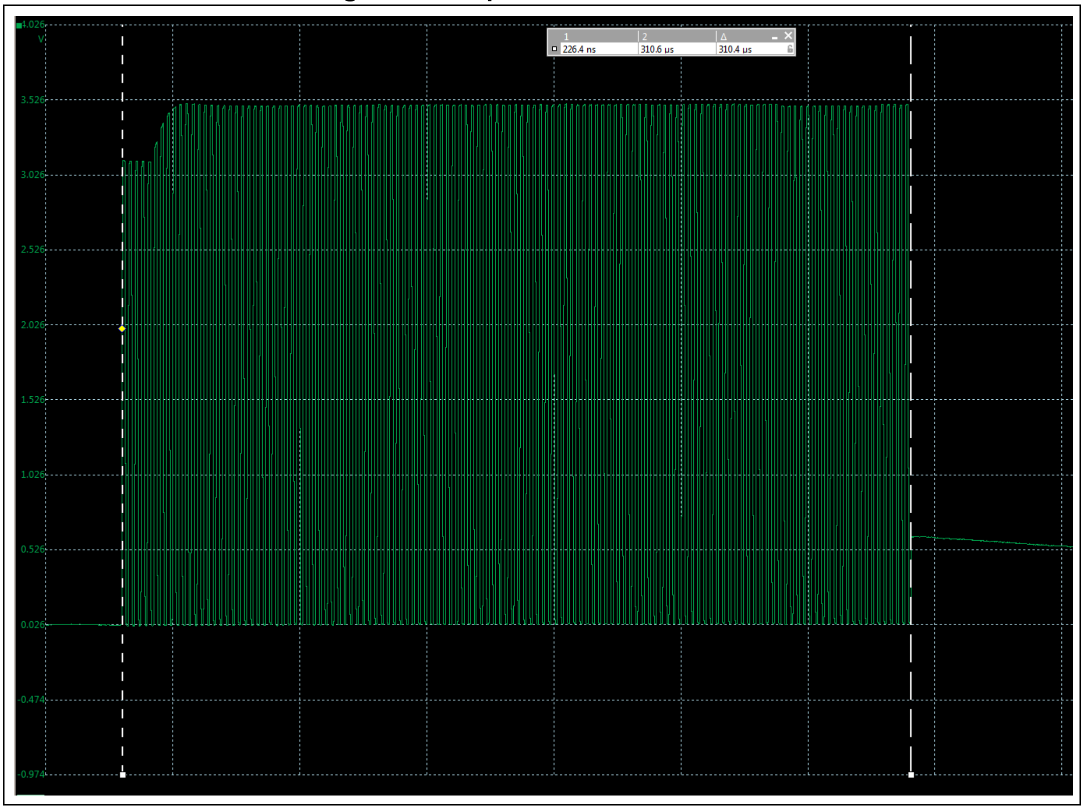
As shown in *Figure 12* and *Figure 13* the amplitude measurement (T_{AWU}) and the phase measurement (T_{PWU}) have a duration of, respectively, ~24 µs and ~35 µs.

When both inductive measurements are combined (as in *Figure 14*) the total duration of the measurement phase is ~59 µs.

Additionally, the voltage drop of V_{SP_RF} can be observed. The voltage drops from V_{DD} and settles at the defined V_{SP_RF} voltage. This is an expected behavior and shows that after reaching the estimated V_{SP_RF} value the voltage stays constant. Oscillations or voltage drops in V_{SP_RF} indicate a problem with the supply voltage and disclose the reason for an unstable measurement during Wake-up mode.

Figure 15 shows the CSO signal in green (RF field channel not shown): the capacitive measurement has a duration (T_{CWU}) of ~310 µs.

Figure 15. Capacitive measurement



The following calculation shows how to estimate the average power consumption in Wake-up mode.

The duration of each measurement is approximately:

- T_{AWU} = 25 µs
- T_{PWU} = 35 µs
- T_{CWU} = 310 µs

The typical consumption values of supply current in Wake-up mode, which can be found on ST25R3916 datasheet, are

- I_{CS} = 1.1 mA
- I_{WU} = 3.0 µA
- I_{RD} = 4.5 mA

The current during an inductive measurement ($I_{IP} = I_{IA}$) depends upon the matching impedance, therefore it varies with each system, typically between 150 and 200 mA.

The timeout interval (T_{out}) between each measurement stage is configurable.

For an estimate of the current consumption I_{AVG} it is required to calculate the current consumption for each individual measurement ($I_{C,AVG}$, $I_{IP,AVG}$ and $I_{IA,AVG}$), using the following equations:

- $I_{C,AVG} = (I_{CS} - I_{WU})\ (T_{CWU} / T_{OUT})$
- $I_{IP,AVG} = (I_{IP} - I_{WU})\ (T_{PWU} / T_{OUT})$
- $I_{IA,AVG} = (I_{IA} - I_{WU})\ (T_{AWU} / T_{OUT})$

When an inductive measurement (amplitude and/or phase) is used there is an additional contribution (while enabling the oscillator) that must be taken into account

$$I_{OSC,AVG} = (I_{RD} - I_{WU})\ (T_{OSC} / T_{OUT})$$

Then, the total current consumption I_{AVG} is

$$I_{AVG}= I_{C,AVG} + I_{IP,AVG} + I_{IA,AVG} + I_{OSC,AVG} + I_{WU}$$

For example, assuming that for a particular system $I_{IP,AVG}$ = 200 mA, T_{OSC} = 0.7 ms and T_{OUT} = 200 ms, the estimated current consumption with inductive amplitude measurement during the Wake-Up mode, can be estimated as:

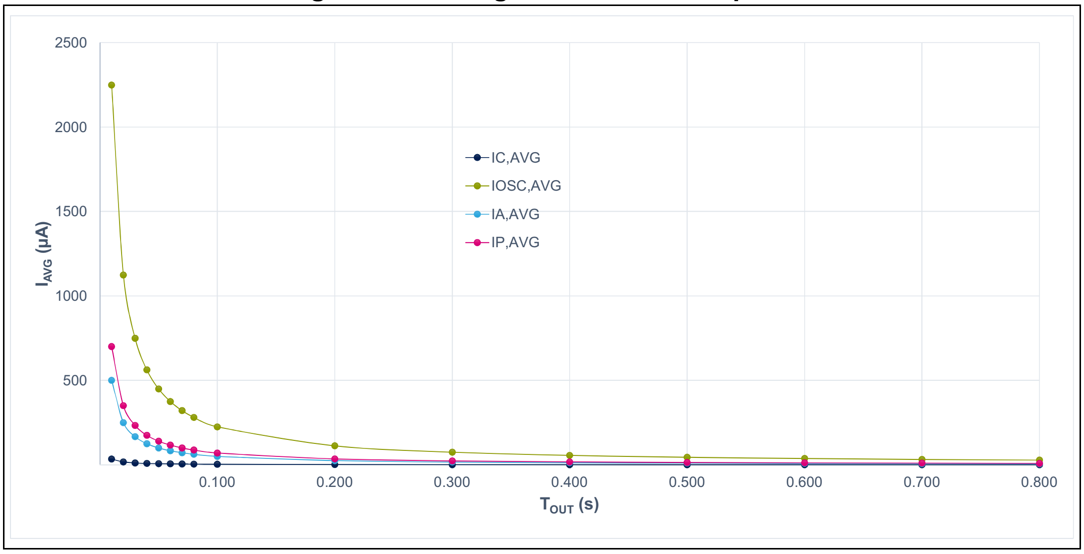
- $I_{C,AVG} = 0$
- $I_{IP,AVG} = 0$
- $I_{IA,AVG} = (200 \times 10^{-3} - 3.0 \times 10^{-6}) \times (25 \times 10^{-6} / 200 \times 10^{-3}) = 25.00$ µA
- $I_{OSC,AVG} = (4.5 \times 10^{-3} - 3.0 \times 10^{-6}) \times (0.7 \times 10^{-3} / 200 \times 10^{-3}) = 15.74$ µA.

The total current consumption of this system (using capacitive and inductive amplitude measurements during the Wake-up mode) can be estimated as

$$I_{AVG} = I_{C,AVG}+ I_{IP,AVG} + I_{IA,AVG} + I_{WU} = 0 + 0 + 25 + 15.74 +3.0 = 43.74\ \mu A$$

In *Figure 16* it is possible to see how each average current consumption relates to the different timeout/period configurations ($I_{IP} = I_{IA}$ = 200 mA).

Figure 16. Average current consumption



6 Wake-up mode with AAT

The ST25R3916 gives the possibility to have designs with fixed matching, or to use a variable tuning by means of the AAT technique, detailed in *ST25R3916 automatic antenna tuning (AAT)* (AN5322), available on www.st.com.

The ST25R3916 AAT is achieved by two DAC outputs driving voltage controlled capacitors (varicaps), which make possible to dynamically change the serial and parallel capacitance of the matching.

Due to power consumption efficiency, these DAC outputs are not enabled when the device is put in Power-down mode, and the AAT_A and AAT_B pins are in undefined/floating state.

Once the Wake-up timeout occurs the DAC outputs are enabled to the defined voltage, and as soon as the oscillator is stable the inductive measurement is performed. The varicaps can still be settling to the new control voltage, this can lead to a different antenna matching during normal operation and in Wake-up mode. As a consequence the reference value obtained in Ready mode can differ from the one acquired in Wake-up mode, causing the system to be woken-up.

To minimize such effects two techniques are available, SW tag detection and measurement delay, described in the next subsections.

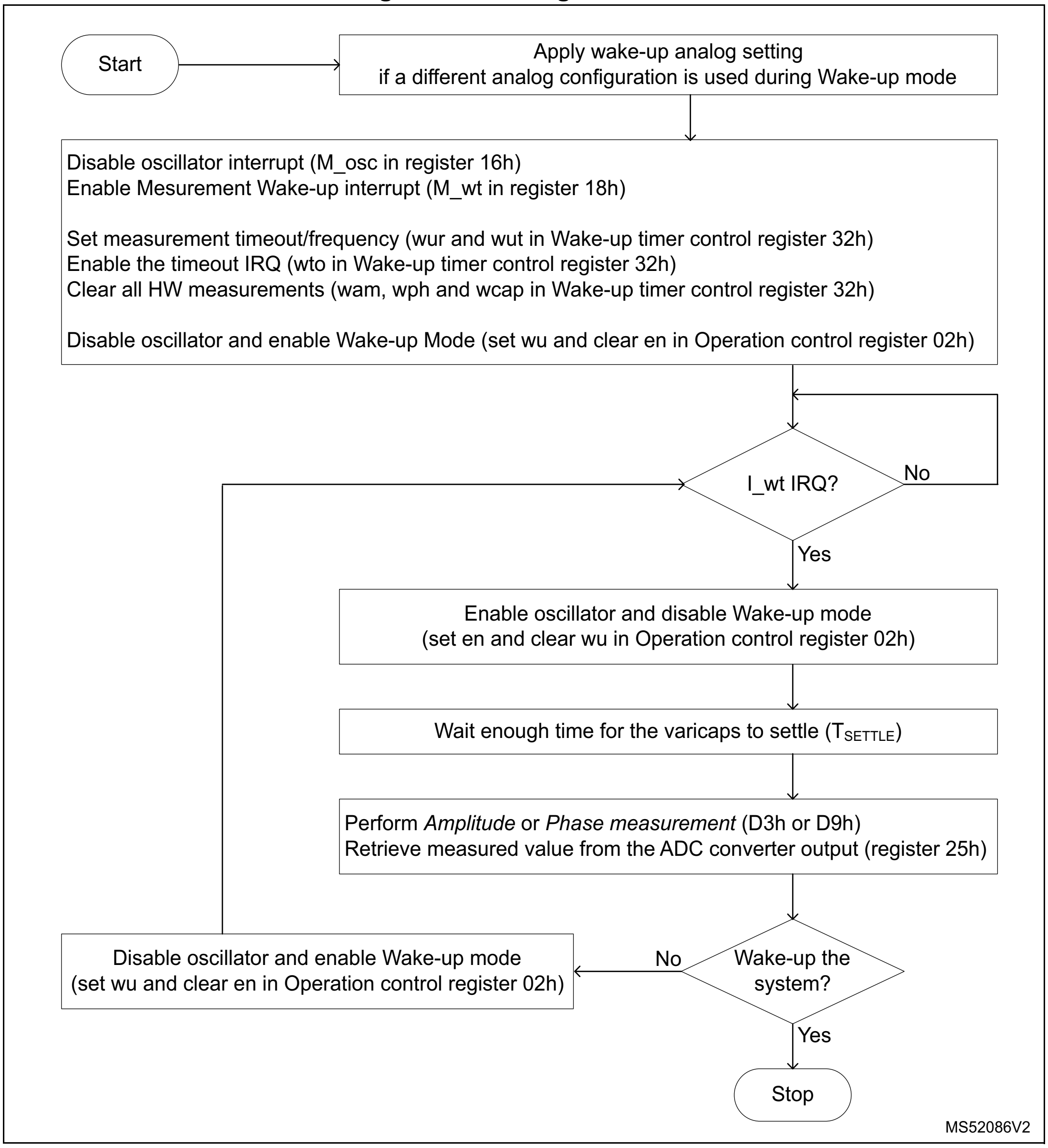
Note: An additional current consumption is expected when varicaps are assembled.

6.1 SW tag detection

In this case (see *Figure 17*) the ST25R3916 is put in Power-down mode, where the power consumption is minimal, and the Wake-up timer is used to wake/trigger the host MCU to periodically perform measurements.

The host MCU can be also placed in a low-power mode during this procedure. Periodically, when it receives the external IRQ from the device, the host puts it in Ready mode, and performs the required measurement(s) after the appropriate varicap settling time (they reach their final capacitance value after T_{SETTLE}, the amount of time to delay the measurement pulse until the varicaps have reached their final capacitance value). Then, it evaluates the difference from previous samples, and decides whether the system must poll for NFC devices, or go back to Low-power mode.

Figure 17. SW tag detection



To terminate the SW tag detection, execute the sequence described in *Section 4.3*.

To improve the robustness of the SW tag detection different wake-up methods can be applied, such as a moving reference (similarly to the procedure described in *Section 2.2*), or a fractional delta concept.

The main difference between the SW tag detection and the Wake-up mode is that the host must be periodically woken-up to execute the measurement(s), and the device is kept in Ready mode for at least T_{SETTLE} each period, with an impact on the overall power consumption and system responsiveness.

With SW tag detection T_{SETTLE} significantly influences the power consumption. Based on calculations described in *Section 5*, and assuming that $T_{OSC} < T_{SETTLE}$, the average power consumption of the ST25R3916 alone can be estimated as

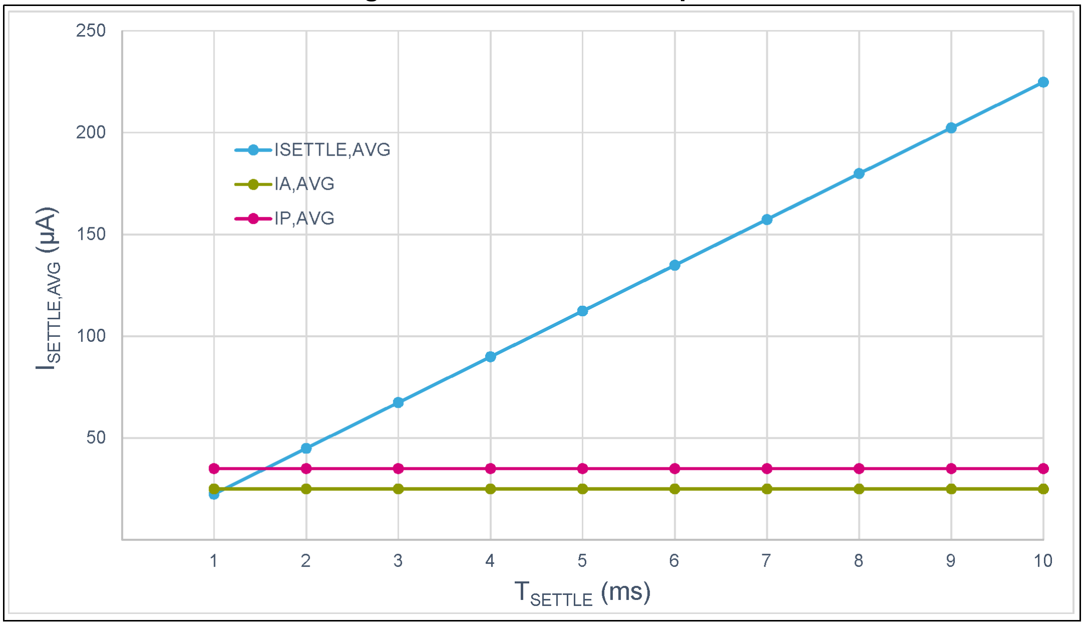
- $I_{AVG} = I_{C,AVG} + I_{IP,AVG} + I_{IA,AVG} + I_{SETTLE,AVG} + I_{WU}$
- $I_{SETTLE,AVG} = (I_{RD} - I_{WU})\ T_{SETTLE} / T_{OUT}$

Using the example presented in *Section 5* ($I_{IP} = I_{IA}$ = 200 mA, T_{out} = 200 ms), and with T_{SETTLE} = 5 ms the power can be calculated as

- $I_{SETTLE,AVG} = (I_{RD} - I_{WU})\ T_{SETTLE} / T_{OUT} = (4.5\times10^{-3} - 3.0\times10^{-6}) \times (5\times10^{-3} / 200\times10^{-3})$ = 112.43µA
- $I_{AVG} = I_{C,AVG} + I_{IP,AVG} + I_{IA,AVG} + I_{SETTLE,AVG} + I_{WU}$ = 0 + 0 + 25 + 112.43 + 3.0 = 140.43 µA

Figure 18 shows how $I_{SETTLE,AVG}$ increases linearly with T_{SETTLE}, impacting the overall power consumption.

Figure 18. Current consumption



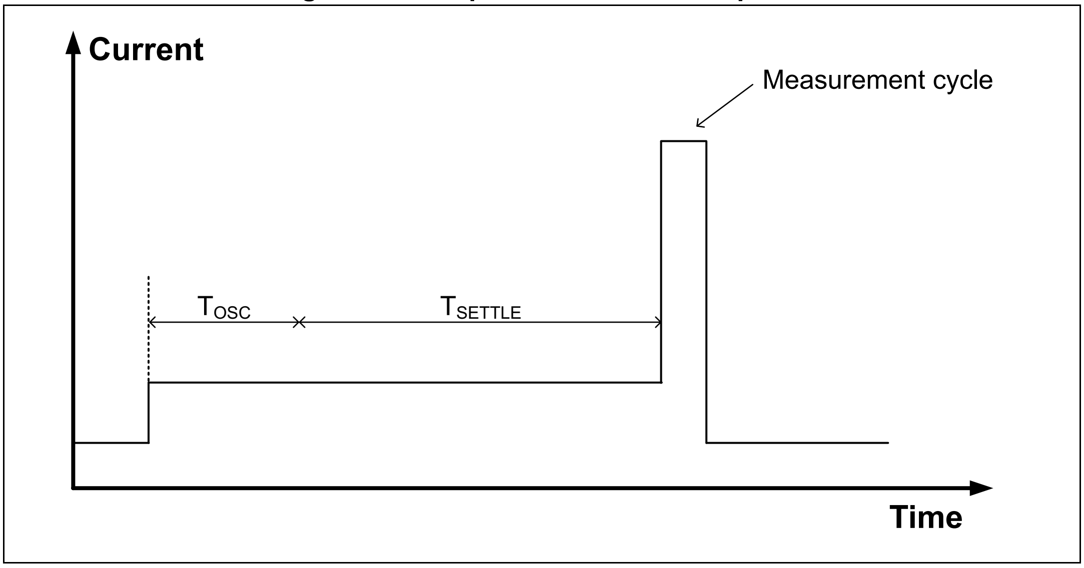
6.2 Measurement delay

This solution is available only on the ST25R3916B device.

It is possible to complete T_{SETTLE} ahead of the measurement pulse, thus enabling the wake-up mode together with AAT, without the need for SW tag detection. The timing can be adjusted via meas_tx_del bits (in combination with wur and wut bits), within a range from 0 to 12 ms. For detailed information refer to the datasheet, available on *www.st.com*.

As shown in *Figure 19*, once the wake-up timer triggers, the device moves into Ready mode, and postpones the inductive measurement pulse by T_{SETTLE}, depending upon the configuration.

Figure 19. Postponed measurement pulse



7 Conclusion

The low power Wake-up mode available on the devices addressed by this document allows the user to implement an optimized card detection, operating in complete autonomy from the microcontroller.

Thanks to this feature, the overall system current consumption is kept at a minimum, while still being reactive to cards approaching the NFC reader.

The availability of amplitude, phase, and capacitive wake-up sources results in a wide flexibility for customer design.

8 Revision history

Table 4. Document revision history

Date	Revision	Changes
09-May-2019	1	Initial release.
09-Jul-2019	2	Updated *Section 2.1: Low-power wake-up generator*, *Section 5: Wake-up mode power calculation* and *Section 6: Wake-up mode with AAT*.
06-Feb-2020	3	Updated *Section 5: Wake-up mode power calculation* and *Section 6: Wake-up mode with AAT*. Updated *Figure 2: Capacitive wake-up block diagram*,*Figure 5: Inductive amplitude block diagram*, *Figure 6: Inductive phase block diagram*, *Figure 9: Capacitive sensor calibration*, *Figure 10: Wake-up mode enable* and *Figure 17: SW tag detection*. Added *Figure 18: Current consumption*. Minor text edits across the whole document.
14-Aug-2020	4	Document scope extended to ST25R3917 and ST25R3920. Updated document title, *Introduction*, *Section 2: Wake-up mode* and *Section 6: Wake-up mode with AAT*. Added *Table 2: Wake-up mode capability*.
17-Dec-2021	5	Document scope extended to ST25R3916B. Updated document title, *Introduction*, *Section 6: Wake-up mode with AAT* and *Section 7: Conclusion*. Updated *Table 2: Wake-up mode capability*. Added *Section 6.1: SW tag detection* and *Section 6.2: Measurement delay*.
20-Oct-2022	6	Updated *Section 6: Wake-up mode with AAT*. Minor text edits across the whole document.
21-Jun-2023	7	Document scope extended to ST25R3917B, ST25R3918, ST25R3919B, and ST25R3920B, hence updated document title, *Introduction*, and *Table 2: Wake-up mode capability*.