Avery Dennison
Smartrac
Technical Guide

June 2021

Passive Sensors

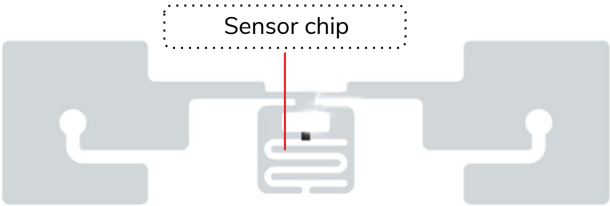
A guide to the working principles and usage of our passive sensor products using Axzon Magnus® S2 and S3 ICs.

Contents

Introduction

Avery Dennison Smartrac is the first manufacturer in the world to launch passive RFID sensors using Axzon's Magnus® S2 and S3 chips.

Traditional sensors usually require batteries or a power source, multiple electronic components, and dedicated sensor modules.



Avery Dennison Smartrac's passive sensor is a single-chip design that uses low-cost construction techniques, and requires no batteries and no maintenance. This results in a solution that costs a fraction of the price of traditional sensors, and its passive nature enables deployment in sensitive environments where an electric power source is not allowed.

The passive sensor is read using standard EPC UHF protocols, which allows for easy and flexible deployment using open international standards.

Sensor Chip Capabilities

There are three primary sensing functionalities of the sensor chip:

Chameleon Engine	The chip has a self-tuning capability to optimize performance for different antenna conditions. In a typical RFID tag, there is a frequency shift and performance loss when the tag is in the presence of water or metallic items. Passive sensor tags with Chameleon Engine can adjust their internal variable capacitance to match the impedance of the antenna in the presence of detuning materials, thereby improving performance. The degree of capacitance adjustment forms the basis for moisture and high-dielectric material sensing capabilities.
On-Chip RSSI	The chip has the ability to measure the amount of RF power received by the chip, and sends this information to the reader as a digital value. On-chip Received Signal Strength Index (RSSI) measures the power transmitted to the tag during the forward (Reader-to-Tag) link, compared to reader RSSI, which measures the power backscattered from the tag to reader, after most of the power has been consumed by the forward link and in powering the chip. Thus it is a better approximation of reader-to-tag proximity and power delivery.
Temperature Sensor Circuit	The chip has a temperature-sensing circuit built into the chip itself. The temperature of the chip silicon die is measured, and this information is sent to the reader as a digital value.

Sensor Working Principles

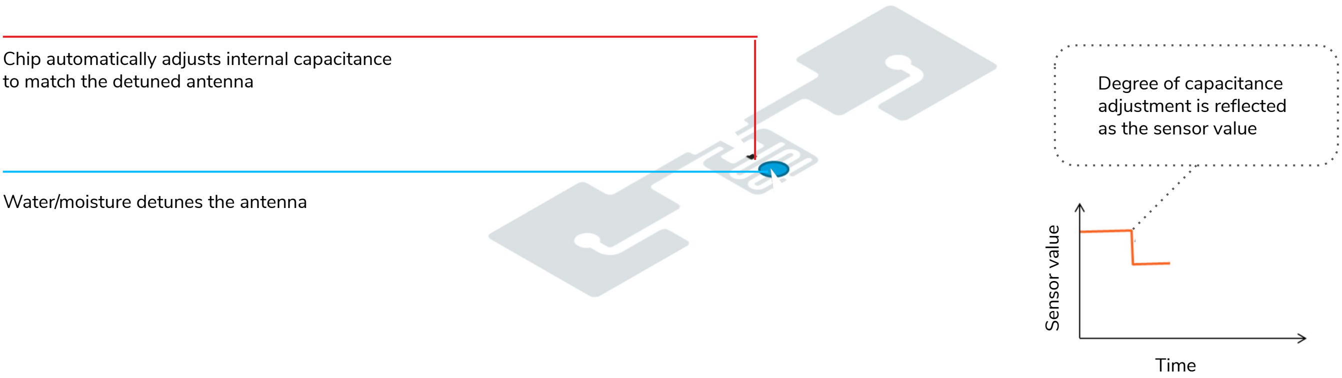
Moisture Sensing

It is well known that water detunes an RFID tag antenna, shifting its impedance away from its intended design value.

Avery Dennison Smartrac's Axzon based passive sensors have the capability to adjust their own internal capacitance to best match the new impedance value of the detuned antenna.

The degree of capacitance adjustment is reflected as the sensor value, or sensor code.

As the amount of moisture increases, the detuning effect becomes stronger. Thus the degree of capacitance adjustment becomes more pronounced, resulting in a larger sensor code change.

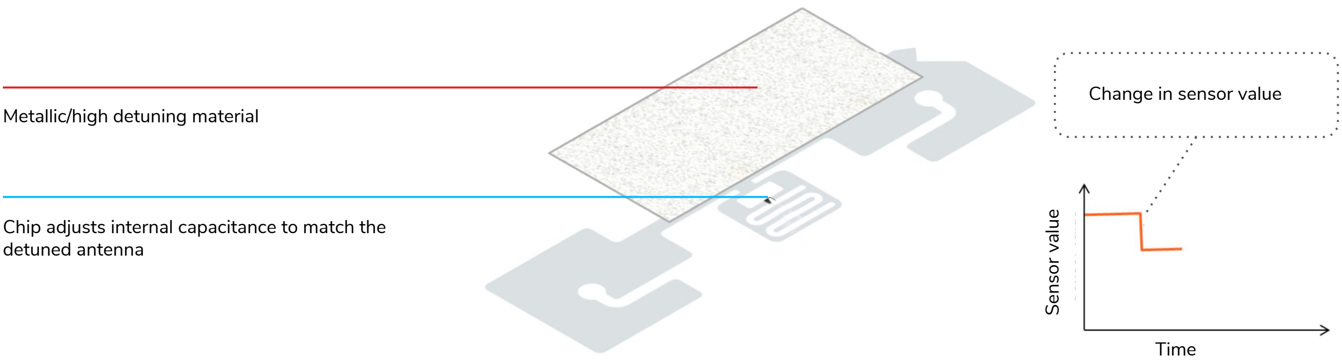


Proximity Sensing

When the antenna of an RFID tag comes into close proximity to a metallic or high-detuning object, it detunes the antenna in a similar fashion.

In this case, passive sensors can adjust their own internal capacitance to best match the detuned antenna, resulting in changes to the sensor code.

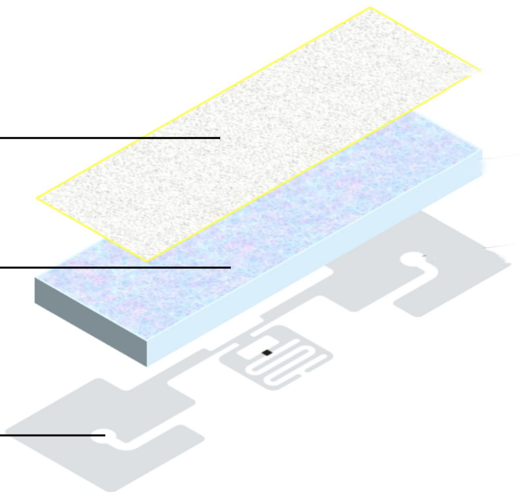
When the metallic object moves even closer to the antenna, the detuning effect becomes stronger and the sensor code changes further. This correlating relationship between proximity and sensor code enables the sensor tag to act as a proximity sensor.



Sensor Working Principles

Pressure Sensing

It is possible to use the same detuning principle to build a pressure sensor by sandwiching a compressible material, such as foam or rubber, in between a sensor tag and a layer of metallic foil, as shown in the diagram below:



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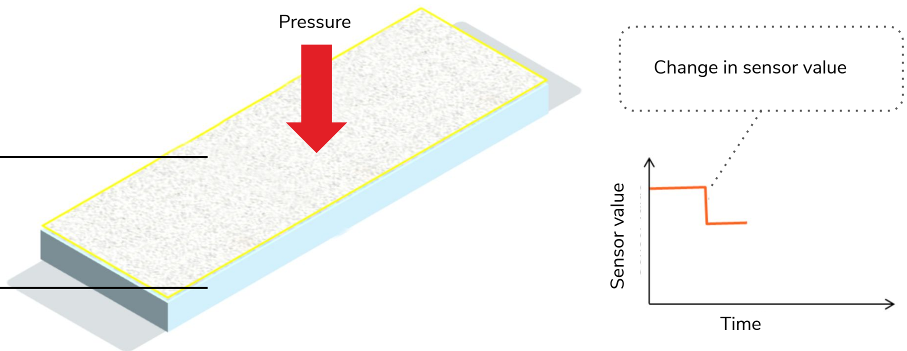


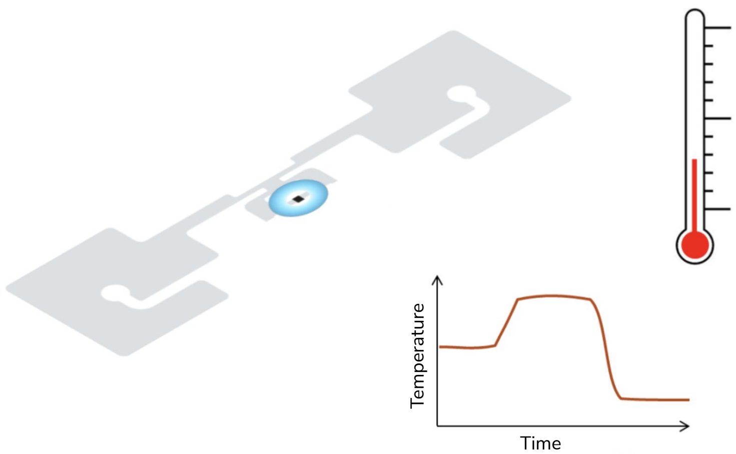
Sensor Working Principles

Temperature Sensing

Unlike moisture, proximity and pressure sensing, which operate using the principle of antenna detuning, temperature sensing is a function of the Integrated Circuit (IC) chip itself and is independent of the antenna.

The chip has a built-in temperature circuit, which is able to detect the temperature of the silicon die.

The temperature of the silicon die approximates to the same temperature as the surrounding materials due to heat transfer principles.

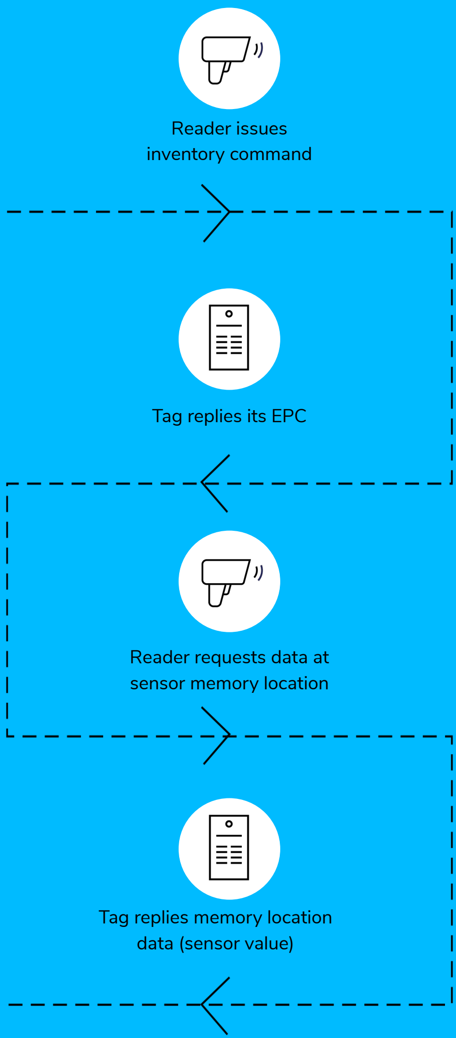


Sensor Tag Communication Method

Avery Dennison Smartrac's passive sensor tags are read using the UHF RFID (EPC Class 1 Gen 2) protocol.

The diagram below shows a simplified schematic of how an RFID reader communicates with a passive sensor tag and retrieves its sensor and temperature codes:

Reader*



Tag

Tag receives power, and continuously writes its sensor value into its own memory

*CSL (Convergence Systems Limited) CS108 handheld sled reader

IC Technical Specifications

Avery Dennison Smartrac passive sensors utilize ICs supplied by Axzon. Initially there were two models being used, the Magnus® S2 and Magnus S3.

The key difference is that Magnus S3 offers temperature-sensing capabilities while the Magnus S2 does not. Magnus S2 version has now End Of Life status.
The technical specifications of the ICs are as follows:

FEATURE	MAGNUS S2	MAGNUS S3
EPC Memory	128 bits / up to 272 bits	128 bits
User Memory	144 bits	176 bits
TID Memory	64 bits	64 bits
Sensor Code Resolution	32 steps (5 bits)	512 steps (9 bits)
On-chip RSSI Resolution	32 steps (5 bits)	32 steps (5 bits)
IC Operating Temperature	-40°C to 85°C	-40°C to 85°C
IC Sensitivity	Read: -16.1 dBm Write: -6.1 dBm	Read: -16.6 dBm Write: -9.9 dBm
Temperature Code Resolution	NIL	4096 steps (12 bits)
Temperature Accuracy	NIL	0°C to 50°C: ± 0.3 °C * -40°C to 85°C: ±1.0 °C *

*With 2-point calibration

Sensor Tag Designs

Standard Designs

Avery Dennison Smartrac offers following inlay designs:

1. Sensor Patch

The Sensor Patch design is targeted for use in diaper applications in the healthcare industry.

The sensor is very sensitive to moisture changes when used on light dielectric materials, but is not suitable for use in high-loading materials such as glass and ceramics.

Sensor Patch is available in different FCC and ETSI versions.

This product version using Magnus S2 will be End Of Life by end of year 2021.

2. Sensor Tadpole

Sensor Tadpole is an on-metal tag that is used for moisture and leak detection when mounted to a metallic surface.

It can be fitted with an optional absorbent paper tail that sucks up moisture and conducts it to the antenna surface. The tail can be attached to assembly interfaces that are prone to leakage, or put inside a crevice that the tag cannot access.

Sensor Tadpole is available in different FCC and ETSI versions.

Sensor Tag Designs

3. Temperature Dogbone®

Temperature Sensor Dogbone is a general-purpose temperature sensor that is designed to work across a wide variety of materials, providing both good read distance and sensing performance.

It is also sensitive to moisture and antenna detuning changes.

Temperature Sensor Dogbone® is available in different FCC and ETSI versions.

4. Customized Designs

There are some cases where customized designs are necessary.

Passive sensors work via the principle of self-tuning variable capacitance. But because there is a finite range to capacitance tuning before the value saturates, this means there is a limited "tuning window" when designing a passive sensor antenna.

This results in a design trade-off: a design that works on a wide range of materials but has lower moisture sensitivity (like Magnus S2 Sensor Dogbone® had), or a design that works on a very specific material but has very high moisture sensitivity (like Sensor Patch).

This means if both designs are used in a diaper application, the Sensor Patch can be used to measure the amount of liquid that is in the diaper (degree of wetness), whereas the Sensor Dogbone can only be used like an on-off switch (wet or dry).

Therefore, in scenarios where a very precise moisture or dielectric change measurement is required, and for a specific material (e.g. wood or concrete), a customized design is usually required.

Compatible Readers

Communications with Avery Dennison Smartrac passive sensor tags use standard EPC C1G2 protocols.

Strictly speaking, all EPC-compliant readers should be able to read the sensor values.

However, to get accurate sensor readings, special communication techniques to the reader are required:

- For on-chip RSSI code measurement, the reader must issue a Select command that will cause the chip to generate the On-Chip RSSI Code, which can then be read from a separate memory address with a standard Read command.
- On-chip RSSI is needed to facilitate accurate sensor code readings.
- For temperature measurements, the reader must issue a Select command that will cause the chip to calculate on-chip temperature, followed by a 3ms continuous wave to power up the temperature circuit, before reading the temperature code in a separate memory address with a standard Read command.

While the above special commands are within the scope of the EPC C1G2 protocol, many reader manufacturers only expose high-level APIs for commonly used commands.

To support these special commands, reader manufacturers may need to make minor firmware extensions to expose new APIs for these commands.

For a list of compatible RFID readers that already support these special commands, please contact your local Avery Dennison Smartrac sales representative.

Software and Sensor Value Acquisition

Overview

There are three main parameters that can be acquired from passive sensor tags:

- Sensor Code (degree of antenna detuning)
- On-chip RSSI (amount of power received by the chip)
- Temperature Code (temperature measured by the chip)

Reading the above codes require specific steps as outlined below:

To read Sensor Codes:
Read command to retrieve sensor code from a specific memory address

To read On-Chip RSSI:
1. Select command to a specific memory address to enable the chip to calculate RSSI
2. Read command to retrieve the On-Chip RSSI value from a separate memory address

To read Temperature Codes:
1. Select command to a specific memory address to enable the chip to calculate temperature. This must be followed by a 3ms continuous wave, to allow enough time for the temperature sensor circuit to operate.
2. Read command to retrieve the temperature code from a separate memory address

To convert temperature code into actual temperature value:
Apply conversion formula using the current measured temperature code and calibration values stored in the chip memory

Reading Sensor Code

Sensor Code can be read using the standard EPC C1G2 Read command. The memory location is shown in the table below:

Sensor Code Address			
Tag Model / TID header	Memory Bank	Word Address	No of bits in Sensor Code
Magnus S2 / E282 402_h	Reserved (Bank 0_h)	B_h	5 bits (0 - 31)
Magnus S3 / E282 403_h	Reserved (Bank 0_h)	C_h	9 bits (0 - 511)

Software and Sensor Value Acquisition

Reading On-Chip RSSI Step 1

Send standard EPC C1G2 Select command to alert all tags with an On-Chip RSSI code greater than or less than/equal to a specified threshold.If the on-chip RSSI falls outside of this threshold, the on-chip RSSI value will not be generated and thus the subsequent Read command fails. The Select command is as follows:

Select Command Parameters for On-Chip RSSI				
Tag Model /TID header	Memory Bank	Pointer Bit Address	Mask Length	Mask Value
Magnus S2 / E282 402_h	User (Bank 3_h)	B_h	5 bits (0 - 31)	See below
Magnus S3 / E282 403_h	User (Bank 3_h)	C_h	9 bits (0 - 511)	See below

Mask Value								
Mask Bit	M7	M6	M5	M4	M3	M2	M1	M0
Mask Bit Value	0	0	0: Match if code is <= threshold 1: Match if code is > threshold	5-bit threshold Most significant bit first				

This allows for filtering to ensure only those tags within desired power thresholds respond to the command. It is also possible for on-chip RSSI to be generated every time regardless of the on-chip RSSI value by setting the threshold to the maximum. This is done by defining M5 = 0 and M0 to M4 as the maximum value of 11111, resulting in an 8-bit mask of 00011111 (1Fh).

Reading On-Chip RSSI Step 2

Send standard EPC C1G2 Read command to retrieve the specific On-Chip RSSI Code for a particular tag that satisfies the power threshold criterion.

On-Chip RSSI Address			
Tag Model /TID header	Memory Bank	Word Address	No of bits in on-chip RSSI
Magnus S2 / E282 402_h	Reserved (Bank 0h)	D_h	5 bits (0 - 31)
Magnus S3 / E282 403_h	Reserved (Bank 0h)	C_h	9 bits (0 - 511)

Reading Temperature Code Step 1

Send standard EPC C1G2 Select command with the parameters described below to initialize the temperature sensor and calculate a Temperature Code, followed by 3ms of continuous wave. The 3ms CW provides time for the temperature sensor circuit to run.

Select Command Parameters for Temperature Code				
Tag Model /TID header	Memory Bank	Pointer Bit Address	Mask Length	Mask Value
Magnus S3 / E282 403_h	User (Bank 3_h)	$E0_h$	0_h	empty

Reading Temperature Code Step 2

Send standard EPC C1G2 Read command to retrieve the Temperature Code from the tag memory at the location given in the table below.

Select Command Parameters for Temperature Code			
Tag Model / TID header	Memory Bank	Word Address	No of bits in on-chip RSSI
Magnus S3 / E282 403_h	Reserved (Bank 0_h)	E_h	12 bits (0 - 4095)

Software and Sensor Value Acquisition

Converting Temperature Code to Actual Temperature and Calibration Data

The Temperature Code can be converted into actual temperature (in degrees Celsius) by translating the measured Sensor Code, using calibration values stored on the chip's memory. This is done at the application software level.

The conversion formula is as follows:

$$\text{Temperature in Deg Celsius} = \frac{1}{10}\left[\frac{\mathrm{TEMP2}-\mathrm{TEMP1}}{\mathrm{CODE2}-\mathrm{CODE1}}(\mathrm{C}-\mathrm{CODE1})+\mathrm{TEMP1}-800\right]$$

Temperature Calibration Data				
Field Name	Memory Bank	Starting Bit No. (MSB)	No. of Bits	Description
CODE1	User (Bank 3_h)	90_h	12	Temperature Code of 1st Calibration Point
TEMP1	User (Bank 3_h)	$9C_h$	11	(Temperature of 1st Calibration Point in °C) x 10 + 800
CODE2	User (Bank 3_h)	$A7_h$	12	Temperature Code of 2nd Calibration Point
TEMP2	User (Bank 3_h)	$B3_h$	11	(Temperature of 2nd Calibration Point in °C) x 10 + 800
C	Reserved (Bank 0_h)	E_h	12	Measured Temperature Code to be converted (note: Select command and 3ms continuous wave must be applied before Temperature Code can be retrieved)

Conversion into the Fahrenheit scale can be calculated from the Celsius values using the standard formula.

For more information on Temperature Calibration, please refer to "Temperature Calibration" in the next section, "Techniques for High Accuracy Reading".

Further Information and Sample Codes

For more detailed information and sample codes, please refer to Axzon's application notes.

Techniques for High-Accuracy Reading

Power Distortion and Modulation

If there is too much or too little power running through the tag chip, the linearity and accuracy of both sensor and temperature codes will be affected.

To ensure the optimal amount of power is running through the chip circuit, the on-chip RSSI should be within a target value (not too high or too low) before the Sensor Code is measured.

For accurate sensor and temperature code measurements, the on-chip RSSI values should be within the thresholds shown below:

Recommended Max and Min On-Chip RSSI for Accurate Sensor Readings

Parameter	IC	Min On-Chip RSSI	Max On-Chip RSSI
Sensor Code	Magnus S2	16	21
Sensor Code	Magnus S3	13	21
Temperature Code	Magnus S3	13	18

If on-chip RSSI is too high, the application software can provide feedback to the reader to reduce power, and vice versa. This technique is known as power modulation.

An alternative method is to simply move the tag and the reader closer or further apart, thus changing the power levels received by the tag.

Reader Channel Frequency Effects

Regulations require UHF RFID readers to hop across different frequency channels when transmitting. However, the sensor code is affected by reader transmission frequency, and frequency hopping affects sensor code accuracy.

To overcome this issue, there are three main software techniques:

- The reader continues to perform frequency hopping, but software only records sensor code values when read at one specific frequency
- Software takes the average of many values across a wide frequency band
- The regression analysis method is used to calculate deviation at specific frequencies

Note that the frequency only affects the sensor code, but not the temperature code.

Techniques for High-Accuracy Reading

Reader Channel Frequency Effects

Due to the analog nature of the IC circuitry, there is inherent noise in the sensor and temperature codes, which can be reduced by averaging multiple readings.

This is especially so for temperature codes. To obtain a 95% confidence level for sensor code accuracy, the recommended number of samples to be averaged is shown in the table below:

Recommended Max and Min On-Chip RSSI for Accurate Sensor Readings	
95% Confidence Intervals for Temperature Code (Not Actual Temperature)	Number of Samples
± 3	1
± 2	3
± 1	9
± 0.5	35
± 0.25	139

Additionally, sensor codes may experience unexpected momentary spikes. Application software can be designed to filter out outliers so that these values do not skew the average.

This is recommended for both sensor and temperature code acquisition.

Temperature Calibration

Avery Dennison Smartrac passive sensor tags chips come with 1-point calibration as default. This calibration value is stored in the memory of the tag. 1-point calibration yields a temperature accuracy of ±2 °C in the 0°C to 50°C range.

For higher accuracy applications, 2-point calibration is required. This yields a temperature accuracy of ±0.3 °C in the 0°C to 50°C range. Avery Dennison Smartrac can set 2-point calibration as an add-on service, by performing the calibration in a highly temperature-controlled temperature chamber.

It is also possible for end users to set 2-point calibration themselves. Temperature accuracy can be further enhanced by pegging the calibration temperature close to the target application temperature e.g 35∘C and 42∘C for body temperature.

Temperature Code Command Timing

To maximize temperature accuracy, it is recommended that the reader send a 3ms continuous wave to the tag by using a specific Select command. This is used to power up the temperature circuit with a continuous power source. The temperature code can be read from a separate memory location thereafter.

However, this is a non-standard command that may not be supported by all readers.

Further Information and Sample Codes

For more detailed information and sample codes, please refer to Axzon’s application notes.

Frequently Asked Questions

Q	A
Can the tags measure air humidity?	Tests have shown that with a hydrophilic layer on top of the antenna, the sensor code does respond to air humidity changes. However, further tests are needed to study the long-term accuracy and linearity of this concept. Humidity is also a function of both ambient temperature and water vapor in air so a simple moisture sensor cannot be used.
Can the tags be used to log temperature and sensor values independently?	No. The tags are fully passive and are only powered up when they are in front of a reader. Logging scenarios require the tags to be constantly powered by a reader, and measurements are logged via the system software.
What is the accuracy of moisture sensing?	This depends on the antenna design. The sensor tag can be designed with a wide sensing window that can work in a broad range of conditions, but has lower sensitivity to moisture changes. These are usually used as on-off switches (wet vs. dry). Alternatively, the tag can be designed with a narrow sensing window that can work well in one specific application, but has very high sensitivity to moisture changes. This design is normally used to measure the degree of wetness.
I have a specific application that requires high sensitivity to very slight moisture changes. Can I use an existing Avery Dennison Smartrac design?	If the specific application is used on the same material as, and has a similar tuning window to, an existing design, then it can be used. In most cases, a dedicated antenna design is required.
How can I determine if I need a dedicated antenna design?	A dedicated antenna design is needed if the tag is operating outside its operating sensing window. This is the case when: • The sensor code is pegging to minimum [0] or maximum [31]; OR • Abrupt sensor code movements are detected (after taking account of on-chip RSSI, averaging and frequency hopping); OR • The tag's moisture detection area is not used as intended in the instructions
Can the temperature sensor be used for measurement in very high temperature applications of more than 100°C?	This is not recommended. The temperature sensor circuit in the chip saturates and is no longer accurate or linear at very high temperatures e.g over +65°C.

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Frequently Asked Questions

Q	A
How can I translate sensor values into physical measurement units? (e.g. volume of liquid, force applied, degrees Celsius)	For temperature, the temperature codes can be directly translated into physical units using a translation table. For sensor codes (moisture, pressure, etc.), external calibration to physical units needs to be performed at the customer application software level.
Can I measure pressure, moisture and proximity independently and at the same time?	No. These specific measurements all use the same antenna detuning compensation concept to achieve sensing capabilities. They are all represented by a single sensor code, thus multiple stimuli cannot be measured independently.
Are there any preferred reader / system integrator partners for passive sensing inlays AveryDennison could recommend?	Yes, multiple actually. Following companies support Axzon technology based passive sensing on HW/SW level and system integration side.

nordic id	Temperature/Moisture
SensThys Sense This World	Temperature/Moisture
CSL Convergence Systems Limited	Temperature/Moisture
TURCK	Automotive, water leakage
TURCK Vilant Systems	Moisture
KATHREIN	Moisture

Contact information
rfid.averydennison.com/contact
North America: +1-866-903-7343 (toll free US)
International: +1-678-617-2359

Connect with us on:

AVERY DENNISON