CO2 sensor Design concept for solar-powered CO2 sensor

1. Introduction

The concentration of carbon dioxide (CO₂) in a room is an indicator for indoor air quality (IAQ). CO₂ sensors are therefore used to measure indoor air quality in a building to perform demand-based ventilation. Sensors for this purpose operate in the range between 500 and 5000 ppm (ppm = parts per million, e.g. 10000 ppm = 1%).

The figure below shows a typical CO₂ concentration in an office during the day.



Figure 1 - example of CO2 level in an office

As shown in the table below a level of 800 to 1200 ppm inside a building is seen as "well ventilated". Achieving lower levels will result in additional energy usage e.g. by the van or heating/cooling. Achieving only higher levels might result e.g. in reduced concentration or well-being of the people in the room.

CO ₂ concentration	Physiological effects
400 ppm	Outdoor – current average level in nature (fresh air)
500 – 700 ppm	Indoor – over ventilated
800 – 1200 ppm	Indoor – well ventilated
1500 – 5000 ppm	Indoor – under ventilated
5000 ppm (0.5%)	MAK-level: max. concentration for an 8 hour working day
1 - 3 %	Reduced concentration, drowsiness, headaches
4 – 5 %	expiratory concentration, increased heart and lung activity
10 - 20%	Flame extinguishes, vomiting, unconsciousness
>20%	Death in a few seconds

CO2 sensor Design concept for solar-powered CO2 sensor

1.1 Purpose

In order to build an energy-harvesting self-powered sensor the main challenge is energy consumption. Most of today's available CO_2 sensors require by far too much energy to be operated in such a system. However, this document demonstrates a self-powered CO_2 sensor using an energy optimized sensor from Gas Sensing Solutions (see **[10.]**) in combination with a smart measuring concept based on EnOcean's STM 300 radio module.



Figure 2 - Solar powered CO2 sensor

This application note describes the principles how to built such a self-powered CO_2 sensor and is intended as basis for own developments. It does not reflect a ready-to-use reference design. The respective software is also available for download from the EnOcean website.

NOTE: The software AN313SW, which is part of this Appnote is provided on an "AS-IS" basis.

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CO2 sensor

Design concept for solar-powered CO2 sensor

1.2 Table of content

1
2
3
4
4
5
6
9
9
. 11
. 11
. 11
. 12
. 13
. 13
. 14

CO2 sensor Design concept for solar-powered CO2 sensor

1.3 References

Further details can be found in the following documentation:

[1.] DolphinAPI user manual, EO3000I_API.chm

- [2.]STM 300 user manual
- [3.]EnOcean Equipment Profiles (EEP)

[4.]COZIR data sheet, GSS COZIR Data Sheet.pdf

[5.]COZIR software user's guide, COZIR Software User's Guide AL12 RevA.pdf

[6.]MAX1595 step-up/step-down charge pump data sheet, Rev. 2

Useful web sites:

[7.]EnOcean, http://www.enocean.com

[8.]EnOcean Alliance http://www.enocean-alliance.org

[9.]Wikipedia http://en.wikipedia.org/wiki/Nondispersive_infrared_sensor

- [10.] Gas Sensing Solutions http://www.gassensing.co.uk/
- [11.] Maxim http://www.maxim-ic.com/

2. Demonstration

The demonstrated system measures CO_2 concentration, ambient temperature (chip temperature) and storage charge level every 10 min and transmits the data via radio. In case of a poor charge level (<20%) the measurement and transmission in ceased until a higher charge level is reached. Additionally, an automatic long-term calibration mechanism is implemented taking care of long-term effects like dust or dirt in the sensor.

Using an existing EnOcean equipment profile (EEP A5-09-04) the humidity level would represent the energy storage capacitor charge level. Using DolphinView and a USB 300 as receiver the system can be easily monitored with the EEP view window.

NOTE: The current FW implementation is only for feasibility demonstration and does not comply with the EEP A5-09-04 specification.



CO2 sensor

Design concept for solar-powered CO2 sensor



Figure 3 – DolphinView / EEP View

2.1 System overview

The block diagram below shows the functional blocks of the self-powered CO_2 sensor system. The energy provided by the solar cell is stored in a long-term storage capacitor (super cap) supplying the system with its operating voltage. The power supply of the embedded CO_2 sensor is controlled from the STM 300 via the WXIDIO pin allowing switching off the embedded sensor during sleep times. The embedded sensor needs a constant 3.3 V operating voltage generated by a step-up/step-down charge pump (DC/DC converter).

CO2 sensor Design concept for solar-powered CO2 sensor



Figure 4 – Block diagram CO2 sensor

As can be seen in the **2.2** Schematics chapter special care is required on the interface between powered and not powered components, in particular between embedded sensor and STM 300 (e.g. ADIO6, ADIO7).

2.2 Schematics

The demonstration is based on an A-Si indoor solar panel similar (bigger size) to ECS 3x0, with following parameters:

Size	67.0 x 28.0 x 1.1 mm
Number of cells	8
open circuit voltage @200 lux, 25°C	4 V
short circuit current @200 lux, 25°C	25 uA
operating voltage @200 lux, 25°C	3 V
operating current @200 lux, 25°C	19 uA

For the storage of the energy provided by the solar cell 2 x 0.22 F super caps (NEC TOKIN FC0H224ZTBR24) are used. For the demonstration, the super caps were selected with a high capacitance combined with the capability to provide some mA required in order to provide the current needed by the STM 300 and embedded CO_2 sensor.

CO2 sensor Design concept for solar-powered CO2 sensor



Figure 6 – STM 300

As the embedded CO_2 sensor requires a fixed 3.3 V (VDD2) supply voltage a DC/DC converter is used to derive this voltage from VDD. The MAX1595 charge-pump regulator generates 3.3 V from a 1.8 V to 5.5 V input. The solar cell generated VDD (operating) can vary from 1.8 V up to 5.5 V during operation. Two MOSFETs enable to turn off the sensor supply for energy consumption reasons. Using the WXIDIO pin for the control, which is also supplied during deep sleep, allows supply the sensor even if the STM 300 is in deep sleep mode. The other pins ADIO 0-7, SCSEDIO0, SCLKDIO1, WSDADIO2 and RSDADIO3 are not powered in deep sleep mode and cannot be used for this purpose.





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CO2 sensor Design concept for solar-powered CO2 sensor

As already mentioned before, special care is needed on the electrical interface between powered and not powered parts of the system. For instance, it is not allowed to apply any voltage on the ADIO6 pin (diode D1) during deep sleep mode (see [2.] 2.3.1 GPIO supply voltage).

Sensor interface



Figure 8 - Sensor interface

To program the STM 300 in system a connector to the EOP 3x0 programmer is foreseen. The EOP 3x0 needs to be operated with 3.3 V.





CO2 sensor Design concept for solar-powered CO2 sensor



Figure 10 – DEMO Implementation example

2.3 Embedded CO₂ sensor

The COZIR[™] ultra low power carbon dioxide sensor uses non-dispersive infrared (NDIR also see **[9.]**) configuration, utilizing unique mid-infrared light emitting diode source and photo diode detector technology.

The sensor is optimized for battery-powered applications and has following key features:

- Low power consumption (3.5 mW in continuous operation)
- Fast power-up time
- Battery operated (3.3 V)
- Auto calibration
- Standard digital output (serial interface)
- Optional humidity and temperature measurement available

The COZIR carbon dioxide sensor is available in two ranges:

COZIR ambient with a 0 to 2,000 ppm range suitable for applications such as heating, ventilation and air conditioning (HVAC), indoor air quality (IAQ), education and horticulture.

COZIR wide range with a 0% to 100% range suitable for process control applications such as diving, industrial, safety and automotive.

2.4 CO2 measurement

In a self-powered application there is not enough energy available to permanently supply the embedded sensor. Therefore, a dynamic power concept is required to reduce the energy consumption.



CO2 sensor Design concept for solar-powered CO2 sensor

After device power up, it takes about two seconds till the sensor delivers the first measurement results on the serial interface. During these two seconds, the sensor has actually performed four internal measurements used to calculate the first result. The STM 300 enters deep sleep mode for these two seconds, in order to reduce current consumption. After receiving of the measurement result, the sensor power supply is switched off and the result is send via radio. Then the STM 300 enters deep sleep mode for the next 10 minutes.



Figure 11 - one measurement cycle

One measurement cycle:

- 1. STM 300 module wakes up from deep sleep mode after the preset time (Watchdog Timer Reset)
- 2. STM 300 turns on sensor power (set WXIDIO to high)
- 3. STM 300 enables wakeup on sensor TX line and sets watchdog timer for sensor timeout (3 seconds in case no answer-> wakeup from sensor)
- 4. STM 300 enters deep sleep mode to wait for sensor result (or timeout)
- Sensor performs CO₂ measurement (actually four single measurements are made internally). After about two seconds the result is output on the serial port TX line: "Z 00879 z 00875\r\n"
- 6. The first falling edge on the TX line generates a falling edge on the WAKE0 pin waking up the STM 300 module
- 7. The STM 300 module starts from reset, enables the UART and receives the remaining characters on the serial line (first <space> is lost) and turns of the sensor power off as soon as it has received the necessary first characters **"Z 00879"**
- 8. STM 300 converts the value and sends the information via radio
- 9. STM 300 sets the watchdog timer to 10 minutes and enters deep sleep mode with WAKE0 wakeups disabled

CO2 sensor Design concept for solar-powered CO2 sensor

2.5 Chip temperature sensor

The demonstration utilizes the possibility to use the internal chip temperature sensor for measuring ambient temperature. This works for an application where the chip is on the same temperature than ambient without any power dissipation to falsify the result.

NOTE: The STM300 module needs to be calibrated in order to use the internal chip temperature sensor.

2.6 Energy monitoring - charge level

To monitor the energy consumption a charge level of the capacitors is calculated and transferred via radio. The charge level is evaluated by measuring the voltage VDD on the storage element. The usable voltage from 2.4 V up to 4.5 V is scaled to 0% up to 100%.



Figure 12 - Charge level

Apart from transmitting the charge level for diagnostic and energy evaluation purposes the value is also used to operate the system in a save operating area (down to 20%). Switching on the embedded sensor causes voltage dips during periods with higher current consumption of up to 0.6 V. These voltage dips might cause under voltage resets.

2.7 Radio telegram

The CO₂ sensor sends the following telegram, similar to the EEP: A5-09-04

As first data field the charge level (see **2.6 Energy monitoring - charge** level) is send instead of the rel. humidity.

NOTE:	The	current	implementation	does	not	comply	to	the	EEP	A5-09-04
	spec	ification a	nd needs modification	ations f	for an	end prod	duct.			

Offset	Size	Description	Valid range	Scale	Unit
0	8	Charge level (linear 0.5%)	0200	0100	%
8	8	CO2 concentration (linear 10ppm)	0255	02550	ppm
16	8	Temperature (linear 0.2°C)	0255	0+51.0	°C
28	1	LRN bit	1 data		
29	1	Humidity valid	0 not valid		
30	1	Temperature valid	1 valid		



CO2 sensor Design concept for solar-powered CO2 sensor

The figure below shows the actual EEP A5-09-04 profile as reference:

RORG	A5	4BS Telegram
FUNC	09	Gas Sensor
TYPE	04	CO2 Sensor

Offset	Size	Bitrange	Data	ShortCut	Description	Valid	Range	Scale	Unit		
0	8	DB3.7DB3.0	Humidity	ним	Rel. Humidity (linear), 0.5 % = 1 bit	0200)	0100	%		
8	8	DB2.7DB2.0	Concentration	Conc	Concentration (linear), 10 ppm = 1 bit	0255	5	02550	ppm		
16	8	DB1.7DB1.0	Temperature	тмр	Temperature (linear), 0.2 °C = 1 bit	025	5	0+51.0	°C		
24	4	DB0.7DB0.4	Not Used (= 0)							
28	1	DB0.3	LRN Bit	LRNB	LRN Bit	Enum:					
						0:	0: Teach-in telegram				
						1:	: Data telegram				
29	1	DB0.2	H-Sensor	HSN		Enum:					
		5			0:	0: Humidity Sensor not available					
					1:	Humidity	Sensor avail	able			
30	1	DB0.1	T-Sensor	TŚN		Enum:					
				0.		0:	Tempera available	iture Sensor r	not		
						1:	Tempera available	ture Sensor			
31	1	DB0.0	Not Used (= 0)							

Figure 13 - EEP A5-09-04

2.8. Embedded CO₂ sensor recalibration

The embedded CO₂ sensor requires a recalibration from time to time due to effects e.g. caused by dust or dirt in the optics. The method for recalibration assumes that during a longer timeframe of e.g. 2-3 weeks the sensor will at least measure once a "fresh air" CO₂ level.

In applications where the embedded sensor is permanently supplied it automatically performs this recalibration. In the self-powered system the STM 300 needs to take care of this functionality.

For the recalibration the STM 300 needs to monitor the lowest measured CO_2 level (in a given timeframe) and the time. This data is stored in RAM0 during deep sleep periods.

```
// -----
// Structure of RAMO area
typedef struct
{
    uint8 u8State; // used to store system state during deep sleep
    uint8 u8ChargeLevel; // used to store charge level during sleep
    uint16 u16MinCO2Level; // used for dynamic sensor calibration
    uint16 u16WakeupCnt; // used for dynamic sensor calibration
} tRam0;
```

CO2 sensor

Design concept for solar-powered CO2 sensor

To monitor the time, simply the number of wakeups is counted. After a defined period, the recalibration would be done by sending an "F" command (see **[5.]**) to the embedded sensor.

2.8.1 Using the "F" command recalibration

The recalibration uses the difference between the lowest measured CO₂ level during the timeframe (assumed to be "fresh air" level) to a known "fresh air" level of e.g. 450 ppm.

For instance if the lowest CO₂ reading was 460 ppm than the STM 300 needs to send a "F" command "F 460 450\r\n" to the sensor.

The following steps need to be handled

- Ensure that the sensor is ready to receive commands (wait at least 100 ms after power on)
- Send the actual F command with the calibration values

Wait till F command is executed and calibration data is stored inside the embedded sensors EEROM memory. This can be evaluated by waiting for the sensor to reply to the F command.



Figure 14- F command recalibration

NOTE: The current implementation does not wait for the reply and simply waits 100 milliseconds and then turns the sensor supply off.

2.9 Some energy considerations

Evaluating energy consumption has shown that the used solar cell provides enough energy to operate the sensor. To maintain a steady state condition (amount of energy provided by the solar cell = amount of energy used by the application) about 180 lux (waking up every 10 minutes) are needed. This are about 16.6 μ A * 600 s = 10000 μ As during a 10 minutes interval.

Fig. 15 shows how the energy is consumed between the different functional blocks. The most energy is related to the CO_2 measurement: about 60% is used by the embedded sensor for the measurement (powered for two seconds). An additional 40% are caused by the DC/DC converter supply current and the converting efficiency.



CO2 sensor Design concept for solar-powered CO2 sensor



Figure 14 - Energy consumption

3. Outlook – Limitations

The demonstration proves the feasibility of a solar-powered wireless CO_2 sensor, but is not optimized for energy management, e.g. will not survive the night (no recharging). To convert this demonstration to a final product still some effort needs to be spent. Some of the things that need to be considered in more detail are

required measurement rate

maybe dynamic adopting measurement rate to available energy (charge level) or day/night time (reduce measurement rate during night time, or when room is dark)

- size of solar cell and capacitors
- need for long term and short term storage including charge management

synchronization to uart communication after wakeup (see 0). This is currently performed by enabling the uart (uart_init()) at fixed time after the wakeup. It has not been evaluated/tested if this will work under all circumstances. An optional approach could be to monitor the first bit changes on the TX line and to enable the uart on detection of a specific "bit" pattern.

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