Hogeschool Rotterdam

Electrical Engineering

Smart Dimmer

Crownstone

Internship Report

Student
Jaap Sontrop

Company Supervisor
Anne van Rossum

Supervisor
Erwin den Boer

November 12, 2021

Contents

List of Figures

List of Tables

Summary/Samenvatting

Samenvatting van het stageverslag

ToDo

1 Introduction

This chapter describes the assignment of the internship and gives a brief description of Crownstone.

1.1 About Crownstone

Crownstone, an innovative company based in Rotterdam, builders of smart plugs and connectors (Dutch: kroonsteentjes). Crownstone develops small form factor modules which can be put behind a power outlet. This module is a 16A switch, LED dimmer, power meter, soft-fuse, standby-killer and presence sensor in one device. Unique selling point is the indoor localisation of smartphones and wearables, which makes it possible to automatically turn on and off or dim lights based on the users presence.

1.2 Problem definition

Crownstone would like to expand their product line around smart home products. The available Crownstone modules are made to be placed behind a wall outlet or light switch. By developing smart wall switches and smart wall dimmers, Crownstone can offer an even more complete range of products.
In this product it's important that no neutral line is necessary for operation, since the switch boxes in older homes are only equipped with a live and switching wire.

1.3 Assignment and objective

The final goal of this internship is realising a prototype of a smart wall switch and dimmer.
Initially the prototype will make use of an nRF52832 microcontroller. This is a Bluetooth 5.2 System-on-Chip (SoC) with support for Bluetooth Low Energy (BLE) and Bluetooth mesh.
In a later prototype an nRF5340 or nRF9160 microcontroller will be used. Where nRF5340 has the same features as the microcontroller used in the first prototype, but has a dual-core and adds support for Zigbee and Thread. The nRF9160 is a low power System-in-Package (SiP) with integrated LTE-M/NB-IoT modem and GPS.

2 Definition phase

2.1 Program of requirements

In this section the system's requirements will be discussed. All requirements are catogorized using the MoSCoW method (Table 1).

Abbreviation	Meaning	
MH	Must Have	This requirement needs to be developed to ensure proper functioning of the product.
SH	Should Have	Not necessary, but meeting this requirement is desirable.
CH	Could Have	Not necessary, only when there is time.
WH	Won't Have	Not needed.

Table 1: MoSCoW abbreviations

2.1.1 Power supply

REQ1.1[MH]	The system shall operate on a voltage between $207V$ and $253V$ RMS.
REQ1.2[MH]	The system shall be able to operate without the need of a neutral wire (2-wire).
REQ1.3[SH]	The system shall be able to operate with the use of a neutral wire (3-wire).
REQ1.4[MH]	Zero crossings of the AC line shall be detected.

2.1.2 Dimmer and switch

REQ2.1[MH]	The system shall have a leading edge dimming mode.
REQ2.2[MH]	The system shall have a trailing edge dimming mode.
REQ2.3[MH]	The system shall dim loads up to $TODO$ Watt.
REQ2.4[MH]	The system shall be able to dim all types of dimmable bulbs.
REQ2.5[MH]	The system will be controlled via Bluetooth.
REQ2.6[SH]	The system will be controlled via buttons.
REQ3.1[CH]	The product will have a relay to switch high power loads.
REQ3.2[CH]	The relay shall be switched on a zero crossing of the AC power.

2.1.3 Microcontroller

REQ4.1[MH]	The system shall use a certified nRF52832 module.
REQ4.2[MH]	The SoC module shall have an integrated antenna.
REQ4.3[MH]	The SoC shall run Crownstone's Bluenet firmware.
REQ4.4[MH]	The system shall have an UART connection for debugging.
REQ4.5[MH]	The system shall be programmed via the SWD connection.

2.1.4 Safety requirements

REQ5.1[MH]	The product will shut down when the temperature gets too high.
REQ5.2[SH]	The product shall have overcurrent protection.

2.1.5 Non-Functional requirements

REQNF1[MH]	The connectors shall be suitable for solid core $2.5mm^2$ cables.
REQNF2[MH]	The connectors shall be suitable for solid core $1.5mm^2$ cables.
REQNF3[MH]	The PCB shall fit within the 3D model of the housing.
REQNF4[SH]	The PCB shall have a debug connector.

3 Architecture phase

In this chapter the structure of the system will be described. When describing the architecture, subsystems and the connections between them will be defined.

3.1 Context diagram

The context diagram in Figure 1 shows how the external sources interact with the system.
1.add text to describe the figure

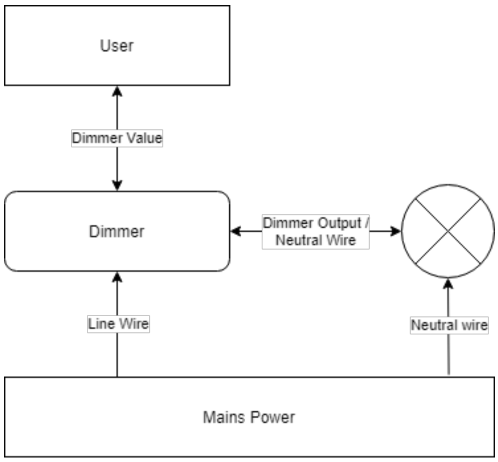


Figure 1: Context diagram

3.2 Architecture Interconnect Diagram

The architecture interconnect diagram (Figure 2) gives a more detailed overview of the system. This diagram shows the connections between the three subsystems (Power supply, Microcontroller and Dimmer) and their external connections as shown in Figure 1.

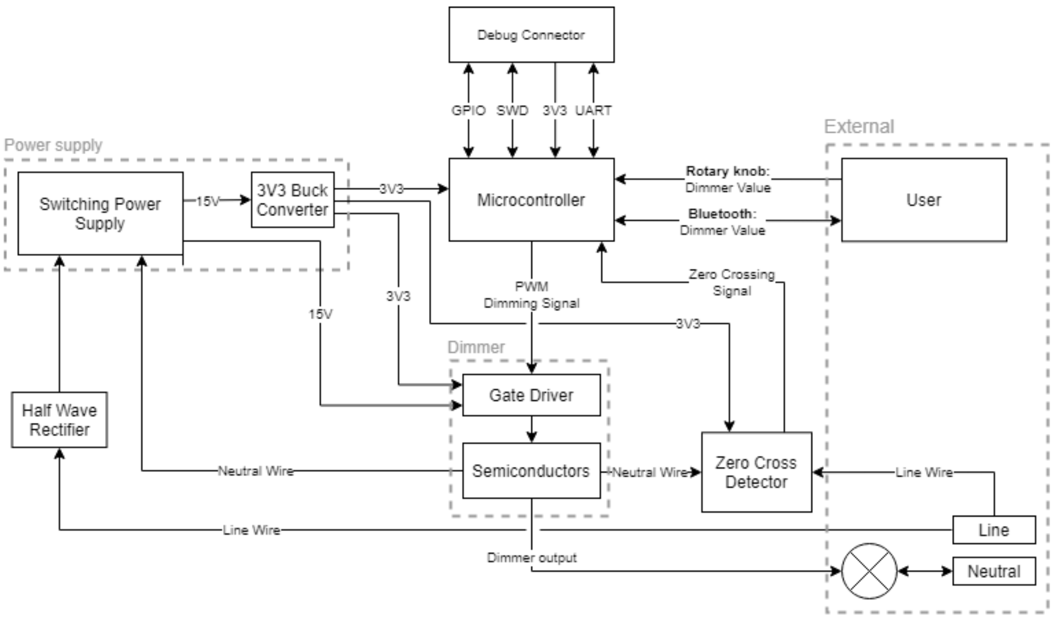


Figure 2: Architecture interconnect diagram

3.3 Subsystems

The system consists of three subsystems, the following sections will briefly describe these three subsystems and the data flows between them.

3.3.1 Power supply

The power supply contains four parts: a half wave rectifier, DC to DC power converters and zero-crossing detection.
This subsystem provides power at the right voltage for the gate driver and microcontroller. The zero-crossing system will supply a square wave signal to the microcontroller.

3.3.2 Microcontroller

The microcontroller is part of the SoC which handles the Bluetooth communication and ensures that all subsystems are connected. It receives the zero crossing detection signal from the power supply, detects use of the rotary knob and sends a PWM signal to the dimmer system.
External connections to the microcontroller for debug purposes are: UART, Serial Wire Debug, four GPIO pins and the ability to power the microcontroller from an external power source.

3.3.3 Dimmer

The dimmer is responsible for generating the phase cut output signal from a PWM signal derived from the microcontroller.
This subsystem consists of two semiconductors for phase cutting the output signal and a gate driver to drive the semiconductors.

3.4 Traceability of requirements

The Requirements traceability matrix shows which subsystem is responsible for a requirement.

	Power supply	**Microcontroller**	**Dimmer**
REQ-1.1	✓		✓
REQ-1.2	✓		✓
REQ-1.3	✓		
REQ-1.4	✓	✓	
REQ-2.1		✓	✓
REQ-2.2		✓	✓
REQ-2.3	✓		✓
REQ-2.4			✓
REQ-2.5		✓	
REQ-2.6		✓	
REQ-3.1	2.todo		
REQ-3.2		✓	
REQ-4.1		✓	
REQ-4.2		✓	
REQ-4.3		✓	
REQ-4.4			
REQ-4.5			
REQ-5.1	✓		✓
REQ-5.2	✓		
NFREQ-1	✓		
NFREQ-2	✓		
NFREQ-3	✓	✓	✓
NFREQ-4	✓		

Table 2: Requirements traceability matrix

3.5 Data dictionary

The data dictionary shows the connections as displayed in the architecture interconnect diagram (Figure 2), Table 3 shows a description of the flow, the unit and range.

Data flow	**Description**	**Unit**	**Range**
Power supply:			
Zero crossing signal	High-low transitioning signal	Volts	0 - 3.3
Power input	Mains AC power input	Volts (RMS)	207 - 253
Microcontroller:			
Dimmer value: knob			0 - 100%
Dimmer value: Bluetooth			0 - 100%
Dimmer:			
PWM dimming signal	Signal from the microcontroller to the dimmer	Duty cycle	0 - 100%
Dimmer output	Phase cut AC power from the dimmer to the light	Duty cycle	0 - 100%
Debug connector:			
UART	Receive, Transmit	Baud	**3.rate**
SWD	Clock, I/O	-	-
GPIO	General purpose IO for debugging	-	-
3V3, GND	External MCU 3V3 power input	Volts	3.0 - 3.6

Table 3: Data dictionary

4 Design phase

This chapter describes all hardware in the subsystems in detail. The schematics can be found in Appendix A and Appendix B.

4.1 Power supply

Two stages are used to realize the power supply. The first stage converts the AC line voltage to $15V$ DC for driving the IGBTs, the second stage converts the $15V$ DC to $3.3V$ DC to supply the SoC.

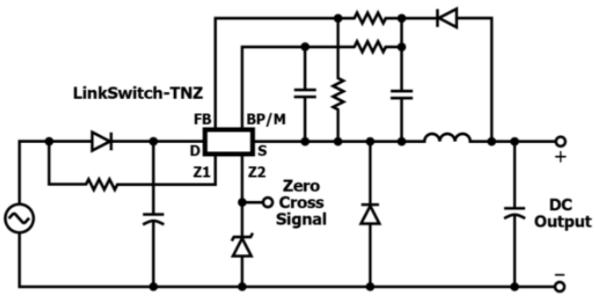


Figure 3: A simplified schematic of a buck converter using a LinkSwitch-TNZ device Source: [4]

4.1.1 Input stage

As shown in Figure 2, the input power is half wave rectified by diode D2. C1 is a bulk capacitor which flattens the rectified AC voltage.
Varistor VAR1 provides input surge protection, fuse F1 is for safety protection against circuit failure.

4.1.2 Input DC/DC converter using LNK3302

LinkSwitch-TNZ combines a high-voltage power MOSFET switch, a power supply controller, and a zero crossing detector in a single device. LinkSwitch-TNZ devices use a simple on/off control to regulate the output voltage.
Based on the typical output current for a non-isolated buck configuration, given in the datasheet [4], LNK33x2D is chosen. This device can supply up to $80mA$ of current in continuous conduction mode. Two versions of this IC are available, LNK3302D and LNK3312D, the difference being the ability to discharge an X-capacitor. Since this will not be necessary, LNK3302D is chosen.

In this design, the LinkSwitch device is configured as a high-side buck converter (Figure 3). For calculating the values of external passive components needed for operation of the LinkSwitch IC, PI Expert's spreadsheet is used (Appendix C). This is a hardware design tool from Power Integrations, manufacturer of the LinkSwitch-TNZ ICs.

The most important input parameters for the design tool are:

- Input voltage of $230V$ RMS $\pm 10\%$ at a frequency of 50 Hertz
- Output voltage of $15V$ DC
- Maximum output current of $60mA$
- Forward voltage drop of the freewheeling diode (D7)

The most useful output parameters of the design tool are:

- Input capacitor value (C1)
- Inductor value (L1)
- Feedback resistor value (R2)
- Feedback capacitor value (C3)

- Bypass pin resistor value (R3)
- Bias resistor value (R1)

4.1.3 Zero Crossing Circuit

To be able to switch the semiconductors for dimming, the microcontroller needs to know when the AC signal crosses zero. LNK3302D is able to provide a zero crossing signal, which toggles each time the AC line crosses zero volts.
For the zero crossing signal to be read by the microcontroller, it needs to be within the operating voltage range of the chip. This is taken care of by N-MOSFET Q1.
C4 and R6 form a low pass filter for the zero crossing output of the LinkSwitch IC. The signal toggles every half AC line cycle, so the frequency should be 50 hertz, the same as that of the AC line. R7 is the pulldown resistor on the gate of Q1. D3 and D4 form the sensing circuit with R4 in series with zener D6.

4.1.4 LDO

To supply a steady $3.3V$ to the SoC module, a Low Dropout Regulator (LDO) is added. According to the datasheet of the module [1], the maximum current consumption of the module is $9.6mA$.
For this purpose the LP2985-N with a fixed output voltage of $3.3V$ is chosen, mainly because of the relatively high DC input voltage of $16V$'[5] as well as it needing a minimal amount of external components.
To power on the regulator, the $ON/\overline{OFF}$ input needs to be pulled high. Since this function will not be used, the $ON/\overline{OFF}$ will be tied to V_{IN} to always keep the regulator on.
Capacitor C7 is a noise bypass capacitor, allowing a low-noise output of the LDO.
The power loss of the device is given by Equation 1, to calculate the efficiency η of the LDO $\frac{P_{IN}-P_{LOSS}}{P_{IN}}$ is used.

$$P_{LOSS} = (V_{IN} - 3.3V) \times I_{OUT} + V_{IN} \times I_Q \approx (15V - 3.3V) \times 15mA \approx 176mW \tag{1}$$

When the LDO is in operation, $I_{OUT} \gg I_Q$. Therefore I_Q is negligible, which allows to further reduce the efficiency to Equation 2.

$$\eta = \frac{V_{OUT}}{V_{IN}} = \frac{3.3V}{15V} = 22\% \tag{2}$$

4.2 Power supply (2nd iteration)

The first version of the power supply as described in subsection 4.1, had some limitations. The biggest limiting factors of the circuit are the availability of certain components and the high power dissipation of the LDO. The schematics for this version can be found in Appendix B.

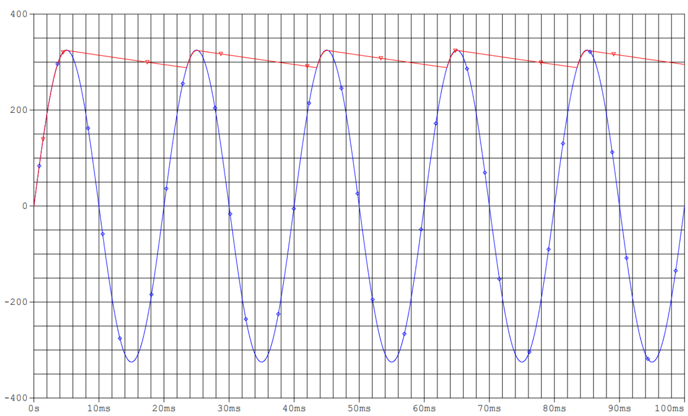


Figure 4: AC line voltage (blue) and half rectified, flattened signal (red)

4.2.1 Input stage

As shown in **??**, the input power is half wave rectified by diode D2. C1 is a bulk capacitor which flattens the rectified AC voltage (Figure 4).
Varistor VAR1 provides input surge protection, fuse F1 is for safety protection against circuit failure.

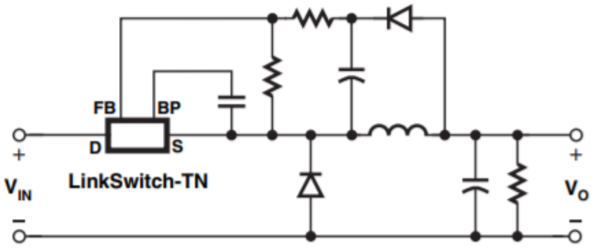


Figure 5: A simplified schematic of a buck converter using a LinkSwitch-TN device Source: [3]

4.2.2 Input DC/DC converter using LNK302

LinkSwitch-TN devices integrate a 700 V power MOSFET and a power supply controller, using simple on/off controlling for regulating the output voltage. LinkSwitch-TN devices are available in four types, with different output power capabilities. According to the datasheet [3], LNK302 can deliver up to 63mA of output current, which suits the needs of the circuit.

In this design, LNK302 is configured as a buck converter with direct feedback (Figure 5). For calculating the values of the external components needed, PI Expert's spreadsheet is used. The complete spreadsheet can be found in Appendix D.
The most important input parameters for the design tool are:

- Input voltage of $230VRMS \pm 10\%$ at a frequency of 50 Hertz
- Output voltage of $15V$ DC
- Target output voltage ripple of $100mV_{pk}$
- Maximum output current of $60mA$
- Forward voltage drop of the freewheeling diode (D4)

The most useful output parameters of the design tool are:

- Input capacitor value (C1)
- Inductor value (L1)
- Feedback resistor value (R2)
- Feedback capacitor value (C2)
- Bias resistor value (R1)

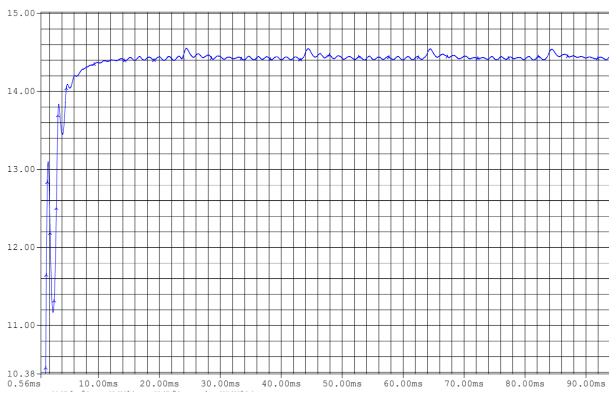


Figure 6: Output voltage of the LNK302 buck converter

As shown in Figure 6, the output voltage ripple is about $14.51V - 14.42V = 90mV$, which meets the requirements.

4.2.3 Zero Crossing Circuit

This new simplified zero-crossing circuit consists of a voltage divider and an opamp used as a comparator. A rail-to-rail single supply opamp is used to be able to create an output signal between 0 and 3.3V. The voltage divider attenuates the AC line signal from $240 \times \sqrt{2} = 340V_{pk}$ to a voltage within the range of the comparator (Equation 3). The current from the AC line leaking through resistors R5 and R6 and the power dissipated by the resistors is given by Equation 4.

$$V_{comperator} = V_{in} \frac{R5}{R5 + R6} = 340V_{pk} \frac{82k\Omega}{10M\Omega + 82k\Omega} \approx 2.8V_{pk} \tag{3}$$

$$I_{ACleak} = \frac{340}{10M\Omega + 82k\Omega} \approx 34\mu A, \quad P_{resistors} = (34\mu A)^2 \times (10M\Omega + 82k\Omega) \approx 12mW \tag{4}$$

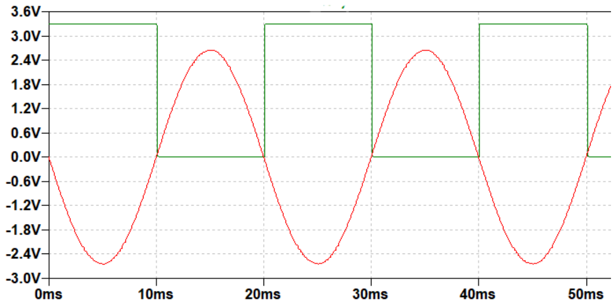


Figure 7: Attenuated AC line (red) and zero crossing signal (green)

The zero-crossing signal is a square wave, which inverts every half AC-line cycle as shown in the simulation results (Figure 7).

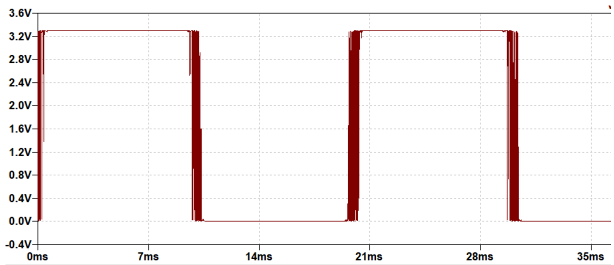


Figure 8: Bouncing output signal caused by noise

In the simulation, a perfect sine wave is used to detect zero-crossings. The mains voltage, however, isn't a perfect sine wave because of the noise present on the power grid. This noise will result in the output of the opamp bouncing around the zero-crossing (Figure 8). To detect a zero-crossing, this bouncing signal will be filtered by the firmware running on the MCU.

4.2.4 3.3V DC/DC converter

To create a stable $3.3V$ for the SoC module in an efficient way, a second DC/DC step-down converter is used. LT1934-1 is chosen for its wide input voltage range of $3.2V - 32V$ [2], as well as its output current of $60mA$. Since the maximum power drawn by the SoC is $9.6mA$, this will fit well within the specifications of the DC/DC converter.

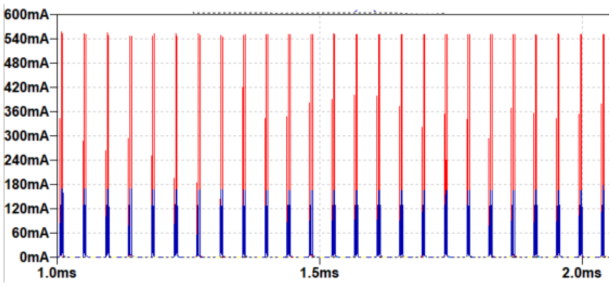


Figure 9: Plot of the input current of the buck converter at the device (red) after the capacitor (blue)

Buck converters draw current from the input in short pulses with fast rise and fall times, as shown in Figure 9. To reduce the current drawn from the output of the LNK302 power supply, input capacitor C5 of $1\mu F$ is added to the input of the device.
At an output current of $45mA$, the manufacturer recommends a minimal inductor value of $100\mu H$.

$$C_{OUT} > 50 \times L \times (I_{LIM}/V_{OUT})^2 \tag{5}$$

The minimum output capacitance can be calculated using Equation 5 The current limit of the switch in the LT1934-1 is $120mA$, this solves for $C_{OUT} > 6.6\mu F$. Capacitor C7 is added to further reduce the output voltage ripple, caused by the feedback comparator.

$$V_{OUT} = 1.25V(1 + R3/R4) = 1.25V(1 + 1M\Omega/620k\Omega) = 3.27V \tag{6}$$

The output voltage is set by a voltage divider of R3 and R4 on the feedback pin (Equation 6). D6 is used as a flyback diode for the inductor. Here, a Schottky diode is chosen for its lower forward voltage drop, resulting in a higher efficiency of the buck converter. Finally, D5 and C6 are used to create a boost voltage higher than the input voltage. This voltage is used to drive the internal NPN switch of the device.

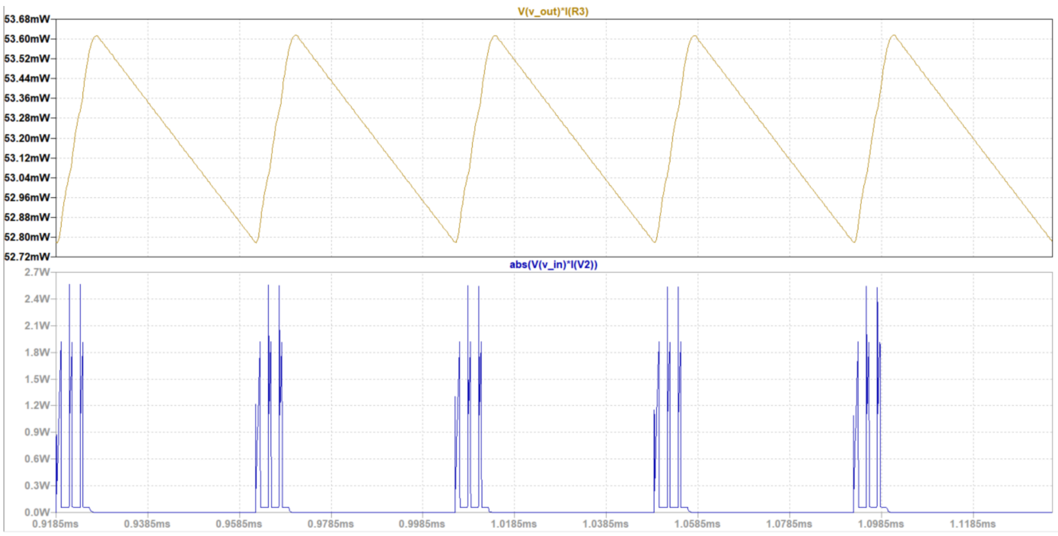


Figure 10: Plot of 5 periods of the output (top) and input (bottom) power

$$\eta = \frac{P_{OUT}}{P_{IN}} = \frac{53.2mW}{73.8mW} = 72\% \tag{7}$$

The efficiency of the step-down converter is given by Equation 7, which uses the average in and output current cumputed by LTspice.

4.3 Microcontroller

To realize the microcontroller subsystem, a Nordic Semiconductor BLE SoC was chosen. This is a highly integrated SoC that contains a 2.4 GHz transceiver, a 32-bit ARM® Cortex™-M4F CPU, a 512 kB flash memory, 64 kB RAM as well as analog and digital peripherals (Figure 11). Crownstone already uses the nRF52832 SoC which is running Bluenet, the in-house firmware for all Crownstone hardware.

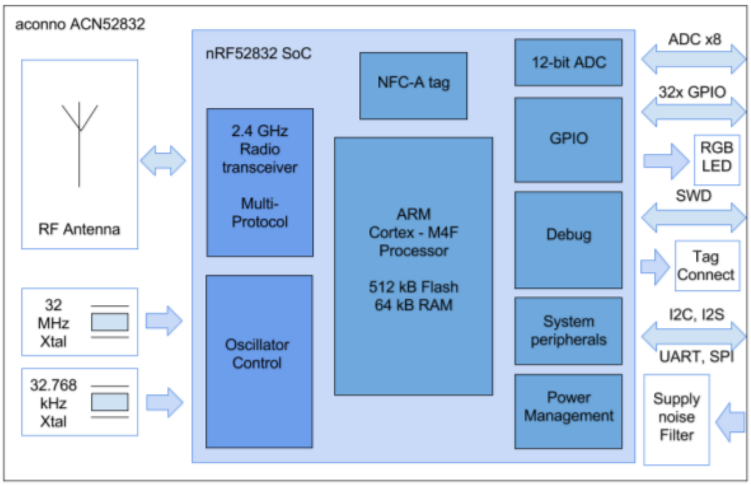


Figure 11: Block diagram of the ACN52832 module Source: [1]

For the dimmer prototype a fully integrated module featuring the nRF52832 SoC will be used: Aconno's ACN52832 [1]. This module integrates Nordic's nRF52832 BLE SoC, the accompanying PCB antenna with RF matching circuit, power supply decoupling capacitors, 32 MHz and 32.768 kHz crystals and load capacitors. This module also includes a RGB LED for optical feedback.
For programming the MCU and debugging software, ARM's 2-pin Serial Wire Debug (SWD) port and a UART connection are used. To be able to easily connect these pins, a debug connector is added to the board.
This connector will have the following connections:

- Supply power: GND, 3V3
- UART: RXD, TXD
- SWD: Clock, IO
- Four GPIO pins

For compatibility, the debug connector will have the same pinout and PCB footprint as the debug connector found on the Crownstone Built-In devices.

4.4 Dimmer

4.4.1 Selecting an IGBT

todo

4.4.2 Driving the IGBTs

todo

References

[1] Aconno. *Datasheet ACN52832 V1.2*, 8 2019.

[2] Linear Technology. *Datasheet Micropower Step-Down Switching Regulators.*

[3] Power Integrations. *Datasheet LNK302/304-306 LinkSwitch-TN Family*, 6 2013.

[4] Power Integrations. *Datasheet LNK33x2-7D LinkSwitch-TNZ Family*, 6 2021.

[5] Texas Instruments. *Datasheet LP2985 150-mA Low-noise Low-dropout Regulator With Shutdown*, 1 2015.

Glossary

LTE-M Long Term Evolution - Machine Type Communication, a low power wide-area network radio technology. 5

NB-IoT Narrowband Internet of Things, a low power wide-area network radio technology. 5

soft-fuse A passive electronic device used to protect against over-current in electronics. 5

standby-killer An electronic device that cuts electricity to devices that are in standby. 5

Thread A low power, IPv6 based, wireless mesh network protocol. 5

Zigbee A low power wireless mesh network protocol. 5

Acronyms

BLE Bluetooth Low Energy. 5, 15

GPIO General Purpose Input/Output. 8

IGBT Insulated-gate bipolar transistor. 10

LDO Low Dropout Regulator. 11

PWM Pulse Width Modulation. 8

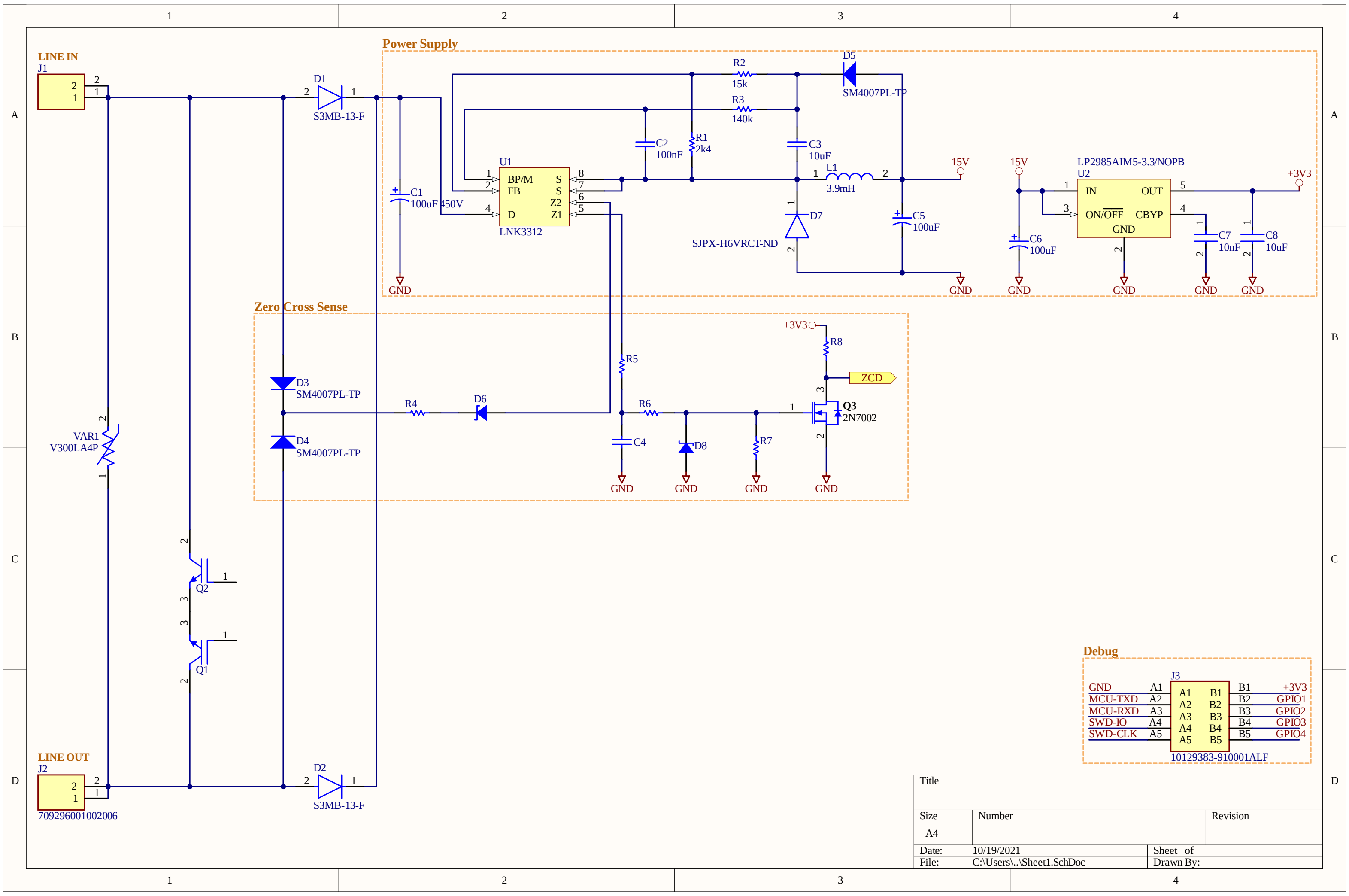
SiP System-in-Package. 5

SoC System-on-Chip. 5, 6, 8, 10, 11, 13, 15

SWD Serial Wire Debug. 6, 8

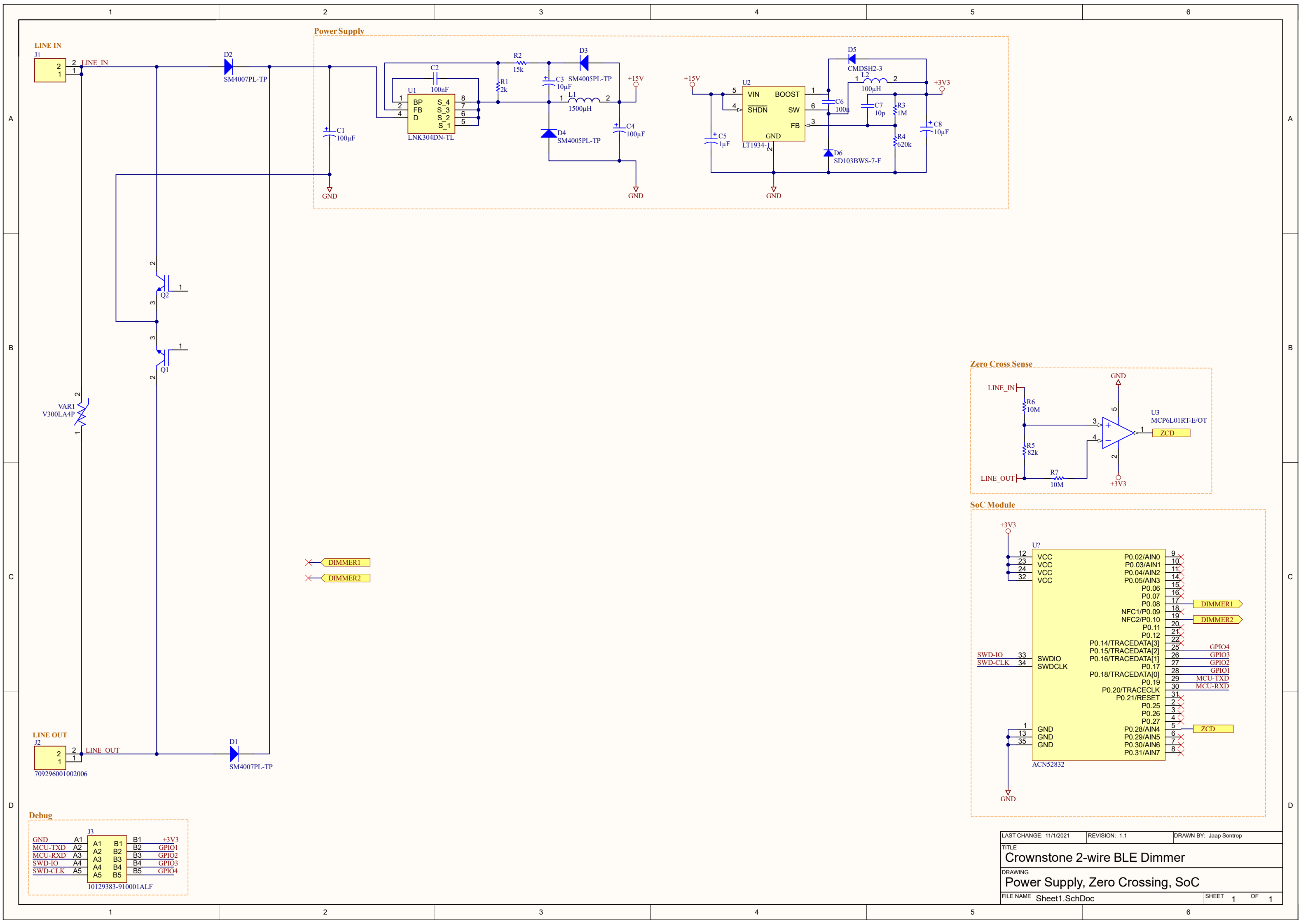
UART Universal Asynchronous Receiver-Transmitter. 8, 15

A Schematic V1



Title		
Size A4	Number	Revision
Date: 10/19/2021		Sheet of
File: C:\Users\..\Sheet1.SchDoc		Drawn By:

B Schematic V1.2



Power Supply
LINE IN
J1
LINE_IN
D2
SM4007PL-TP
C1
100µF
GND
U1
BP
FB
D
S_4
S_3
S_2
S_1
LNK304DN-TL
C2
100nF
R2
15k
R1
2k
C3
10µF
D3
SM4005PL-TP
L1
1500µH
D4
SM4005PL-TP
C4
100µF
+15V
U2
VIN
BOOST
SHDN
SW
FB
GND
LT1934-1
C5
1µF
D5
CMDSH2-3
L2
100µH
C6
100n
C7
10p
R3
1M
R4
620k
C8
10µF
D6
SD103BWS-7-F
+3V3
Q2
Q1
VAR1
V300LA4P
LINE OUT
J2
LINE_OUT
709296001002006
D1
SM4007PL-TP
DIMMER1
DIMMER2
Zero Cross Sense
LINE_IN
R6
10M
R5
82k
LINE_OUT
R7
10M
U3
MCP6L01RT-E/OT
ZCD
SoC Module
U?
VCC
SWDIO
SWDCLK
SWD-IO
SWD-CLK
P0.02/AIN0
P0.03/AIN1
P0.04/AIN2
P0.05/AIN3
P0.06
P0.07
P0.08
NFC1/P0.09
NFC2/P0.10
P0.11
P0.12
P0.14/TRACEDATA[3]
P0.15/TRACEDATA[2]
P0.16/TRACEDATA[1]
P0.17
P0.18/TRACEDATA[0]
P0.19
P0.20/TRACECLK
P0.21/RESET
P0.25
P0.26
P0.27
P0.28/AIN4
P0.29/AIN5
P0.30/AIN6
P0.31/AIN7
GPIO4
GPIO3
GPIO2
GPIO1
MCU-TXD
MCU-RXD
ACN52832
Debug
J3
GND
MCU-TXD
MCU-RXD
SWD-IO
SWD-CLK
+3V3
GPIO1
GPIO2
GPIO3
GPIO4
10129383-910001ALF
LAST CHANGE: 11/1/2021
REVISION: 1.1
DRAWN BY: Jaap Sontrop
TITLE
Crownstone 2-wire BLE Dimmer
DRAWING
Power Supply, Zero Crossing, SoC
FILE NAME
Sheet1.SchDoc
SHEET 1 OF 1

C PI Expert LinkSwitch-TNZ Buck converter design

D PI Expert LinkSwitch-TN Buck converter design