Texas Instruments Innovation Challenge: Europe Analog Design Contest 2015
Project Report

ceLEDsTIal positioning

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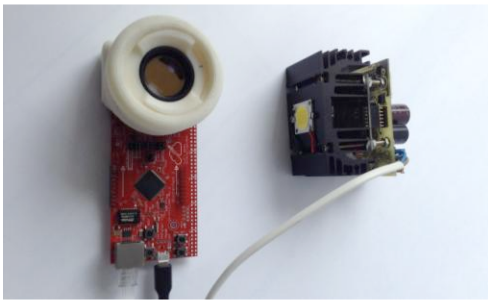
Date:	[31.07.15]

Qty.	TI Part Number & URL	Qty.	TI Part Number & URL
4x1	LM3421MH	4x1	TPS71550DCKR
4x1	MSP430G2302IPW14R	4x1	TL431AIDBZR
4x1	LM3480IM3-3.3	1	LMH6682MA
4x1	CSD88539ND	1	OPA2846IDR
4x1	UCC28740DR	1	TPS60403DBVT
4x1	UCC24610DR	1	EK-TM4C1294XL
4x1	CSD19531Q5A		



Project abstract: Current indoor localization systems generally underperform and involve complex installations. Therefore, a complete innovative visible light positioning system was designed, providing easy installation, scalability and high accuracy. The system consists of an optical receiver and an unlimited amount of independent transmitters generating illumination and data. The modular transmitter design consists of a constant current LED driver with 16 kbps on-off keying CDMA data transmission, as well as a mains power supply with secondary-side synchronous rectification. This results in a total system efficacy of 79 lm/W. The optical receiver consists of a 3D-printed lens mount, a TIVA C Launchpad and a self-designed boosterpack featuring analog signal manipulation circuitry. The system allows 16 location refreshes per second, with median positioning errors in a test environment ranging from 6.5 to 20.6 cm. Accuracy can further be refined with post-localization techniques. The extensive TI product range enables a total hardware design consisting of solely TI ICs. All 13 distinct pieces were carefully selected for their efficiency, flexibility, cost and size. For the design of the circuits, the WEBENCH and TINA-TI simulation tools were used, as well as TI evaluation modules and comprehensive documentation.

1. Introduction

Localization systems form an enabling technology for numerous location based services, such as guidance, asset tracking and location based information. For outdoor navigation and LBS, the Global Positioning System (GPS) is a well-known standard with sufficient accuracy and world coverage. In indoor environments, GPS accuracy drops due to the loss of a Line-Of-Sight (LOS) connection between the receiver and the satellites. A lot of research has gone into alternative RF-based technologies, but the complex indoor multipath environment forms a major obstacle. This leads to inaccurate solutions, requiring expensive installations of network backbones and wireless reference nodes using the already crowded RF spectrum. In addition, RF signals aren't always desirable in indoor environments (hospitals, etc.) due to Electromagnetic Interference (EMI). Other solutions with InfraRed (IR) and ultra-sound have shown good performance, but they still require invasive installations of dedicated hardware. With the introduction of white LEDs as illumination source, a new communication technology arises, called Visible Light Communication (VLC). With this technique, information is transmitted to users by modulating light intensity. VLC is characterized by numerous advantages, such as the dense distribution of light fixtures in comparison to RF base stations. In many environments (e.g., hospitals, warehouses, shops,…), continuous lighting is already present, forming an ideal field of application for VLC. Also, light has a local character and cannot be received in nearby rooms (channel reuse). VLC systems allow low cost hardware at the transmitter side, which combines both illumination and communication functionality. Furthermore, the visible light spectrum is large (approximately 700 THz) and unlicensed. These characteristics make VLC technology a perfect basis for a Visible Light Positioning (VLP) system. This ambitious project focuses on the design of a complete VLP system called 'ceLEDsTIal positioning'. Major requirements include low transmitter complexity, easy installation, scalability and of course high localization accuracy. For the design, a reference case of a forklift in a warehouse was assumed. The vehicle is equipped with an optical VLP receiver aimed at the ceiling, enabling localization by recognizing VLP LEDs, in analogy to the ancient celestial navigation technique. This system could enable automatic navigation of robot forklifts or a productivity increase of manned forklifts.

2. System overview

A VLP system contains a set of individual LEDs, broadcasting data. In order to distinguish the information of different LEDs, a suitable multiple acces technology is required. The LEDs are generally controlled by switched mode power supplies with on-off keying (OOK) for communication. With on-off keying, a digital bit '1' and '0' is represented by respectively turning the LED fully 'on' or 'off'. In order to reduce installation time and cost, a transmitter design with limited logic is appropriate, eliminating the need for a backbone for synchronization. This reduces transmitter installation to replacing existing light points with VLP transmitters.
A multiple access technology which can easily use OOK and doesn't require a backbone network for synchronization, is Code Division Multiple Access (CDMA). In this solution, every LED gets a unique code to encrypt its data. The receiver can use the correlation properties of the codes to distinguish data and determine the received optical power (RSS) for every LED. The receiver can then calculate its position using information of light fixtures on a floorplan. Fig. 2 represents a block diagram of the total system. The grey blocks represent the newly designed circuits that together

form the VLP system. All these boards were self-designed and manually developed and assembled. White blocks represent already available hardware that was used in the project, but not self-designed.

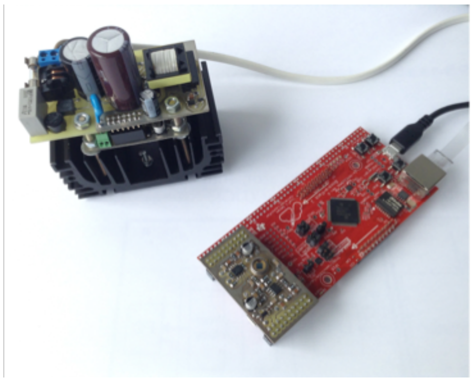


Fig. 1. One transmitter and receiver

The VLP system consists of transmitters and a receiver. The transmitters are stand-alone devices, connected to the mains and broadcasting data while illuminating the room. A fly-back converter with synchronous secondary-side rectification was designed with the UCC28740 and UCC24610 controllers, transforming the AC input to 12 V DC. This is the supply voltage for the LED driver (LM3421) and the microcontroller (MSP430g2302), which generates the transmitted data. The information of the LEDs is transmitted through the VLC channel to the receiver. A photodiode transforms the optical power to a current, which is converted by a Trans Impedance Amplifier (TIA) (OPA2846). After anti aliasing (LMH6682), the analog signal is sampled by a TI Launchpad (EK-TM4C1294XL), which transmits measurement data over Ethernet to a PC.

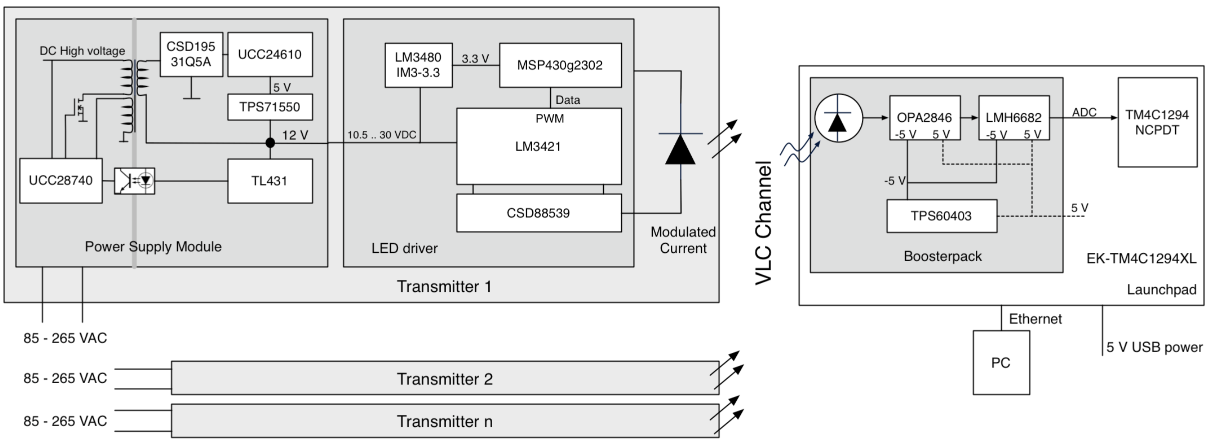


Fig. 2. System architecture

2.1. A VLP system using CDMA as multiple access technology

In order to use CDMA in a VLP system, address codes are needed with good auto- and cross-correlation properties. This is required for synchronization with every LED, but most importantly it ensures that the error on the RSS used by the location algorithm, is kept to a minimum. The RSS of every LED can be calculated from the auto-correlation peak value. However, interference with cross-correlation values of other LEDs should be taken into account in an asynchronous system (Multiple Access Interference). The RSS value is a function of the channel response *H(0)* and the transmitted optical power P_T. Using this response, the distance *d* between the receiver and every LED can be calculated. The position of the receiver can then be found by using a triangulation localization algorithm. Evaluation of different address codes led to the use of Extended Quadratic Sequences. With these address codes a set of 22 distinct codes is designed, with a length of 1035 chips and good auto- and cross-correlation functions. Since these codes mainly exist of zeros, they are inverted. This mainly high signal is OOK-modulated on the LED current, resulting in a large average duty cycle of 98%, barely affecting illumination.

3. Transmitter

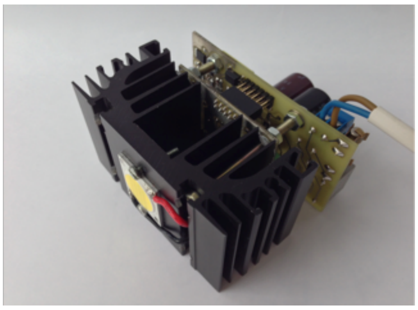


Fig. 3. Transmitter assembly

For this project, four identical VLP transmitters were built for a test configuration, each with a unique code. However, the number of transmitters in a room can be increased infinitely because codes can be reused in space (cf. cells in mobile phone networks). In this case, each LED transmits a unique ID. Every transmitter consists of a power LED, a LED driver and a mains power supply. The LED driver and power supply are designed as two separate modules. This design choice is justified by the (relatively) low DC input voltage rating of the considered LED driver and VLC logic. Furthermore, a modular setup provides more system flexibility. For example, the mains AC power supply can be replaced by a supply module for integration in low-voltage lighting systems. A disadvantage of this 2-stage approach lies in the accumulation of losses. Therefore, system efficiency was always considered of uttermost importance during circuit design and component selection.

3.1. LEDs

For the LEDs, the Bridgelux BXRA-56C2600 was selected. This 26 W LED shows a high efficacy of 116 lm/W, providing a nominal pulsed flux of 3040 lm at 25°C. This is sufficient for lighting up to 15 m^2, since European standards prescribe a minimum illuminance of 200 lux in a working environment. The distribution of light can be adjusted with a reflecting bracket or lenses. However, this technique was currently not applied because the radiation pattern of the bare LED is used by the localization algorithm. The LEDs are equipped with a 50 mm RAWA730-0B heatsink with a thermal resistance of 1.7 K/W. Given the large contact area (825 mm^2) and thermal grease, a contact resistance of 0.079 K/W was obtained between the LED and heatsink. The LEDs exhibit 14.9% efficiency at 70°C, resulting in 22.3 W of heat loss. The heatsink limits the LED's temperature to 60°C at ambient room temperature (20°C), preventing severe performance loss and preserving component lifetime. The maximum operation temperature of 105°C is only achieved at an ambient temperature of 65°C.

3.2. LED driver

The LED driver provides a constant current of 700 mA with OOK-modulated data to the LED. This requires a constant current controller, a microcontroller for generating the data signal and a voltage regulator for the microcontroller. The PCB design of the driver focused on practical development and assembling, as well as efficient routing, preventing large loops and enabling miniaturization. Of course general design guidelines (e.g., wider high-current traces) were also taken into account. The result is a double-layer PCB of only 43x53 mm^2 with a single component side, as depicted in Fig. 4

3.2.1. Controller

A study of LED driver controllers led to the **LM3421** as optimal device. This IC is able to drive the selected LED at 700 mA, 37 V. An output voltage up to 72 V assures proper operation, even when the forward LED voltage increases due to degradation. The boost topology allows safe low input voltages, which can also be used for powering the microcontroller. A PWM dimming input is indispensible for the intended data transmission. The 16HTSSOP package is small yet manageable for manual assembling.

The design of the circuit was facilitated by straight-forward datasheet information with comprehensive application examples. All design formulas can be found in the datasheet. This report presents the most important system parameters. The result is a 700 mA boost driver circuit operating at input voltages of 10.5 V to 30 V. The switching frequency was fixed at 694 kHz, which satisfies a rule-of-thumb stating that the switching frequency should be at least 10 times higher than the PWM frequency (the data rate in this case). This PWM frequency is further limited to 30 kHz by the dimming FET, as laid down in the datasheet. The considered design makes use of a main N-channel MOSFET and a dimming MOSFET. Including safety margins, these MOSFETs should at least permit respectively 44 V, 3.3A and 38 V, 770 mA, with minimal $R_{DS,on}$ and Q_g. Therefore, the **CSD88539ND** device was selected. This Dual N-channel MOSFET IC meets the requirements with up to 60 V V_{DS} and 6.3 A I_D. The low values of $R_{DS,on}$=23 mΩ (@ V_{GS}=10 V) and Q_g of 7.2 nC keep losses to a minimum and the SO-8 package is easy to solder. Alternatives require double components with generally higher Q_g values. Another important component in the circuit is the recirculating diode and the boost inrush diode. The PDS5100-13 100 V, 5 A schottky diode was chosen twice, amply satisfying requirements and limiting losses.

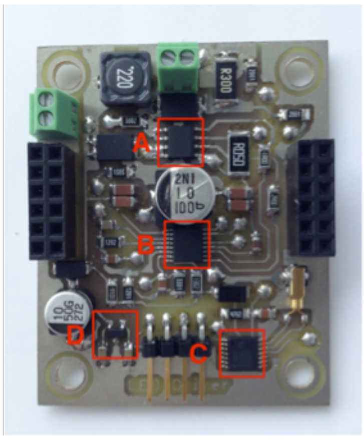


Fig. 4. LED driver with (A) CSD88539ND, (B) LM3421, (C) MSP430G2302, (D) LM3480

3.2.2. Microcontroller

The microcontroller is responsible for the generation of a data signal that is sourced into the PWM input of the LED driver controller. This operation requires little computational power and few IO pins, leading to the MSP430G2x series of microcontrollers. However, accurate timing is important in this application, implying the need for an external crystal. The most basic device that suits these requirements, is the **MSP430G2302** microcontroller in 14TSSOP package, combined with a 32.768 kHz crystal. This configuration is used for the generation of a 16.384 kbps data signal, which is under the 30 kHz PWM limit of the LED driver. This means that the unique 1035 chips code can be sent roughly 16 times per second.

3.2.3. Voltage regulator

The microcontroller requires a voltage of 1.8 V to 3.6 V. Therefore, a 3.3 V linear regulator was selected that regulates the input DC voltage of the LED driver. The **LM3480-3.3** device was selected for its small form factor, few peripheral components and high input voltage range up to 30 V. The 100 mA output capability is more than sufficient for this application. Possible alternatives include the TPS715, TLV701 and TLV704, but these devices offer a lower input voltage range.

3.3. Power supply

In order to enable VLP transmitters to be mounted at any place with mains connectivity, a flyback converter was designed that turns 85 VAC - 265 VAC to 12 VDC. Given the LED driver efficiency of 86.1%-87.4% @ V_{in}=12 V, at least 2.53 A should be provided. However, the inrush current of the boost converter demands a safety margin (even though an inrush diode was foreseen), so an output capability of 3 A (36 W) was determined. For the design, the **UCC28740** flyback controller with optocoupled feedback was selected. This controller for relatively low power isolated power supplies performs constant-voltage regulation of the secondary side through optical feedback. Furthermore, the device supports extensive fault protection features for safe handling of voltage or current errors. Viable alternatives include the UCC2871X series without optocoupler, resulting in slightly less accurate voltage regulation.

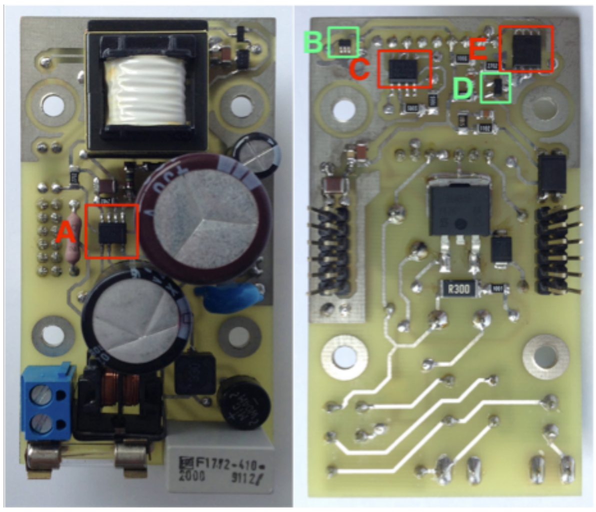


Fig. 5. Power supply with (A) UCC28740, (B) TPS71550, (C) UCC24610, (D) TL431, (E) CSD19531Q5A

As suggested in the datasheet of the UCC28740, optocoupler feedback is controlled with the **TL431A** adjustable precision shunt regulator.

In order to prevent diode losses, a synchronous rectifier was implemented in the secondary side of the power supply, emulating a quasi-ideal rectifier. The **UCC24610** Green rectifier controller was designed for this specific purpose and supports operation frequencies up to 600 kHz, making it a perfect fit for this power supply with a switching frequency up to 100 kHz. However, this device requires a 5 V input voltage, so an extra 5 V is derived from the 12 V output voltage with a linear regulator. The **TPS71550** was used for this purpose, featuring 50 mA output current in a small form factor, with an input voltage range up to 24 V. The TLV704 and LM3480 are equivalent solutions. The **CSD19531Q5A** was selected as rectifying MOSFET for its extremely low $R_{DS,on}$=5.3 mΩ (@ V_{GS}=10 V) and Q_g=37 nC, as well as its leadless package (SON5x6), limiting inductance as required for this application.

The design of this power supply, which is presented in the block diagram in Fig. 2, resembles the architecture of evaluation module PMP9715, which was used for circuit testing and design, together with datasheets of the used components. Noticeable components in the power supply design include the SiHB6N65E HV-MOSFET, 5-windings Würth transformer (7508112339), PS2561A optocoupler and fast switching diodes RGL34G, ES1PD and MURS160. Power supply design is not considered as a major innovation in this project but rather an addition for system completion. Therefore, in-depth parameter calculations and design details are not discussed here, since they can be found in device datasheets (UCC28740, UCC24610, PMP9715). The power supply was designed on a 83x43 mm^2 PCB with separated primary and secondary side. At the primary high-voltage side, large inter-trace distances were provided, while the secondary side features extra wide traces for larger currents.

3.4. Results

Four VLC transmitters were assembled, each consisting of a LED driver module and a power supply module. Each device transmits a unique code at 16.384 kbps, as depicted in Fig. 6, representing the data signal and LED current. With these codes, an average duty cycle of 98% is achieved, resulting in a nearly maximum light output. Performance of the four LED drivers was investigated, revealing efficiencies of 86.1%-87.4% @ V_{in}=12 V. Delivered output power was 26.1-27.8 W. The designed power supplies were tested at 234 VAC, sourcing 12.0-12.1 V, 2.51-2.63 A to the LED driver. The efficiencies of the power supplies were shown to be 88.6%-88.8%. Total system efficiency from AC mains to the LED was measured as 76.5%-77.6%. This means that 33.5 W of input power results in a luminous flux of 2630 lm (taking LED temperature into account), enough for lighting a work place of 13 m^2. This brings total transmitter efficacy at 79 lm/W, exceeding performance of many commercially available LED lights without VLC capabilities, such as the Philips D 5.5-50W GU10 830 40D, with an efficacy of 73 lm/W. Further improvement can be achieved by merging the LED driver and power supply in a single circuit.

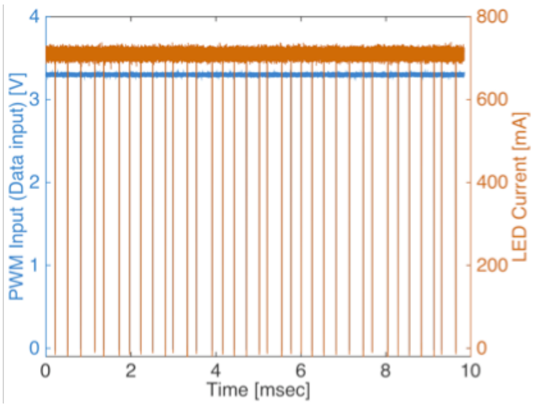


Fig. 6. PWM input signal and LED current

4. Receiver

The VLC receiver consists of an optical sensor, generating an electrical signal that is sampled and processed by the localization algorithm. Given the computational load of the localization algorithm and flexibility of a graphical user interface, data processing was offloaded to a PC. For data sampling and communication with the PC, the **EK-TM4C1294XL** Tiva C Series Launchpad was selected. The choice for a launchpad instead of a custom PCB design is motivated by the difficulty of manually soldering the microcontroller, together with excellent characteristics of the available launchpad and dual boosterpack expandability. The launchpad is equipped with an Ethernet interface, facilitating high data throughput. The device is equipped with a powerful TM4C1294NCPDTI digital signal controller, featuring 12-bit ADCs for sampling up to 2 MSPS, a specification that benefits localization accuracy and leaves room for future expansion in the field of VLC. The analog VLP receiver was designed as a single boosterpack module, equipped with the optical sensor and analog signal circuitry.

Fig. 7. Receiver assembly

4.1. Receiver Boosterpack

The receiver converts optical power to an electrical signal. A photodiode is required for this purpose, producing a current proportional to the light falling on the active area. The BPX61 photodiode was selected for its spectral response in the visible light region (400 .. 1100 nm) and active area of 7 mm^2. Despite the large active area, which is important in order to capture a sufficient amount of light, the photodiode has a bandwidth of 17.5 MHz and good noise characteristics. The active area of the transmitter is artificially enhanced with a factor 70 by adding the

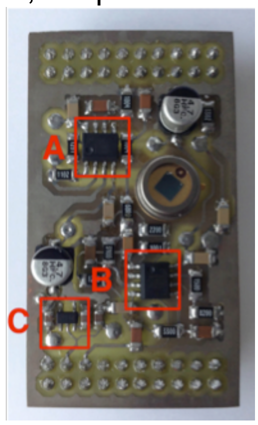


Fig. 8. Boosterpack with (A) OPA2846, (B) LMH6682, (C) TPS60403

LA1951-A lense. Therefore, a focusable lens mount was designed and 3D-printed for mounting on the photodiode, as depicted in Fig. 7.

The output current of the photodiode is transformed into a signal that can be sampled by the ADC. First, the current is converted to a voltage by use of a Trans Impedance Amplifier (TIA) and filtered by an ambient light filter in the feedback loop. Ambient light can originate from surrounding light sources that don't send data and produce a DC current at the photodiode, e.g., the sun. In order to use the maximum dynamic range of the amplifiers, the DC current should be filtered out in the first stage. The TIA needs a large open loop gain because of the large amplification and a low input bias current due to the small current from the photodiode. Because this is the first stage of our receiver it should also have good noise characteristics because the noise factor of the total receiver will mostly be determined by the first stage. The **OPA2846** meets these requirements and was designed for TIA applications. An additional advantage is the second OPAMP in the casing, which can be used to implement the ambient light filter using "General Active Feedback" in the feedback loop of the TIA. The human eye can't observe flickering when the frequency is above 300 Hz, so in VLC systems all signals should be above this threshold. This results in a cut-off frequency of 300 Hz for the ambient light filter.

The received signal is processed in the digital domain, so the analog signal of the TIA is sampled by an ADC. Therefore, an amplifier and anti-aliasing filter are placed after the TIA to make use of the full range of the ADC input and prevent frequency overlap after sampling. The anti-aliasing filter is a low pass filter that requires a low pass band ripple, steep roll-off in the stop band and a constant phase in the pass band. The cut-off frequency was fixed at 400 kHz, as explained in the next section. The photodiode produces currents between 10μA and 40μA, resulting in a voltage between 100 mV and 400 mV after the TIA. The used ADC has a range of 0 V to 3.3 V, so a DC offset of 1.65 V is added before sampling. This means that the output signal of the TIA should be amplified by 16 dB. These specifications were used in the TI WEBENCH Filter Design tool that generated a reference design. With these results, the **LMH6682** was picked, satisfying the required GBWP and offering a low noise solution. Besides the characteristics for the filter design, the LMH6682 is also suited as ADC buffer amp. Another advantage of the LMH6682 is its dual OPAMP configuration, simplifying the two-stage filter design on PCB. The complete analog design was simulated using TINA-TI Simulation software and measured to verify system specifications. Fig. 10 shows these measurement and simulation results for a configuration with and without ambient light filter.

The used OPAMPS rely on a 5 V supply voltage, derived from the launchpad pins. However, also a -5 V supply voltage is needed. Therefore, the **TPS60403** charge

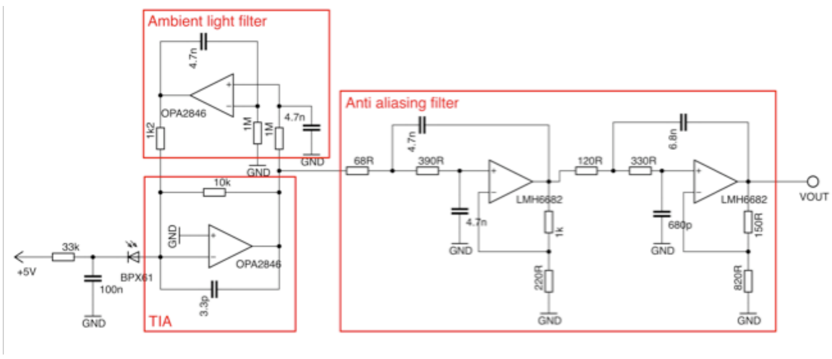


Fig. 9. Schematic of the filter and amplifier design

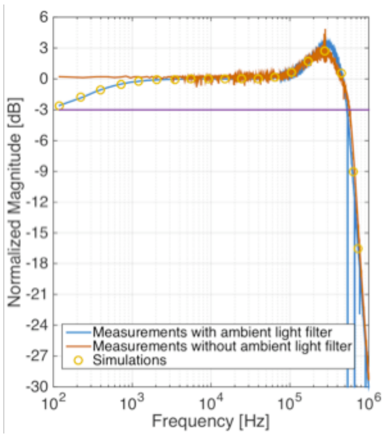


Fig. 10. Measured and simulated circuit response design

pump voltage inverter was used, designed for bipolar amplifier supplies and requiring few peripheral components.

4.2. Digital signal processing

Since the LEDs transmit Extended Quadratic Sequences at 16.384 kbps, the system needs a sample rate of at least 16384 sps to distinguish different LEDs from each other. A much higher sample rate of 800 ksps was chosen for the receiver to accommodate future applications that require higher data rates, e.g., faster location refreshes, higher accuracy, communication,… This sampling rate defines the 400 kHz cut-off frequency of the anti-aliasing filter on the boosterpack and requires that F_{ADC}=16 MHz, N_{SH}=8 and R_S<3500 Ω, as defined in the microcontroller datasheet. Since the high sampling rate of 800 ksps is currently not necessary, hardware averaging was enabled with a factor of 32. This limits Ethernet data traffic to 37.5 kBps and increases sample precision. The sample data are processed by the localization algorithm on a PC, returning the position of the transmitter.

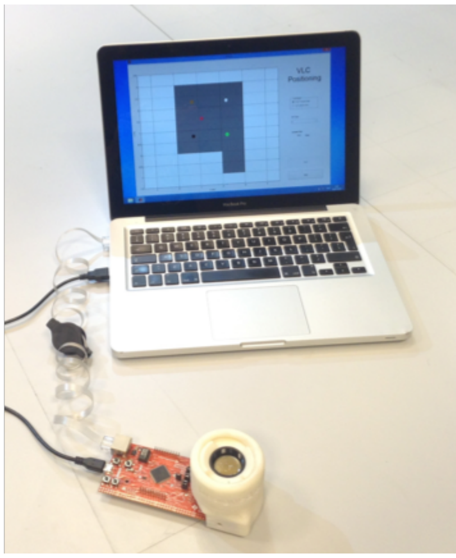


Fig. 11. Localization setup and software running

4.1. Evaluation of the system

For the evaluation of the localization system, a test configuration was developed in a lab environment (Fig. 12). The test configuration consists of a table of 3 x 3 m^2 and the four VLC transmitters evenly distributed on the ceiling. The receiver is placed on the desk, 1.22 m below the LEDs. In this environment, five representative positions were chosen and 1000 measurements were performed at each position, enabling a statistical analysis of localization accuracy. Table 1 shows the 50^{th} and 95^{th} percentiles of position errors for the 5 different positions. In the considered configuration, a localization error will almost certainly be smaller than 40 cm. In a 3 x 3 m^2 environment, this might seem rather unreliable for the envisioned application. However, 16 location measurements are performed every second because 1035 chips codes are transmitted at 16.384 kHz. Also, simulations have shown that more extensive configurations with more VLC transmitters will exhibit better performance. But most important for the envisioned application of localizing moving vehicles, post-localization techniques can be used, such as dead-reckoning and map matching, bringing into account previous positions, speeds and building layout. These techniques dramatically improve accuracy, enabling positioning with 5 cm precision in the test configuration.

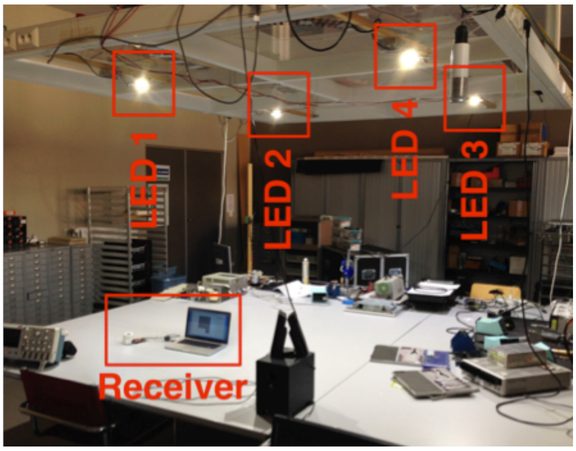


Fig. 12. Test configuration

	localization error [cm]	
	50th percentile	95th percentile
Position 1	17.4	39.3
Position 2	6.5	8.56
Position 3	8.3	17.2
Position 4	20.6	34.8
Position 5	17.6	35.1

Table 1. Localization errors in the test configuration

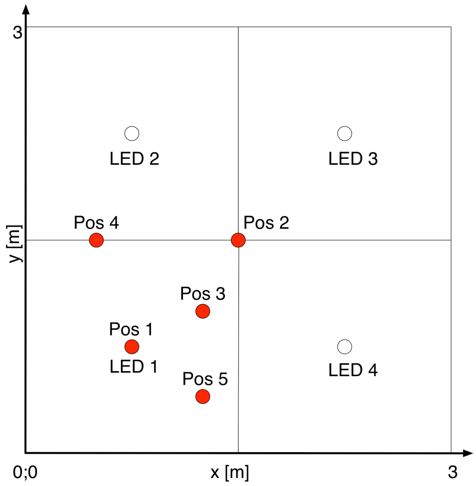


Fig. 13. Test positions

5. Conclusions and Future work

An innovative visible light positioning system was designed. The independent transmitters are equipped with a mains power supply, containing a flyback converter with synchronous secondary-side rectification, providing high conversion efficiency. Also a LED driver was designed, providing a constant LED current with 16.384 kbps OOK CDMA data modulation. The receiver exists of a TIVA C launchpad with a custom boosterpack design, offloading optical data to a PC for complex data processing. The boosterpack contains a combination of analog filters and amplifiers, simulated with the WEBENCH and TINA-TI simulation tools. The result is a scalable and easy to install VLP system with 79 lm/W luminous efficacy and median position errors of 6.5 to 20.6 cm in a test configuration. This 'raw' accuracy can further be improved with post-localization techniques. The hardware design houses 13 distinct TI components in a modular yet compact form factor.

Future work lies in a large-scale deployment of the VLP system in a warehouse for the evaluation of environment-specific position errors. Besides the use in a warehouse, the system can also be used in public places, such as hospitals, airports, etc. The hardware design at transmitter and receiver side allows configurable data speeds through simple software adjustments. This enables easy changes of the location update frequency and localization accuracy, depending on the application. Further hardware improvements at the transmitter side could be achieved by merging the LED driver and power supply. At the receiver side, a custom PCB design could reduce the size of the current Launchpad solution. Also, the receiver could be equipped with an RF data uplink (CC3100 Wi-Fi or CC2540 bluetooth) for wireless transmission of sample data.

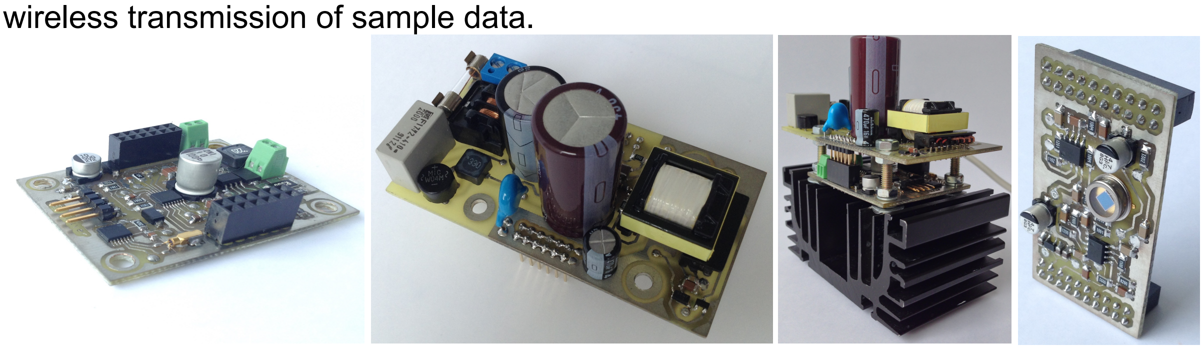


Fig. 14. LED driver, Power Supply, Transmitter assembly, Boosterpack

Component list					
Device	*Value*	*Qty*	*Device*	*Value*	*Qty*
Transmitter LED driver module		**x4**	Inductor 33uH	744777133 (Würth)	1
LED driver control.	**LM3421MH**	**1**	Transformer	7508112339 (Würth)	1
Microcontroller	**MSP430G2302IPW14R**	**1**	Pinheader	2X6, M	2
Voltage regulator	**LM3480IM3-3.3**	**1**	PCB terminal block	MKDSN 2,5/2	1
Dual N-MOSFET	**CSD88539ND**	**1**	AL capacitor	22 uF, 450 V	1
Schottky diode	PDS5100-13 (diodes inc)	2	AL capacitor	68 uF, 450 V	1
Schottky diode	SL13 (Vishay)	2	AL capacitor	470 uF, 16 V	1
32 kHz Crystal	MS1V-T1K (microcrystal)	1	Film capacitor	100 nF, 250 V	1
22 uH inductor	7447789122 (Würth)	1	Film capacitor	2.2 nF, 400 V	1
ISP connector	Pinheader 1X4 90°, M	1	Capacitor 1210	4.7 uF, 100 V	2
Pinheader	2X6, F	2	Capacitor 1206	2.2 uF, 100 V	2
PCB terminal block	MPT 0,5/2-2,54	2	Capacitor 0805	100 nF, 100 V	3
Resistor 2512	300 mΩ	1	Capacitor 0805	1 nF, 100 V	1
Resistor 2512	50 mΩ	1	Capacitor 0805	4.7 nF, 100 V	1
Capacitor 1206	2.2 uF, 100 V	4	Resistor 0309	22 Ω	1
SMD AL capacitor	10 uF, 50 V	1	Resistor 2512	300 mΩ	1
SMD AL capacitor	10 uF, 100 V	1	Resistor 1206	30 Ω	1
Resistor 1206	9k1	1	Resistor 1206	91k	1
Resistor 1206	1k2	1	Resistor 1206	24k	1
Resistor 1206	36k	1	Resistor 1206	1k	2
Resistor 1206	12k	1	Resistor 1206	27k	2
Resistor 1206	2k	2	Resistor 1206	11k	1
Resistor 1206	13k	1	Resistor 1206	5k1	1
Resistor 1206	130k	1	Resistor 1206	100k	2
Resistor 1206	3k3	1	Resistor 1206	360k	1
Resistor 1206	47k	1	**Receiver Boosterpack**		**x1**
Resistor 1206	1 Ω	1	**Dual OPAMP**	**LMH6682MA**	**1**
Resistor 1206	2 Ω	1	**Dual OPAMP**	**OPA2846IDR**	**1**
Capacitor 0805	100 nF, 100 V	3	**Voltage inverter**	**TPS60403DBVT**	**1**
Capacitor 0805	1 nF, 50 V	2	Photodiode	BPX61 (osram)	1
Capacitor 0805	47 pF, 100 V	1	Pinheader	2X10, F	2
Capacitor 0805	4.7 uF, 10 V	1	SMD AL capacitor	4.7 uF, 35 V	2
PowerLED 26 W	BXRA-56C2600	1	Capacitor 0805	1 uF, 10 V	3
Heatsink-schaffner	RAWA730-0B, 50mm	1	Capacitor 0805	100 nF, 100 V	6
Transmitter Power Supply		**x4**	Capacitor 0805	4.7 nF, 100 V	4
Flyback controller	**UCC28740DR**	**1**	Capacitor 0805	6.8 nF, 100 V	2
Green rectifier	**UCC24610DR**	**1**	Capacitor 0805	680 pF, 100 V	1
N-MOSFET	**CSD19531Q5A**	**1**	Capacitor 0805	3.3 pF, 100 V	1
Voltage regulator	**TPS71550DCKR**	**1**	Resistor 1206	33k	1
Adjustable shunt	**TL431AIDBZR**	**1**	Resistor 1206	1k2	1
Diode	RGL34G (Vishay)	1	Resistor 1206	1M	2
Diode	MURS160-M3 (Vishay)	1	Resistor 1206	10k	1
Diode	ES1PD-M3 (Vishay)	1	Resistor 1206	68 Ω	1
N-MOSFET	SIHB6N65E-GE3 (Vish.)	1	Resistor 1206	390 Ω	1
N-MOSFET	PMV213SN (NXP)	1	Resistor 1206	1k	3
Optocoupler	PS2561A (CEL)	1	Resistor 1206	220 Ω	1
Rectifier bridge	MIC W04M (MCC)	1	Resistor 1206	330 Ω	1
Fuse + holder	250 V, 400 mA	1	Resistor 1206	150Ω	1
Choke	744861018 (Würth)	1	Resistor 1206	820Ω	1