Design and Implementation of a Sustainable Light-based IoT Node on a System-on-Chip

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***Abstract*—The concept of the Light-based Internet of Things (LIoT) describes nodes that use light both to harvest energy to operate and to support full-duplex wireless communication. In this study, we investigate the design and implementation of a LIoT node using low power System-on-Chip based boards. The selection of the boards was carried out following performance and power consumption criteria. Benchmark tests included computational power and speed of executing I/O tasks, which are considered key performance metrics. The design considered the use of key components exploiting printed electronics (PE) technology to create a sustainable node solution. In the research, printed photovoltaic cells are used to harvest energy. However, the use of printed components poses some challenges, as the performance of these components is typically inferior to that of conventional components. Since the LIoT nodes are energy-limited, managing node energy is crucial to achieving energy autonomy. Thus, one of the main selections metric for the implementation of technology was the evaluation of power consumption during sleep modes. The paper discusses system architecture and design of the functionalities and provides a comparison between different System-on-Chip (SoC) based implementation platforms. The paper finally selects the most suitable SoC-based platform to implement a sustainable LIoT node supporting duplex communication operation.**

***Index Terms*—IoT, Light-based IoT, Printed Electronics, VLC, SoC, energy autonomy, sustainability**

I. INTRODUCTION

Over the last decade, the Internet of Things (IoT) paradigm has started to connect our world in a massive manner supported by the rapid development of wireless communication technologies. The IoT paradigm has greatly extended the domain of what can be wirelessly connected, and as such, in principle, anything could be connected, from people to vehicles, and from machines to any possible object. Of course, this requires that there is a networking infrastructure supporting all connected objects. The requirements for the connections depend on the type of object being connected and the required service. There are a great deal of applications developed for IoT and machine-to-machine (M2M) communication systems, such as health monitoring, smart meters, logistics and transportation, product management, and many others. According to Cisco, there will be more than 15 billion IoT connections by 2030 [1]. Other predictions forecast figures much higher. Creating such a massive network of interconnected devices has a price that needs to be understood not only by its economic value but also by the overall cost of producing, operating, maintaining, and disposing of such a network. The emergence of a number of connected devices contributes to the overall global carbon footprint. Generally, the carbon dioxide emissions from IoT devices mainly consist of the production, recycling, and energy usage during the lifetime of these devices.

There is a huge potential for switching to develop sustainable IoT devices by using cutting-edge PE technology and Visible Light Communication (VLC), which can play key roles in developing truly sustainable IoT solutions. The LIoT is a concept where light is used to power up the IoT node as well as to provide wireless connectivity in booth directions [2]. This strategy is also referred to as Expose and Connect because nodes are linked to the internet once they are exposed to light. Even while LIoT may be performed using discrete/integrated component technologies, this notion becomes very appealing when implemented using PE technology. The main idea of using VLC in the development of sustainable IoT nodes comes from the advantages of VLC over Radio Frequency (RF) media, because of RF spectrum is becoming more scarce, which in turn is contributing to an increase in spectrum congestion. Sustainable LIoT wireless sensing networks are based on bidirectional VLC communications, where energy autonomous nodes are powered by the indoor light Energy Harvesting Unit (EHU) using Harvest-Store-Use (HUS) protocol [3]. Utilization of the visible light and infrared spectrum to connect edge mobile and stationary devices frees the system from using the radio spectrum. Other notable advantages of optical wireless systems include ultra-high bandwidth, robustness to electromagnetic interference, a high degree of spatial confinement bringing unlimited reuse, and inherent physical security. The LIoT concept provides secure communication in indoor environments without the need of using sophisticated and power-hungry cryptographic algorithms. Furthermore, considering devices operate in an unregulated spectrum, no licensing fees are necessary, resulting in a cost-effective option.

This research article discusses the design and implementation of an energy-autonomous LIoT node-to-gateway duplex communication prototype. The most critical aspects in the implementation of the considered communication system components are the selection of the SoC used in the Main Computing Unit (MCU), the PE energy harvesting unit, and

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the transceiver unit. Initially, we analyze and identify requirements for suitable low-power SoC-based development boards, then we compare the selected boards in terms of power consumption and computational capability, which are crucial for the LIoT concept deployment. Then, we design and execute the prototype system, which consists of LIoT access points and energy-independent edge nodes. In addition, the article discusses LIoT-friendly data transmission techniques, system algorithms, and the practicality of employing general-purpose hardware and transceiver circuits for implementation.

The paper is organized as follows. Section II describes the LIoT concept challenges to achieving a sustainable IoT network design. Section III presents the methodology for system design. Section IV discusses performance evaluation and comparison of the boards, and finally, Section V concludes the article.

II. LIoT CONCEPT CHALLENGES

In our work, we consider the design of bidirectional LIoT nodes, meaning that the communication by edge LIoT nodes is done by VLC in the downlink and infrared (IR) communication in the uplink. Depending on the application, the node will include necessary components such as actuators, sensors, signal processing units, displays, additional energy-storing units, etc. It should be noted, that the LIoT node will benefit from ambient lighting, but at the same time, it may cause interference on the uplink affecting the maximum signal reception distance. Taking into account the massiveness of possible applications in terms of the number of devices per square meter, the LIoT network should be designed with advanced multiple access control protocols. The low or medium-size LIoT networks can be implemented with Time Division Multiple Access (TDMA).

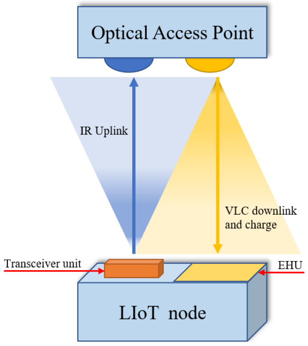

Fig. 1. Basic architecture of the bidirectional LIoT concept.

A. Requirements for the light source

In our previous work on the design of VLC-IoT node [4], the color temperature for indoor light wavelength was calculated by Wien's law [5], which was necessary to tune the light source to achieve maximum efficiency of the selected PV cells in the study. Authors in [6] demonstrated, that the amorphous or polycrystalline-based PV cells exhibit higher efficiency at the spectrum between 400 and 525nm.

One of the requirements for light sources is to guarantee eye-friendly, flicker-free indoor illumination. The IEEE 802.15.7 standard [7], specifies the maximum flickering time period for the illumination source brightness as less than 5 milliseconds. VLC connection violating this recommendation might potentially be unpleasant to the eye and eventually trigger epilepsy seizures. The light source flicker rate depends on the chosen type of modulation scheme. The Pulse Position Modulation (PPM) is recognized as a prominent technique in comparison to On-Off Keying (OOK), which suffers from baseline wandering phenomena at the receiver, resulting in the link Bit Error Rate (BER) degradation [8].

B. Challenges to achieving sustainability by PE-based LIoT edge node design

In contrast to conventional electronic technologies, sustainable electronic technologies such as printed electronics are not yet fully mature. Consequently, finding particular active and passive components for the development of a complete prototype utilizing printable or biodegradable electronics appears to be a significant obstacle at present moment. In line with the general objective of the sustainability requirements, the structure of the complete objective is comprised of the three life cycle phases: (1) production phase, (2) operation phase, and (3) recycle [9].

- Production phase - the assessment of environmental consequences and the identification of environmental hotspots are crucial for making informed strategic choices. During manufacturing, there is a significant opportunity to increase the product's sustainability;
- Operation phase — printed and embedded electronics have sustainability potentials during the operation phase. Nevertheless, some applications have no effect on the system in which they are embedded or may have a detrimental impact on their environmental profile.
- Recycle phase — the use of expensive raw materials in printed and embedded electronics is seen as a significant issue, and closed-loop techniques are regarded as essential to ensure product sustainability.

The design of fully PE-based LIoT is not possible at this moment, but we will consider a hybrid LIoT design based on conventional and PE components. Currently, there are printed photodiodes, OLEDs, indoor PV cells, displays, temperature sensors and a great range of printed passive components are now accessible as stable integration components, according to [10]–[12].

The sustainable operation of the LIoT node prototype is achieved by using an organic EHU by [13], which provides PE industry-leading performance under indoor light conditions combined with a flexible, lightweight design and a 6-cell 50x50mm sized PV cell. The output voltage of 3.3V allows us to directly connect EHU with other components of the LIoT node.

C. LIoT node power consumption management

The node has to operate by changing power consumption modes, due to limited energy resources. An adaptive periodic switch between power modes: sleep and active needs to be designed. The energy-autonomous LIoT node should follow the energy flow model given by [14], described in Eq. 1; being E and P, energy and power terms, respectively:

$$E_{BUF}^{t=0} + \int_{\tau=0}^{t} P_{scv}(\tau) d\tau \geq \int_{\tau>0}^{t} P_{DEV}(\tau) d\tau = E_{DEV}(t) \tag{1}$$

The energy stored in the buffer E_{BUF} and the additional energy scavenged from the medium $E_{scv} = \int P_{scv} d\tau$ must be greater than that required by the device to operate E_{DEV}. The energy needed to operate can not be higher than the accumulated energy in the supercapacitor, Taking into account the limited energy resource, the LIoT operates under the condition, that the smaller the duty cycle the larger average available power.

III. SYSTEM DESIGN

An SoC is an integrated circuit that houses numerous electronic system peripherals (memory, connections, analog, and digital peripherals) on a single substrate and is powered by a CPU. SoCs are becoming increasingly popular because of their smaller size, lower power consumption, and lower assembly costs as compared to older microcontroller designs. The SoC platform combines numerous functionalities into a single Si chip, notably digital and analog peripherals, system memory, interfaces like I2C, SPI, and UART, a microprocessor, and communication units— in other words, all of the necessary electronic components and circuits. The ARM Cortex M series-based SoC can be considered one of the most popular solutions for ultra-low power-required applications. The Seeed XIAO platform [15] is represented with four different chipsets like nRF52840, RP2040, SAMD21, and ESP32C3. The main idea behind the XIAO platform is to provide high-performance, low-power, coin size, and affordable development boards for low-power IoT and wearable applications.

The MCU of the LIoT node prototype is considered to be selected among the Seeeduino XIAO development boards [15], which are represented by the following features: small size of 20x17.5 mm; multiple development interfaces; low power System-on-Chip. Later, we will evaluate and compare the performance of these boards.

The selected XIAO development boards from Seeeduino with the following MCU are considered in this study:

- XIAO nRF52840 Sense ARM M4 at 64MHz;
- XIAO RP2040 Dual-core ARM M0 at 133MHz;
- XIAO SAMD21 ARM M0+ at 48MHz;

From [15], we can find the specifications comparison table of the boards, all of the considered boards satisfy the general requirements for LIoT prototyping. Notably, the XIAO board powered by nRF52840 offers integrated Bluetooth 5.0 low-power wireless connectivity and additional built-in sensors such as a pulse density modulation microphone and a 6-axis LSM6DS3TR-C inertial measurement unit.

1) LIoT node prototype: The system design was adapted from [16], which presents a feasibility analysis and implementation work for an energy-autonomous LIoT node based on AVR Atmega328P-powered Arduino mini board. The implementation of LIoT node based on ARM M0+ microprocessor using Seeeduino XIAO SAMD21 [15] development board was designed in this study Fig.2.

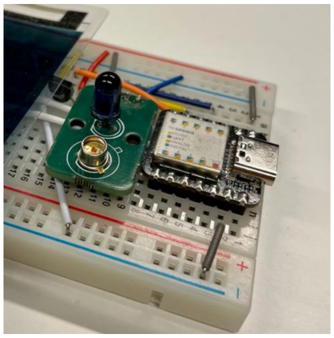

Fig. 2. XIAO SAMD21 based LIoT node prototype.

The LIoT node harvests energy from indoor illumination via a printed organic energy harvesting unit by Epishine [13], which consists of the AEM 10941 power management IC (PMIC) as a boost converter and the Maximum Power Point Tracking (MPPT) module to keep input voltage at the maximum efficiency region. A Texas TPS 62740 step-down buck DC-DC converter is used to output voltage only if the supercapacitor charge is higher than 3.9V. The energy buffer is GA230F 0.4F supercapacitor by CAP-XX. The EHU harvests indoor light energy via 6-cell PE photovoltaic cells with a measured 260μA output current at 700lx, Fig.3 illustrates the structure of EHU.

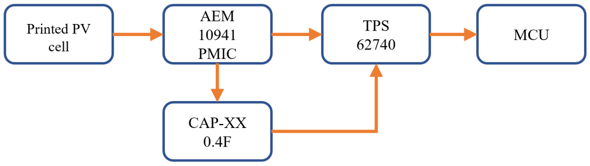

Fig. 3. Structure of the EHU.

The LIoT node utilizes VLC and IR communication for downlink and uplink, respectively, and Fig. 4 shows the block diagram of the main components. The transceiver unit operates as follows: the VLC downlink signal is received by a 525nm PIN photodiode at 38kHz carrier frequency, then a Trans-Impedance Amplifier (TIA) converts the current signal to a voltage-electrical signal, which is amplified by using an Automatic Gain Control amplifier (AGC). The output signal from AGC is filtered by a bandpass filter with a 38kHz center frequency. All above-mentioned operations are done by a transceiving circuit based on the VSOP 38388IC. The uplink

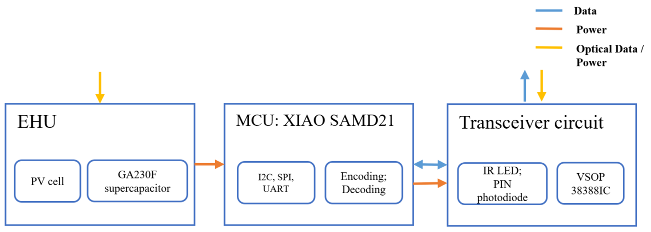

Fig. 4. Structure of the LIoT node.

signal was selected to be at the infrared spectrum to avoid optical channel interference and naked eye perceivable flicker, which is emitted by TSAL6200 IR LED at 940nm wavelength.

The LIoT node scripts were developed by using the following open-source libraries:

- IRremote.hpp [17] library for encoding and decoding both VLC and IR signal using the RC5 protocol;
- RTCSAMD21.h [18] library was used to schedule an internal real-time clock to generate the internal interrupts to switch node operation mode from sleep to active mode and set the alarm for the next duty cycle;
- Energysaving.h [19] library was necessary to put the node into sleep mode after completion of the tasks;

2) LIoT access point: The input data was initially generated from the computer connected to the access point via a serial port. The same XIAO SAMD21 board was used as an MCU for the access point as well, Fig. 5 illustrates the overall structure of the access point. The access point uses a 2B5C Chip-on-Board LED for VLC and is connected to MCU via IRF 520 MOSFET transistor, which is designed to provide sufficient modulation depth for both uplink and downlink signals using PPM at 38kHz carrier signal frequency, in order to minimize the ambient noise from the VLC channel. The uplink IR signal is received by VSOP382 IR receiver module.

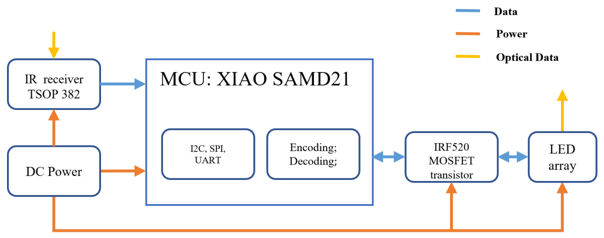

Fig. 5. Structure of the access point.

IV. EVALUATION

In order to compare the computational power and power consumption of the selected XIAO boards, two benchmark tests were performed. The MCU speed test was carried out using two different tests, where the main metric is time to complete the task per iteration. The interoperability of the LIoT node with a variety of sensors should be as fast as possible, which is why the I/O speed benchmark was considered in the first test. The first performance test was mainly focused on the main functions of the embedded hardware, such as digital read, digital write, Power Width Modulation (PWD), analog read, mapping, and an empty loop. The number of iterations considered in the test was 10000 and the values are given in seconds, Fig.6. There is a necessity of expanding the LIoT concept to the network level through the implementation of Machine Learning (ML) models for synchronization and power consumption prediction in future versions of the nodes. There are available ML models based on TinyML and benchmarks of various development boards [20], [21], which can be run on the selected boards. Basic arithmetic operations are the core tasks of complex ML algorithms. In order to have a better understanding of the computational capability of MCUs, the second test was performed, including the following mathematical operations: addition, division, square root, sinus, and Fast Fourier Transform (FFT) functions. Table I shows the main measured data regarding the computing performance of the XIAO boards, where XIAO SAMD21 outperforms XIAO nRF52840, but XIAO nRF52840 completed the second test three times faster than XIAO SAMD21 and had a similar result with the dual-core XIAO RP2040. The boards generally showed relatively similar marks, except for XIAO SAMD21 performance during the second benchmark test, which can be explained by the architecture of the SoC. The SAMD21 is powered by ARM M0+ with a lower 48 MHz clock speed in comparison to nRF52840's 64MHz ARM M4 chip. It should be noted that another significant selection criterion of MCU is the power consumption of boards at active and deep sleep modes since the LIoT energy is strictly limited on the node.

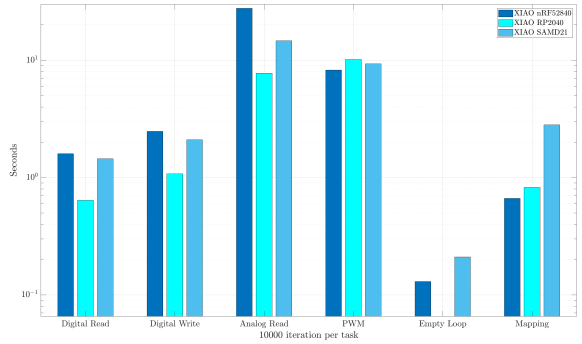

Fig. 6. Results of the speed test 1 per task.

TABLE I
RESULTS OF BENCHMARK TESTS

Board	**XIAO SAMD21**	**XIAO RP2040**	**XIAO nRF52840**
Test 1, ms	306	205	408
Test 2, s	153.82	47.47	44.97

The power consumption of the boards was measured by a Nordic Power Profiler Kit 2, which comes along with a user-friendly open-source software tool. The measurement was

TABLE II

THE MAXIMUM DRAWING CURRENT OF THE XIAO BOARDS DURING ACTIVE AND DEEP SLEEP OPERATING MODES

Board	**XIAO SAMD21**	**XIAO RP2040**	**XIAO nRF52840**
Active, mA	16.8	28.2	13.01
Sleep, mA	0.018	3.8	0.925

taken under the execution of the same script for all boards. The boards return from the deep sleep modes by an internal interruption created by the chipsets oscillators, and the power consumption results of RP2040 and nRF52840 are higher than the expected values, a fact that can be explained by the additional components on the board: built-in RGB LED in the XIAO RP2040 and sensors in the XIAO nRF52840 board, respectively. From table II the maximum drawing current in sleep mode for XIAO SAMD21 board was measured 18μA, representing the lowest value among selected boards. The obtained results are the average of multiple iterations of the above-discussed tasks. It was decided, that the initial self-powered LIoT edge node prototype should be first designed on the base of the lowest power-consuming board - XIAO SAMD21.

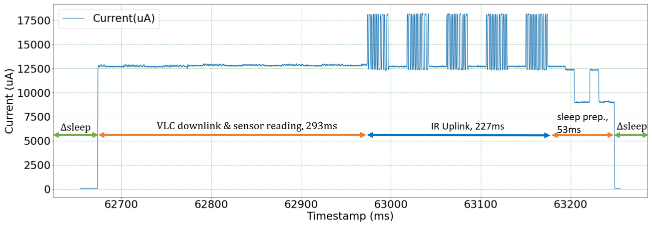

Fig. 7. Duty-cycle power profiling of XIAO SAMD21 based LIoT node.

Fig. 7 depicts the duty cycle of the LIoT node sending temperature sensor TMP36 readings according to the received code either in Celsius or Fahrenheit. The LIoT node woke up from sleep mode by internal interruption, then the node demodulated the received signal from the access point. During the next step, the node sent the modulated uplink signal 5 times to assure the data delivery during transmit stage. The final active mode stage shows the set of the alarm using the chip's Real Time Clock (RTC), which triggers the internal interruption and wakes up the node for the following duty cycle. The average duration of the duty cycle was measured at 0.57 seconds. The duty cycle duration is linearly related to the power consumption of the node, and ARM-based M0+ SoC provides the sufficient computational capability to achieve a higher frequency of duty cycles and shorter sleep mode duration. The shorter sleep mode duration was measured at the 50s at 700lux average indoor illuminance. Notably, the average current consumption of the node during IR upload is 14.15mA, which is 56% lower than the previous work [16].

This paper mainly focuses on the selection of the SoC-based low-power MCU for the LIoT concept. The system design is relatively similar to the ones proposed by the [16], [22]. However, we can see the clear advantage of ARM core-powered SoCs over the conventional AVR-based LIoT prototype. The XIAO SAMD21-based LIoT node outperforms the previous LIoT prototypes in terms of both computational power and power consumption both in active and sleep mode. The advantage of the alternative nRF52840-based board will be explored in our future works when hybrid optical- and radio-based IoT nodes will be investigated.

V. CONCLUSION

This work explored the feasibility of using low-power, low-cost SoC-based boards and their selection, which are one of the ideal solutions for LIoT edge nodes MCU. We found that the selected XIAO SAMD21 board in the MCU has sufficient computation capability and acceptably low power consumption to be used in the implementation of a sustainable LIoT node. The higher computational power of ARM M0+ based LIoT MCU allows achieving short duty-cycle duration, ultra power consumption, and low sleep mode period. To conclude, we believe that the LIoT concept has huge potential as a sustainable solution for the massive wireless communication niche, the possible applications can be: smart product labels, wearable LIoT nodes, LIoT-based precise positioning, smart packaging, etc. In the future, when PE technologies are mature, fully printed LIoT nodes will be manufactured, a truly sustainable solution to the massive use of IoT technology. Despite the diversity of applications, common challenges appear related to synchronization, traffic scheduling, distributed computing, and dynamic resource allocation. Adaptive sleep time scheduling algorithms need to be developed for the further versions of LIoT nodes to have communication synchronization at the network level.

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