



A smart-sensing AI-driven platform for scalable, low-cost hydroponic units

D2.1 Multi-modal Sensor Kit Specifications and Requirements







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COORDINATOR	Panagiotis Zervas
COORDINATOR EMAIL	panagiotis@scio.systems
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RESPONSIBLE AUTHOR	Niklas Galler (nr21 Design)
RESPONSIBLE AUTHOR EMAIL	niklas.galler@nr21.com
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CONTRIBUTORS	Alexandros Salapatas (NCSR-D), Panagiotis Zervas (SCiO) and Pythagoras Karampiperis (SCiO)
REVIEWER	Panagiotis Zervas (SCiO)

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PARTICIPANTS		CONTACT PERSON
<p>SCiO P.C. (SCiO, Greece) Coordinator</p>		<p>Panagiotis Zervas Email: panagiotis@scio.systems</p>
<p>Department of Plant and Environmental Sciences, University of Copenhagen (UCPH, Denmark)</p>		<p>Bhim Bahadur Ghaley Email: bbg@plen.ku.dk</p>
<p>Holisun SRL (Holisun, Romania)</p>		<p>Oliviu Matei Email: oliviu.matei@holisun.com</p>
<p>nr21 DESIGN GmbH (nr21 DESIGN, Germany)</p>		<p>Niklas Galler Email: niklas.galler@nr21.com</p>
<p>Institute of Nanoscience and Nanotechnology, National Centre for Scientific Research “Demokritos” (NCSR-D, Greece)</p>		<p>Eleni Makarona Email: e.makarona@inn.demokritos.gr</p>
<p>Department of Technical and Soil Sciences, University of Agricultural Sciences and Veterinary Medicine Cluj- Napoca (USAMV, Romania)</p>		<p>Teodor Rusu Email: trusu@usamvcluj.ro</p>

ACRONYMS LIST

BB-MZI	Broad-band Mach-Zehnder Interferometry or Broad-band Mach-Zehnder Interferometer
CHSK	Crop Health Sensor Kit
CSU	Communication and Storage Unit
MMS	Multi-modal Sensor
NCK	Nutrient-content Kit

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recorded with a typical spectrometer (Maya Pro 2000, Ocean Optics) and the BB-MZI had a sensing arm of only 600 μ m

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EXECUTIVE SUMMARY

Deliverable 2.1 is the comprehensive outcome of Task 2.1, which sets the specifications and the requirements of the sensor kits to be employed for the monitoring of the crop health, of the environmental factors and of the nutrient contents of the microgreen GOHydro hydroponic installations. These sensor kits, collectively referred to as “Multi-modal Sensor Kits” (and for brevity referred to as “MMS Kits” hereafter) are the components that will be responsible for data collection and data communication; it is upon these data that the AI-based platform of the e-agronomist is going to be built around. Therefore, Task 2.1 and the corollary Deliverable 2.1 are of paramount importance for the successful implementation of the project, since they need to set in a precise and concise way the design rules and to carefully select the essential components of the MMS Kits. In addition, the design rules and components must ensure that the MMS Kits are cost-efficient and easy-to-use so as to be pertinent to the envisioned goal of urban hydroponic installations accessible to and affordable for anyone. Furthermore, the MMS Kits must be designed in such a way that are not plant-specific, but they can be expanded to a wide-range of hydroponically cultured plants in future applications and forecasted products.

Towards that end, Task 2.1 and Deliverable 2.1 realized the design of the MMS Kits taking into account key features, such as (a) analysis of the users’ needs, their profiles, the use scenarios and the definition of the design requirement for functions, ergonomics, morphology and semantics, (b) ease-of-use, (c) the most important environmental parameters that are pertinent to microgreen hydroponic cultures (e.g. temperature, light intensity, humidity), (d) nutrient contents of microgreens affected by the environmental parameters in hydroponic cultures, (e) technical specifications of all the mechanical and electronic component, (f) ease-of-installation and (f) final cost versus expected performance. This task was closely interlinked to the first stages of T1.1 “Review on nutrient and production parameters and light requirements” and the literature reports as well as the requirement of WP3 “Data-driven platform”. All the above are presented in Chapter 1 (Introduction) and Chapter 2 (Crop Health Sensor Kit)

Last but not least, WP2 also includes an innovative, but high-risk element, namely the development and application of a novel immersible photonic sensor for the nutrient-content monitoring of the hydroponic plants. This particular approach is *being applied for the first time* and due to its high degree of novelty, it was decided to develop a separate sensor kit (hence the already foreseen separate Task 2.2) independent of the Crop Health Sensor Kit (Task 2.3). The design rules and specifications had been examined separately and are presented in an independent chapter (Chapter 3) of this deliverable.

1 INTRODUCTION

GOHYDRO as a whole aims at developing a cost-efficient smart-sensing ICT platform capable of monitoring the crops' health and nutrient content of hydroponically cultivated microgreens in order to optimize the cultivation process and allow the harvest of the best possible products in an urban setting. GOHYDRO aspires to culminate in the production of a platform that will be a shifting paradigm of how AI-driven technological innovation can become an affordable, accessible-by-all tool, applicable to all forms of urban farming. With this aim in mind, the GOHYDRO platform has a “dual core” one that consists of the platform's hardware and one that consists of the AI component. The former, collectively described as the MMS Kits, is the core that in essence monitors, collects and transmits the data pertinent to the health and nutrient content of the hydroponically cultivated microgreens and can be envisaged as the “front-end” of the GOHYDRO platform responsible for the continuous monitoring of all parameters for the successful cultivation of plants at the hydroponic installation, as shown schematically in Figure 1.1. Apart from the monitoring and collection of data, this front-end will also be responsible for the data transmission to the computational back-end of the platform. Moreover, this front-end will be also in charge during the first year of the project to amass as much data as possible in order for the AI component to be properly developed and trained. It is thus of paramount importance that its design must be as meticulous as possible, must include all functionalities and cover all fronts early-on in the project in order to minimize technical risks.

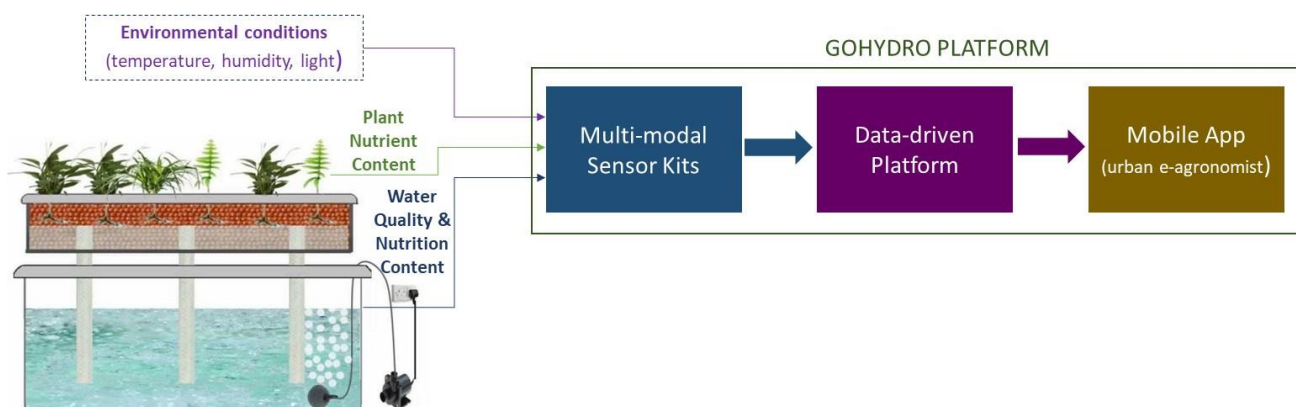


Figure 1.1 Schematic Representation of the GOHYDRO platform concept. The MMS Kit are shown in blue and serve as the front-end (input) of the GOHYDRO platform

In addition to the above, the MMS Kits design must revolve around the central idea of the project that the GOHYDRO platform is addressed to all allowing any user to implement an affordable hydroponic culture at his/her urban setting of choice (home, garden, office, communal buildings, schools etc). Therefore, the MMS Kits design should first and foremost obey **three basic requirements**: (1) low cost, (2) ease of installation, and (3) ease of use (mostly in terms of maintenance, like re-charging). Deliverable 2.1 was based on these three requirements, which dictated the entire set of specifications and requirements compiled herein.

Finally, it should be noted at this point that the MMS Kit specifications and requirements were additionally based on the choice that was made at the kick-off meeting of the project to proceed with a **wick type hydroponic installation**. That choice also stemmed from the three basic requirements of low cost and ease-of-installation/use, since it allows anyone to build on his/her own a very quick, affordable and low-maintenance installation with everyday items and on-line orders of very basic

hydroponic components (trays, mats, seeds and pumps). As show in in Figure 1.2 and Table 1.1, SciO and NCSR-D have already selected the components of the hydroponic installation (since they will built the first **pilot installation of the project** in Greece in order to collect data as expeditiously as possible), which costs in total ~720 €.



Figure 1.2 Images of the already selected components of the pilot wick-type hydroponic installation to be realized at the premises of SciO (Athens, Greece) and where NCSR-D will first implement and test the MMS Kits (also listed in Table 1.1).

Table 1.1 List of the pilot GOHYDRO hydroponic installation components and their cost

Component #	Site for on-line ordering	Cost
Shelving Unit	https://www.ikea.gr/proioda/kouzina/rafiere-rafia-kouzin/rafiere/omar-monada-rafiwn/69829083?gclid=CjoKCQjw9YWDBhDyARIsADt6sGZGanXE8FuOkjTptS3ZdY2aLGMp-sd1-GC-3yUZIwLR664b8JwArXMaAqkNEALw_wcB	79.90 €
Hydroponic Tent	https://www.gadget-shop.gr/idroponiki-skini-esoterikou-chorou-kalliergias-fiton-120-x-60-x-150-cm-outsunny-845-263-845-263?skr_prm=WyJhNTcyZTgyYi1mOTFhLTQoY2EtYTBkZCoxNWVmNGNmNjQ3MGQilDE2MTcwMTgwNDkwNDQseyJhcHBfdHlwZSI6IndlYiIsImNwIjoYiIsInRhZ3MiOiliVo#prettyPhoto	99.95 €
Trays (x4)	https://aeroponic.gr/kanali-kalliergeias-1m.html	4×11= 44 €
Grow Pads (x100 – minimum order)	https://www.alibaba.com/product-detail/Hot-Sale-Outdoor-Biodegradable-Jute-Felt_1600072664839.html?spm=a2700.7724857.normal_offer.d_title.6f097281m2Q8ty	199 €
Pump	https://aeroponic.gr/boyu-fp-1000-adjustable-pump-1000l-hr-eu-plug.html	21,90 €
Airstone	https://www.growit.gr/%CF%80%CF%81%CE%BF%CE%B9%CE%BF%CE%BD/%ce%ba%cf%85%ce%ba%ce%bb%ce%b9%ce%ba%ce%b7-%ce%b1%ce%b5%cf%81%ce%bf%cf%80%ce%b5%cf%84%cf%81%ce%b1-175mm/	9,50 €
Tubes	Generic hardware store	~ 10 €
Sweet Basil Seeds (1kgr minimum order)	https://www.alibaba.com/product-detail/Top-Quality-Ocimum-basilicum-Sweet-Basil_1600131992747.html?spm=a2700.pc_countrysearch.main07.37.657f4462cF63Jc	9.90 €
Water Tank	Any aquarium type acrylic water tank is suitable and will be purchased from a pet shop	~ 30 €
Hydroponic Lamp	https://www.amazon.com/Sun-Blaze-Fluorescent-Hydroponic-Greenhouse/dp/B009GCQWX2/ref=pb_allspark_session_sims_desktop_2?pd_rd_w=N9otb&pf_rd_p=bfefd6e2-acb1-463d-94d0-38a6e00f41d3&pf_rd_r=P2KT6ZQXZGDRK31XSV4R&pd_rd_r=3db928d6-530f-4d77-a274-fbf74edea30c&pd_rd_wg=P6zAh&pd_rd_i=B009GCQWX2&pssc=1	~ 70 €
Nutrient Powder	Commercially available at several sites	~50 €
TOTAL COST		718.20 €

2 CROP HEALTH SENSOR KIT

Based on the choice for the wick type hydroponic installation, it was decided that the Crop Health Sensor Kit (CHSK) should be divided into two separate sub-units, one measuring the water and nutrition quality to be located at the water tank and one monitoring the environmental conditions to be placed on the racks of the installation (Fig. 2.1). Each sub-unit will have its own set of sensors and power autonomy and will be sending the data to a “central” communication’s unit that will be plugged in close to the hydroponic unit. This division into smaller sub-units makes the CHSK kit even more modular and more profitable commercially-wise as each component may be sold separately or used interchangeably at several locations and hydroponic units. Moreover, the central communications unit may be used with multiple hydroponic installations and not just a single one transmitting data from multiple crops.

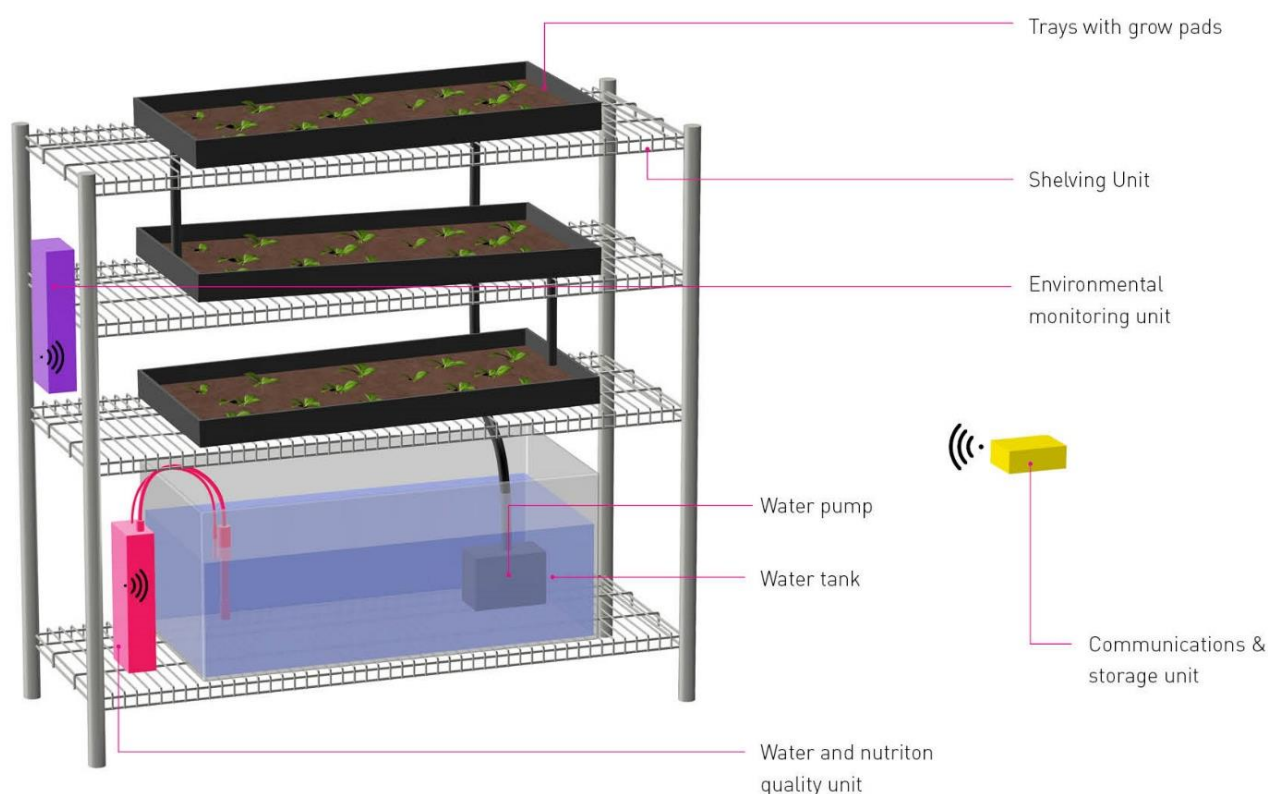


Figure 2.1 Schematic Representation of the two sub-units of the Crop Health Sensor Kit and their locations within the DIY hydroponic unit. The magenta triangle represents the immersible Water and Nutrition Quality Sub-unit that will monitor the water feeding the microgreens. The purple hanging element represents the Environmental Conditions Kit that can be hanged on any shelf of the unit or that can be interchangeably used in another hydroponic unit. The yellow circle represents the central communication unit.

2.1 ENVIRONMENTAL, WATER AND NUTRITION QUALITY MONITORING SUB-UNITS

Unit Description

The CHSK will be providing monitoring information of the environment temperature, humidity and light medium surrounding the crops and monitoring information for the liquids (water, minerals etc.) feeding the plants. A mass production cost is expecting to be of the order of \$100. Low battery usage is expected offering an autonomous solution but it needs to be examined through experimentation due to indeterminate factors surrounding the commercial, low-cost sensors. The unit should be placed on one of the racks of the hydroponic installation (Fig. 2.1). Water sensors should be continuously immersed in the water tank.

From an operation point-of-view the CHSK is divided into two separate sub-units, one destined to monitor the environmental conditions and one monitoring the water and nutrient quality, but it was decided that both should be packaged as a single unit to maintain scalability and efficient production cost. Both sub-units will share the same microcontroller and power supply. The concept is depicted in Figure 2.2, while Table 2.1 compiles all the components selected so far. Based on the components a first approach in designing the CHSK is shown in Figure 2.3. This way we only need one housing, one microcontroller and battery by bundling the data transfer to the Communications and Storage Unit. An All-In-One unit in our perspective will have its biggest advantages in the ease of use.

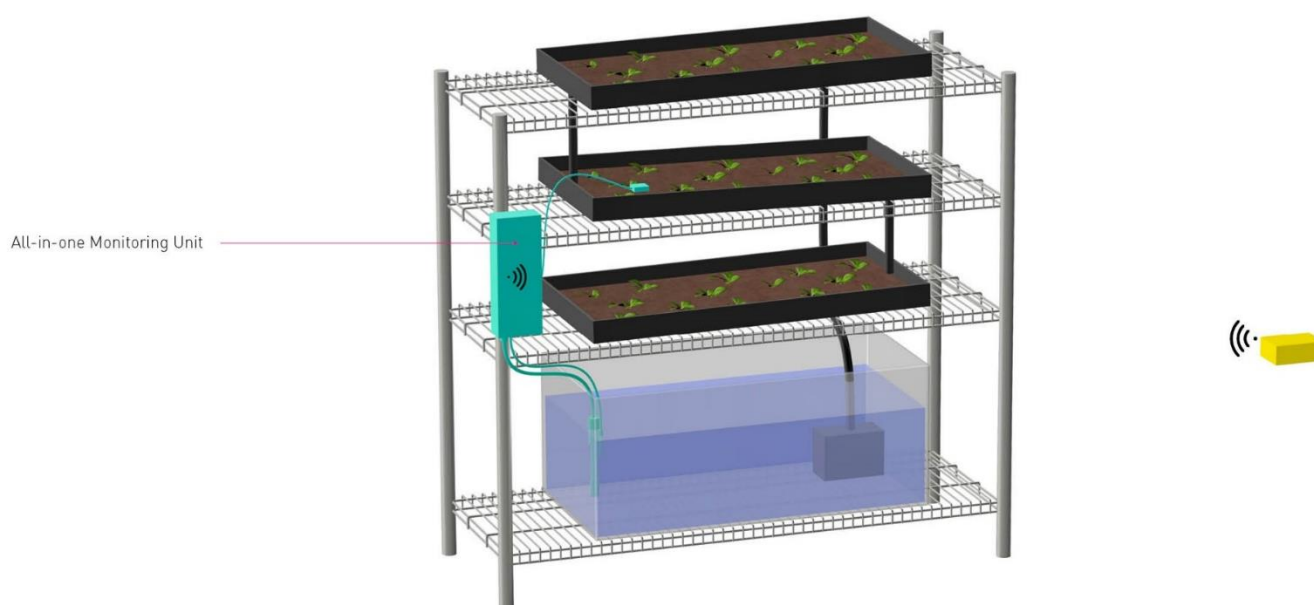


Figure 2.2 Schematic Representation of the CHSK. The communications sub-unit is also shown in yellow.

Table 2.1: Components of Environmental Monitoring Sub-Unit*

Component	Model
Air Temperature Sensor	Adafruit Si7021 Temperature & Humidity Sensor Breakout Board
Air Humidity Sensor	Adafruit Si7021 Temperature & Humidity Sensor Breakout Board
Light Sensor (UV)	SI1145 Digital UV Index / IR / Visible Light Sensor
Water Temperature Sensor	Temperature Sensor – Waterproof (LM35)
Digital pH Meter	Liquid PH Value Detection Sensor Module
Electroconductivity Sensor	Analog TDS Sensor Water Conductivity Sensor
Microcontroller	Raspberry Pi Zero W (BLE, WiFi included)
Battery	Xiaomi Redmi 18W Fast Charge 20000mAh

Enclosure	To be developed within WP2
Momentary switch for ON/OFF operation	16mm Illuminated Pushbutton - Red Momentary
Status LED	3mm LED Diffused Red
Bluetooth pairing button	Adafruit 16mm Illuminated Pushbutton - Blue Latching On/Off Switch
USBA to micro-USB adapter for powerbank to RPi	Powertech USB 2.0 Cable USB-A male - micro USB-B male 3m (CAB-U009)
Heatsink (optional)	Heatsink for Raspberry Pi Zero
Power supply used for testing	Raspberry Pi Zero Power Supply 2.1A

*more details about each part can be found in the *List of major commercial components*

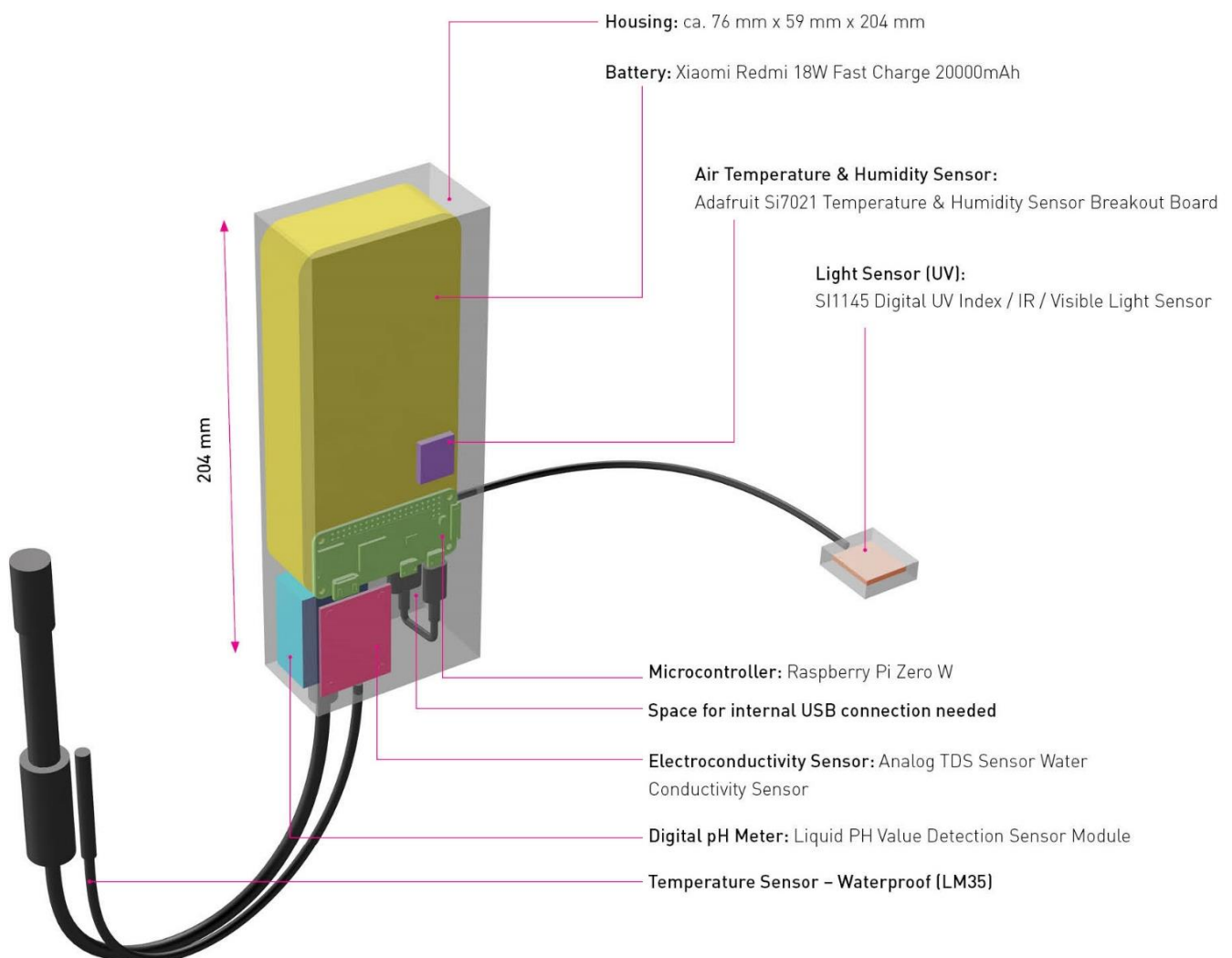


Figure 2.3 First design of the CHSK based on the data sheets of the selected components

2.2 COMMUNICATIONS AND STORAGE SUB-UNIT

The Communications & Storage Unit (CSU) will act as the central-hub of communication and storage acquiring the measurement data from the sensor-kits. We chose to use for communication the included Bluetooth Low Energy (BLE) on the Raspberry Pi which uses a piconet topology, where the comms & storage kit will have the master role and the sensor nodes the slave roles. Up to 7 simultaneous connections to the slave nodes are supported in this manner and unlimited sensor pairings. While the possibility of extending the topology to a scatternet by interconnecting two or more piconets is expected in the near future, the proposed connectivity already fulfils the requirements for a solution for our current understanding of the communication requirements. Even though there is no theoretical limit on the maximum number of sensor pairings with the central-hub, we will try to examine its limits by further experimentation.

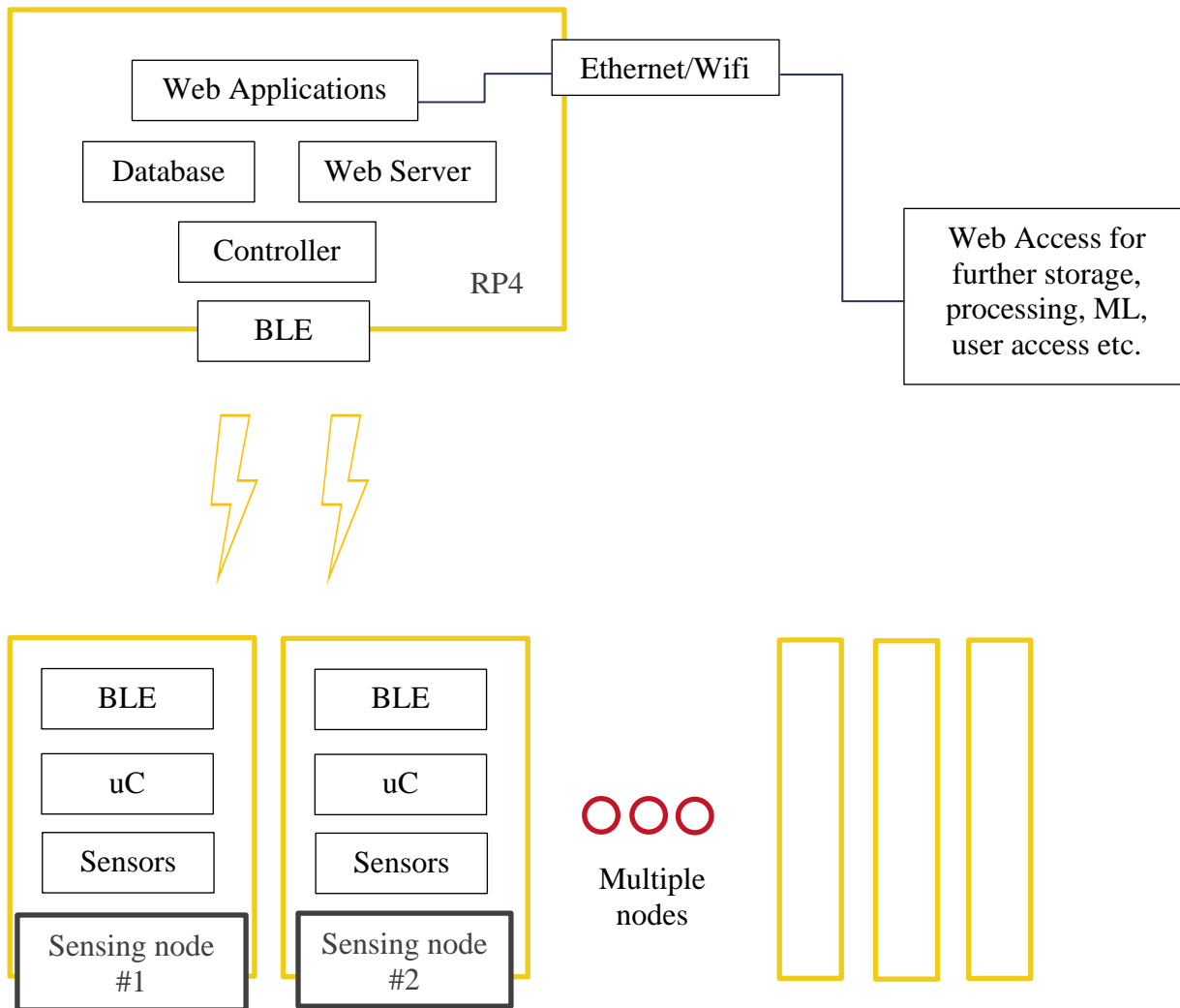


Figure 2.4 Block Diagram of the CSU and its connectivity to the GOHYDRO application

Each sensor subunit will interrogate its internal sensors in the required times and every measurement will be stored locally in a simple manner. In more detail, coding requires a script for each sensor with custom machine instructions on how each measurement has to take place. Each measurement data will be characterized and stored temporarily in a txt file entry which will provide us with simple

retrieval. Script execution will be timed by adding a **cron** entry requiring the execution of an external script in predetermined times. In case of change e.g. the measurement timing, this way will require minimal effort. Each sensor subunit will be able to communicate to the **CSU** through a BLE connection.

The **CSU** will be focused on collecting the data from the sensor nodes, local storage, local processing and data communication in the corresponding to the external users. Before storage the data will be pre-processed if-necessary and characterized in a local **mysql** database which will provide us with the ability for robust storage and agile post-processing and retrieval through code in the PHP language and Apache server. For retrieval and further cloud processing a JSON or any other applicable communication format will be used after communication with the developed algorithms and mobile application by SCiO and Holisun.

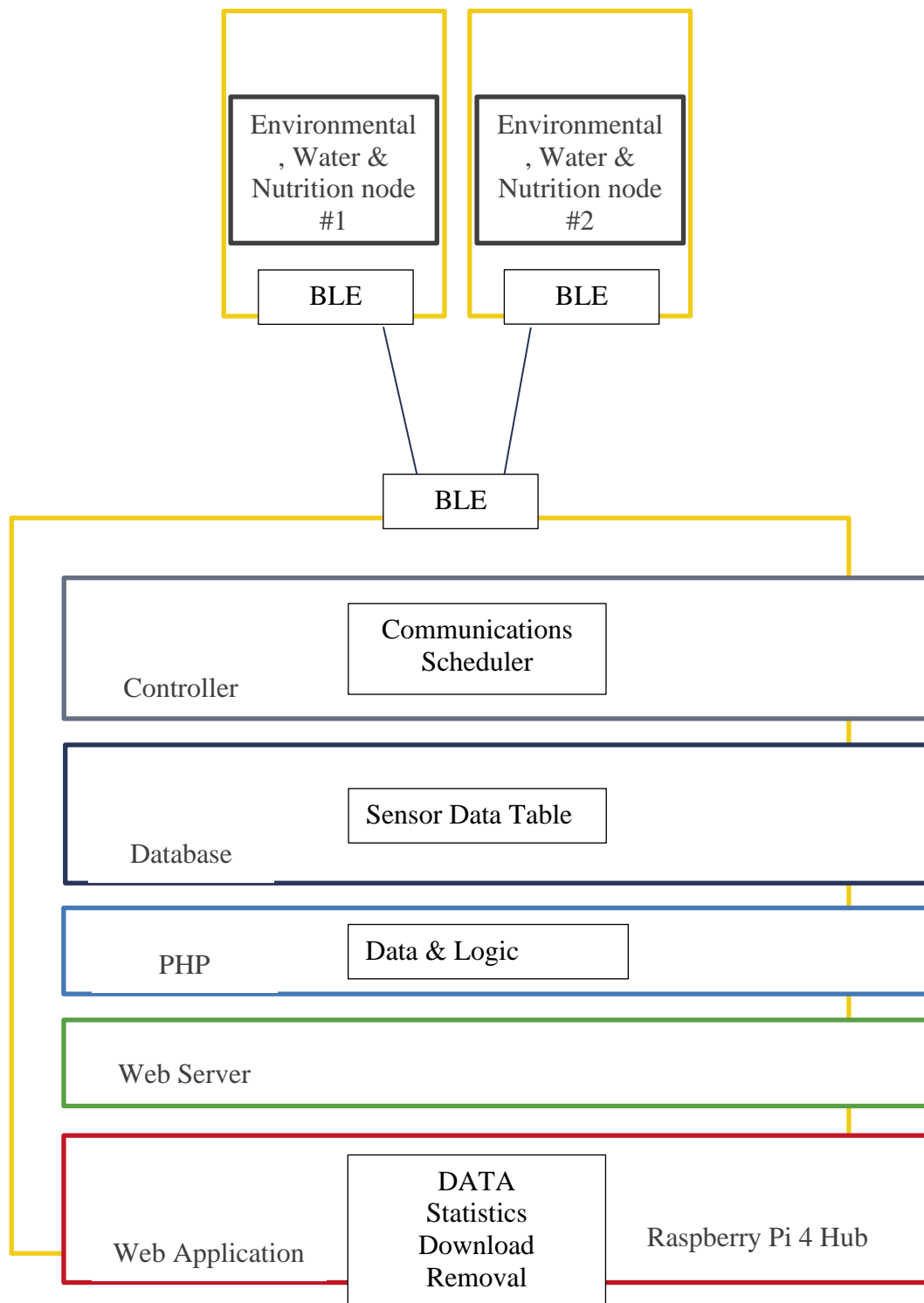


Figure 2.5 CSU high-level software architecture.



Table 2.3: Components of the Communication & Storage Unit




Component	Model
Microcontroller	Raspberry Pi 4 Model B (BLE, WiFi & Ethernet onboard)
Power Source	Raspberry Pi 4 Official power 3A (15,3W) USB-C
Box	To be developed within WP2 (Task 2.3)
Momentary switch for ON/OFF operation	16mm Illuminated Pushbutton - Red Momentary
Status LED	3mm LED Diffused Red
Bluetooth pairing button	Adafruit 16mm Illuminated Pushbutton - Blue Latching On/Off Switch
USB-C power adapter	Raspberry Pi 4 Official power 3A (15,3W) USB-C
Heatsink (optional)	Raspberry Pi 4 Heatsink/Ψυκτρα 40x30x5mm
Enclosure	To be developed within WP2

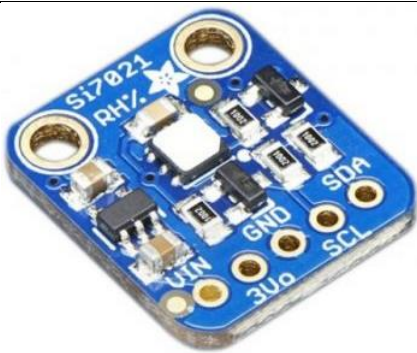


This sub-unit will be collecting all monitoring information from the sensor-kits and serving them to internet for further cloud processing and storage. A mass production cost is expecting to be of the order of \$45.







2.3 LIST OF COMPONENTS

Table 2.4 List of major commercial components

Component	Model
Microcontroller	Raspberry Pi 4 Model B 
Microcontroller	Raspberry Pi Zero W 
Power Source	Raspberry Pi 4 Official 3A (15,3W) USB-C

	<p>https://nettop.gr/index.php/raspberry-pi/aksesouar/trofodotika/raspberry-pi-4-official-μετασχηματιστής-στα-3a-15,3w-usb-c-άσπρος.html</p> 
Power Source	<p>Raspberry Pi Zero Power Supply 2.1A https://nettop.gr/index.php/raspberry-pi/raspberry-pi-zero/raspberry-pi-zero-aksesouar/raspberry-pi-zero-power-supply.html</p> 
Power Bank (x2) -tbd	<p>Xiaomi Redmi 18W Fast Charge 20000mAh Λευκό https://www.skroutz.gr/s/19828940/Xiaomi-Redmi-18W-Fast-Charge-20000mAh-Λευκό.html</p> 
Temp & Humidity Sensor	<p>Adafruit Si7021 Temperature & Humidity Sensor https://grobotronics.com/adafruit-si7021-temperature-and-humidity-sensor-breakout-board.html</p>

	
Liquid PH Sensor	https://www.aliexpress.com/item/1005001612930856.html 
TDS Sensor Water Conductivity Sensor	https://www.aliexpress.com/item/4001042249785.html 
Temperature Sensor – Waterproof	https://grobotronics.com/lm35.html 
Momentary switch for ON/OFF operation x2	https://nettop.gr/index.php/eksartimata/diakoptes/16mm-illuminated-pushbutton-red-momentary.html

	
Status LED x2	https://nettop.gr/index.php/hlektronika/leds/3mm-leds/3mm-led-diffused-red.html 
Bluetooth pairing button x2	https://nettop.gr/index.php/eksartimata/diakoptes/16mm-illuminated-pushbutton-blue-latching-on-off-switch.html 
USBA to micro-USB adapter For powerbank to RPi	https://www.skroutz.gr/s/7141918/Powertech-USB-2-0-Cable-USB-A-male-micro-USB-B-male-3m-CAB-U009.html?from=catspan 
Heatsink (optional)	https://nettop.gr/index.php/raspberry-pi/raspberry-pi-zero/raspberry-pi-zero-aksesouar/raspberry-pi-zero-heatsink.html 
Heatsink (optional)	Raspberry Pi 4 Heatsink/Ψυκτρά 40x30x5mm https://nettop.gr/index.php/raspberry-pi/aksesouar/cooling/raspberry-pi-4-heatsink40x30x5mm.html 

3 NUTRIENT CONTENT KIT

The Nutrient Content Kit (NCK) is based on a newly-patented technology by NCSR-D. The technology is based on immersible silicon photonic sensors. The high-risk and innovative aspect of this kit is not just the new types of photonic sensors, but the fact that the GOHYDRO project will attempt to correlate the collected data of the NCK to the nutrient content of the hydroponically cultivated microgreens through an AI—based suitable algorithm. This Chapter is devoted to a short description of the photonic sensors and their principle of operation followed by the laying out of the kit's specifications and requirements that emerged as a corollary of their underlying technology.

3.1 NUTRIENT-CONTENT KIT BASED ON IMMERSIBLE PHOTONIC PROBES –SHORT DESCRIPTION OF TECHNOLOGY AND PRINCIPLE OF OPERATION

The general concept behind the NCK is the creation of fully-immersible photonic circuits alleviated of any microfluidic compartments and electrical interfacing and which can be used as dip-stick probes, similar to immunochromatographic strips, but with the accuracy of optical biosensors. The related technology has been patented under US20200064260A1. In brief, the NCK concept is:

1. A silicon-based photonic chip containing a photonic circuit capable of optical biosensing. (Figs. 3.1 and 3.2a).
2. The photonic integrated circuit has optical inputs and outputs on the same chip side enabling light coupling in and out through a bifurcated fiber and a specially-designed optical adapter (Fig. 3.2a).
3. Light coupling is achieved directly from chip to fiber through a mechanical adapter (Figs. 3.2 and 3.3) without the use of lenses, grating couplers or any other external or on-chip integrated components. One branch of the coupled bi-furcated fiber feeds the light from an LED, while the other branch collects the output signal and directs it to the recording medium.
4. The waveguides are photonic-engineered and lithographically patterned to contain two optical sensors (Figs. 3.1 and 3.2) in the form of Broad-band Mach-Zehnder Interferometers (BB-MZIs). The sensing windows of the BB-MZIs are exposed areas of the waveguides that allow direct contact with the liquid samples and their probing by the waveguided light.
5. The output signal is recorded by a spectrometer monitoring in real time shifting spectra. The observables are either the spectral shifts as well as the phase of the peak of the Fourier transform of the nearly sinusoidal spectrometer signal (to be further analyzed below). Each sensor is designed with its own distinct peak in the Fourier domain and all peaks are independently, but simultaneously tracked by monitoring their phases.
6. The LED and spectrometer can be powered through a USB port from a power bank rendering the system autonomous, lightweight and relatively low-cost (Fig. 3.2b).

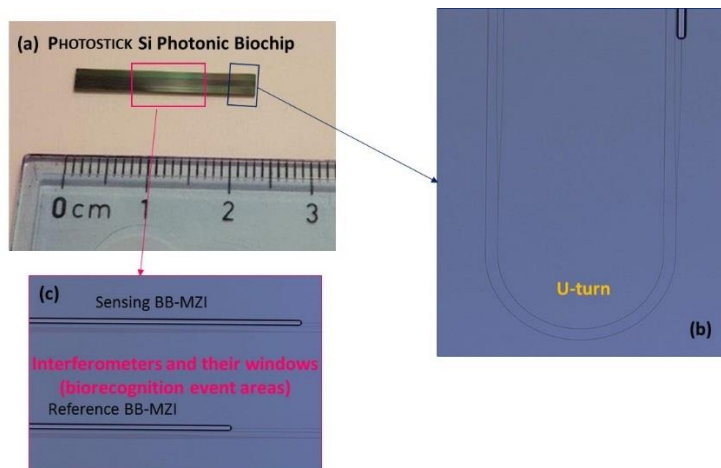
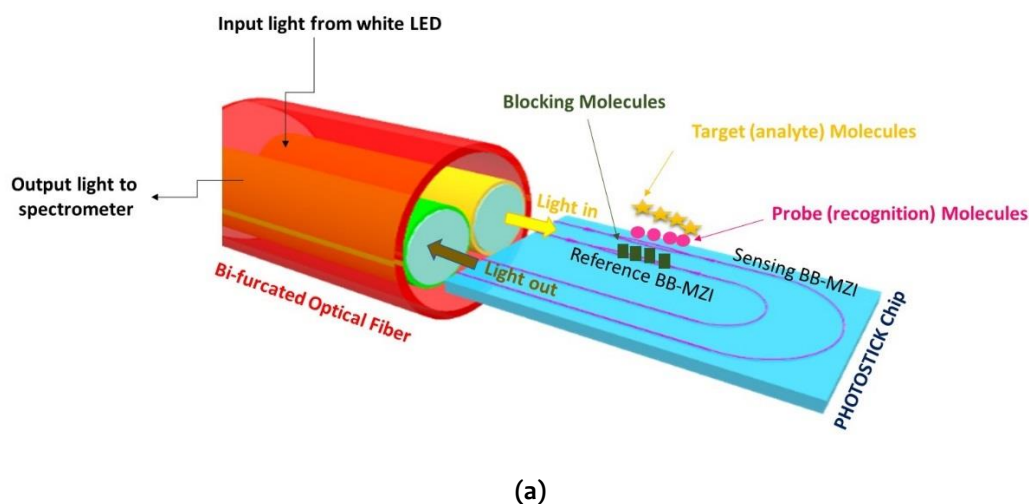
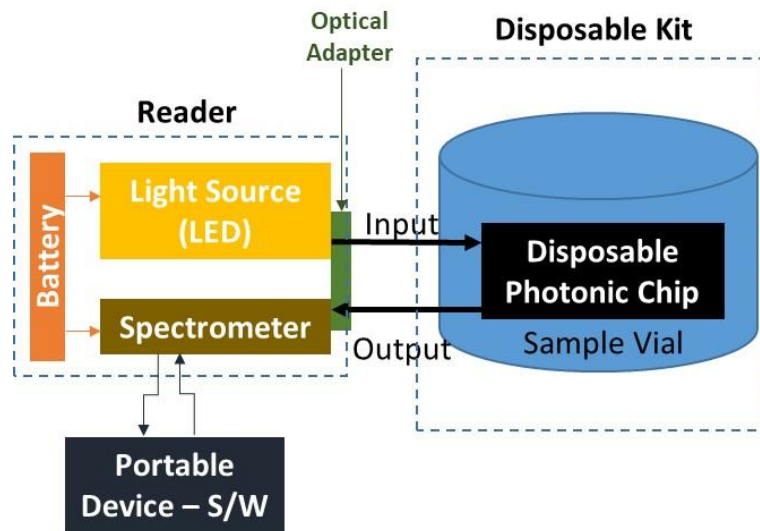


Figure 3.1. (a) Photograph of the photonic chip showing its actual dimensions. Optical microscope images of (b) the U-turn of the waveguides at the dipping end of the chip (zoom-in of the blue rectangle in (a)), and (c) the window openings of the two BB-MZIs which are appropriately spotted with biomolecules to perform the biorecognition event (sensing BB-MZI) and the baseline measurement (reference BB-MZI). (c) is a zoom-in of the magenta rectangle in (a)

7. The signal processing algorithm and user interface can be installed as an application on a mobile device (laptop or smart-phone). For each analyte the basic software can be upgraded with an add-on application that recognizes the targeted analyte.

8. The measurements can be performed by simply dipping the photonic chips into a liquid medium (in the case of GOHYDRO diluted microgreen leaf pulp in acetone) rendering its use in a **simple dip-'n'-read format similar to an immunochromatographic strip** (Fig. 3.4).



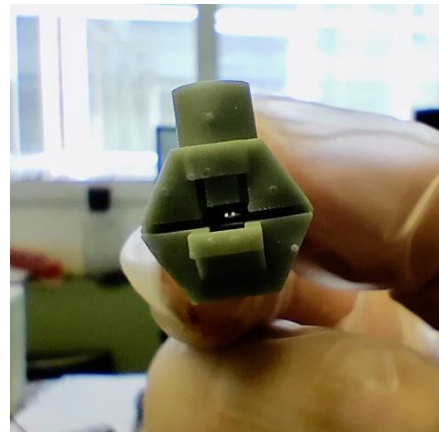


(b)

Figure 3.2. Schematic representations of (a) the photonic chip and its coupling to a bi-furcated fiber and (b) of the NCK concept



(a)



(b)

Figure 3.3. (a) Photograph of the optical adapter interfacing the photonic chips with the bi-furcated fiber. Light from the white LED can be seen on the left (b) close-up view of the optical adapter where the light from the two branches of the bi-furcated fiber can be seen



Figure 3.4. Photograph of the photonic chip immersed directly in 2µl of a liquid sample demonstrating the dip-'n'-read measuring format

As a result, the design for the NCK resulted into a system that is comprised of two main components:

(1) A portable, light-weight and power-autonomous instrument, called the “**Reader**”, operated through a mobile device such as a laptop, a tablet or a smartphone through a specifically-designed software (S/W) and accompanying user interface (UX). The S/W and UX are collectively described thereafter with the general term “**S/W**”. The S/W being an integral part of the Reader is conceptually regarded as a component of the Reader and not as a stand-alone component.

(2) The photonic chips that can be cleaned and re-used.

As far as the principle of operation is concerned this has been added as an Annex.

3.2 NUTRIENT-CONTENT KIT SPECIFICATIONS AND REQUIREMENTS

The Reader is designed to be truly portable, light-weight and power-autonomous. The Reader is “responsible” for the following functions: (a) to provide the input light for the photonic chips to operate, (b) to record the chips’ output signal, (c) to optically interface the recording medium to the chip, (d) to send the data to the central CSU and (e)) to provide power to all components. Table 3.2.1 correlates the basic functions to the essential components in order to facilitate the descriptions that follow.

Table 3.1 Components of the Nutrinet Content Kit

Spectrometer	Ocean Insights Flame
Cartridges	Photonic chips fabricated at NCSR-D
Microcontroller	Raspberry Pi Zero W
Power Supply	via USB or Raspberry Pi charger

The Reader’s basic components are a light source that provides the input signal to the chips, a handheld spectrophotometer that acts as the recording medium, a bi-furcated fiber that interfaces the chips to both the light source and the recording medium and a custom-designed optical adapter that allows seamless interfacing of the bi-furcated fiber to the chip.

i. Light Source (Broad-band LED)

For the photonic sensors contained on the chip to operate, the input source must have a broad emission band. In order to keep the weight, cost and power consumption of the platform as low as possible, the optimum choice is high-brightness Light Emitting Diodes (LEDs) emitting in the VIS-NIR. The manufacturer does not provide housing nor a board for the LED, therefore a custom-made PCB with integrated heat sink was designed and manufactured. Figure 3.5 shows the packaged LED with the interconnect PCB, the heat sink, a USB connector for power supply and a connector for coupling with the bi-furcated optical fiber.

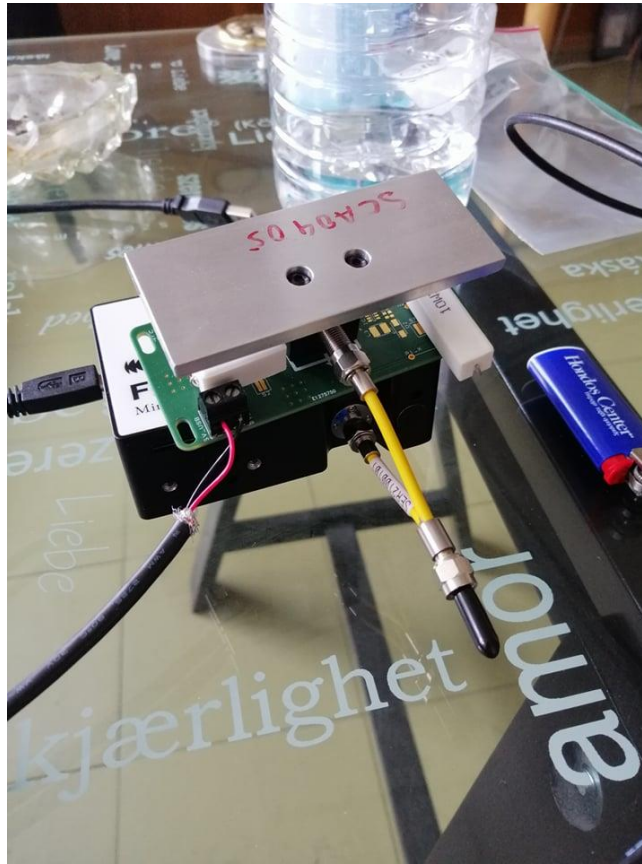


Figure 3.5. Photograph of the in-house built housing of the high-brightness white LED on top of the handheld spectrometer. The metallic plate is the heat sink. The PCB is the green plate in the middle. A short bi-furcated fiber is connected to the LED and the spectrometer for demonstrative purposes.

ii. Recording Medium (Spectrophotometer)

The signal recording medium is a hand-held mini spectrophotometer operating in the VIS-NIR. This spectrometer was selected because of its very small size (89.1 mm x 63.3 mm x 34.4 mm) and low weight (265 g) as well as the quantum efficiency and resolution it can offer (Figure 3.2.3).



Figure 3.6 Photograph of the handheld spectrometer with respect to a palm

iii. Light In- and Out-Coupling to the Reader (customized bifurcated fibre)

The light in- and out-coupling to the chip is achieved through a bi-furcated fiber operating in the VIS-NIR. Bifurcated optical fiber assemblies have two fibers in the common end and break out into

two legs at the other end (Figure 3.6). The fiber assembly in the common end must be optomechanically coupled to the photonic chip.

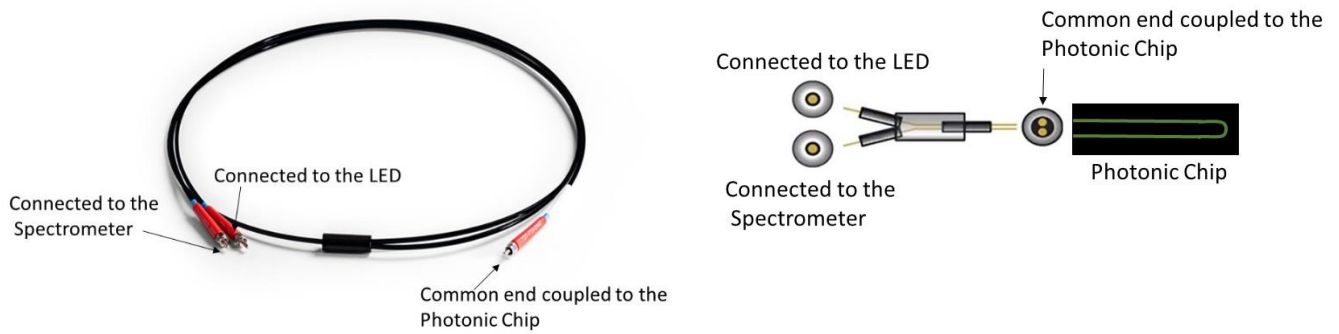


Figure 3.7 Photograph (right) and schematic representation (left) of a bi-furcated fiber.

iv. Communication

Because Raspberry Pi Zero W uses the Linux operating system the Ocean Insight's Omnidriver spectrometer driver can be used for communication between the microcontroller and the spectrometer. This communication enables command and retrieval of data measurements which will then be compressed and stored in the microcontroller's storage. At regular intervals all data will be send to the CSU and from there they will be available for external users for future processing.

A very first conceptual design of the Reader can be seen in Figure 3.8

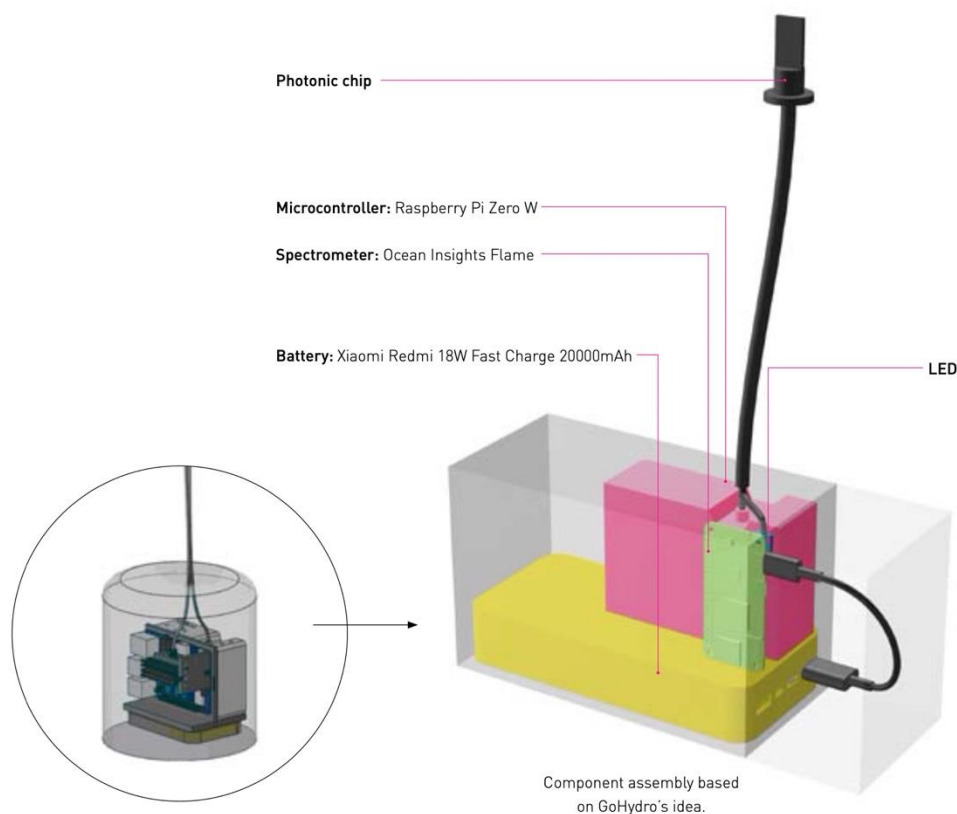


Figure 3.8 Conceptual design of the NCK containing all components in a small, light-weight and portable Reader

4 CONCLUSIONS

The determination of the specifications and requirements of the MMSK was successfully concluded on time. The components of the test installations have been identified as well as the shapes and materials to be used for their enclosures.

5 ANNEX

During the past two decades, the progress in micro/nano-fabrication techniques and in-depth understanding of photonic circuits have allowed the “transfer” of optical biosensing modules into Silicon-based photonic integrated circuits (PICs). The key driver for such a choice is the growing -but still unmet- need for practical biosensors satisfying the growing demand for effective medical diagnostic technologies. Silicon-based solutions take advantage of three major parameters: (1) due to the compatibility with complementary metal-oxide semiconductor (CMOS) foundry processes, silicon PICs can be manufactured with great efficiency at high volume and relatively-low cost; (2) the high refractive index contrast between silicon and silicon dioxide/silicon nitride, or other surrounding media, enables the development of miniaturized compact sensing devices, with the additional possibility of fabricating multiple sensors on one single chip; and (3) silicon photonics are excellent transducers for continuous and quantitative label-free biosensing, which can directly respond to affinity interactions between analyte and receptor molecules in real-time.

Nonetheless, despite the impressive progress the existing Si PICs have not managed to escape the laboratory settings and satisfy the need for efficient point-of-care biodiagnostics. The only marketable solutions to date are the SPR Biacore, the microring resonators of Genalyte and ForteBio White Light Interferometers, which are still **laboratory-bound and require bulky, unmovable and expensive instruments**. The reason is that Silicon inherently does not emit light and there is always the need to find a way to couple light in- and out-of-the PIC chips. Thus, even though the chips themselves are miniaturized and compact, the fact that their driving and readout system requires a laboratory setup makes the chip miniaturization and improved analytical performance almost seem futile and the use of PIC sensors in everyday life impractical. The need for large laboratory equipment gives rise to the so called “**chip-in-a-lab dilemma**” for PIC sensors. To transform them from laboratory-based demonstrations into practical devices that can be commercialized and used easily in everyday life, it is necessary to develop a compact PIC sensor system, where not only the sensor chip itself, but its readout system is also compact and easy to operate by a non-expert.

Development of the Immersible Photonic Probes Concept

Faced with the “chip-in-a-lab dilemma” that has been hampering the development of Silicon Photonic Sensors to real PoC/PoN products, the NCSR-D team tried to find a way to transform the photonic chips into single-shot consumables that could be used in a similar manner to immunochromatographic strips. This was achieved in a two-fold way: (1) by appropriate photonic engineering of the PICs that allow their operation in a dip-stick manner and alleviate the need for microfluidic compartments, pumps and wires, and (2) by developing a new principle of operation, the so-called Broad-band Mach-Zehnder Interferometry (BB-MZI), which allows the system to function with a simple high-brightness LED and for each chip to be self-referenced. As a result, the system basically relies on coupling light to the photonic chip, which is used as an immersible probe, reading a spectrum with a portable spectrophotometer and analyzing in real-time (a few minutes) the recorded spectra. The dynamic behaviour of the recorded spectra is directly related to the concentration of the targeted analyte.

In order to facilitate the testing at an external evaluation site and given the current status of development of the system, it is imperative that a brief description of BB-MZI is given at this point. This short description is intended to make the operation of the proof-of-concept system more self-explanatory.

Traditionally, interferometry is used with monochromatic sources (i.e. lasers) and operates with light of a single wavelength and single polarization. Very briefly, MZI relies on the following concept (Fig. 6): light propagating in a waveguide is split into two arms each carrying 50% of the input light intensity. Then the arms recombine at a second point. If the two arms are identical the two 50% packets will add up and the light intensity will remain unaffected and whatever one feeds at the input will get at the output. If one of the two arms (the so-called sensing arm) is modified through specially-designed probe molecules and a bio-reaction takes place, the formation of the biomolecular layer due to the reaction between the probe and target molecules causes the optical path to change and for the light propagating through the sensing arm to be “delayed” (a phenomenon termed “phase change” and measured in units of angle). As a result, when the two propagating beams are joined back together, they interfere in a different manner causing the intensity of the light to change. This change is directly related to the concentration of the analyte in the sample and is described by a “classical” sinusoidal equation (Fig. 5.1) and the output light intensity is a periodically oscillating function of the phase change difference ($\Delta\phi$) of the beams from two arms. In other words, the MZI output is always *a light intensity change following a sinusoidal pattern*. An additional feature of MZI is the fact that its sensitivity (as with all interferometric sensors) is directly proportional to the length of the sensing arm L (typically a 1mm MZI arm can yield an LOD in terms of effective refractive index units of $\Delta N \sim 10^{-6}$, which is amongst the lowest LODs).

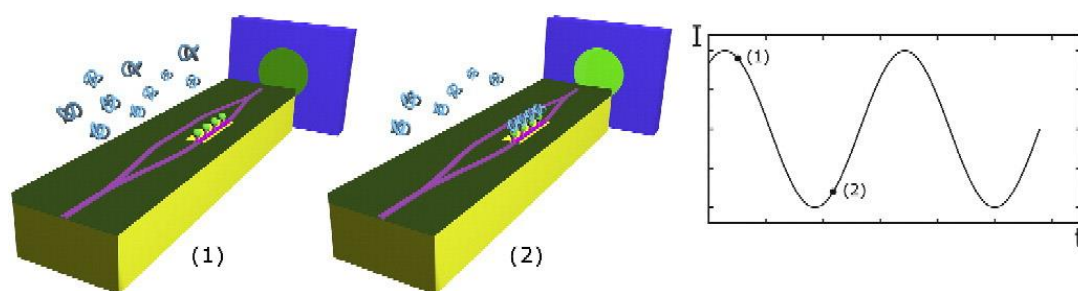


Figure 5.1. Schematic representation of the MZI principle of operation. The graph on the right shows the output signal of the MZI, which is the sinusoidal modification of the light intensity due to the binding of the target molecules onto the probe molecules of the sensing arm

This sinusoidal nature of the output signal, however, imposes three very limiting factors, technically referred to as “phase ambiguity”, “directional ambiguity” and “signal fading” (not to be analyzed further in this document). In addition, the dependence of the sensitivity on the length of the sensing arm can be deceptive, since simply increasing the length to several mm to increase the sensitivity, totally beats the point of miniaturization, while it indirectly increases the noise levels due to thermal fluctuations. Careful analysis of the noise levels reveals that increasing the sensing arm length to more than 2mm has adverse effects on the sensitivity and puts a practical unsurpassable upper limit.

The NCSR-D team realized that one can still take advantage of the sensitivity of MZI as a technique and employ a broad-band source instead of a monochromatic one. Contrary to common beliefs up to that point, employing a wide input spectrum does not scramble the output signal, but counter-intuitively adds more information to the observables and circumvents the limitations of “classical” single-wavelength MZI (SW-MZI). Contrary to SW-MZI, the signal to be recorded is not an intensity change, but the shift of an entire wide spectrum, which shifts by several tens of nm upon a bioreaction or a change on the cover medium. These shifts are very large and easier to record compared to the spectral shifts of resonators or SPR sensors, which are usually in orders of pm. This allows the use of standard off-the-shelf spectrometers for the signal recording and do not require elaborate setups. Still, the observation is not deduced by the shifting spectrum. The signal analysis is performed through a very standard mathematical technique, the so-called Fast Fourier Transform (FFT), since the output BB-MZI spectrum has a sinusoidal dependence and can be easily transformed to a single frequency in the Fourier space. In that way, what is misleadingly apparent as a complicated spectral shift is translated into **observing the phase change of the unique BB-MZI frequency in the Fourier domain** (attention: these phase changes are not to be confused with the phase changes induced to the optical path because of the bioreaction described in the SW-MZI operation. Unfortunately, both measurables are described by the same nomenclature). This allows at the same time to employ light containing both polarizations (TE and TM) translated to a spectrum containing two distinct frequencies and the simultaneous observation of two phase signals (Fig. 5.2).

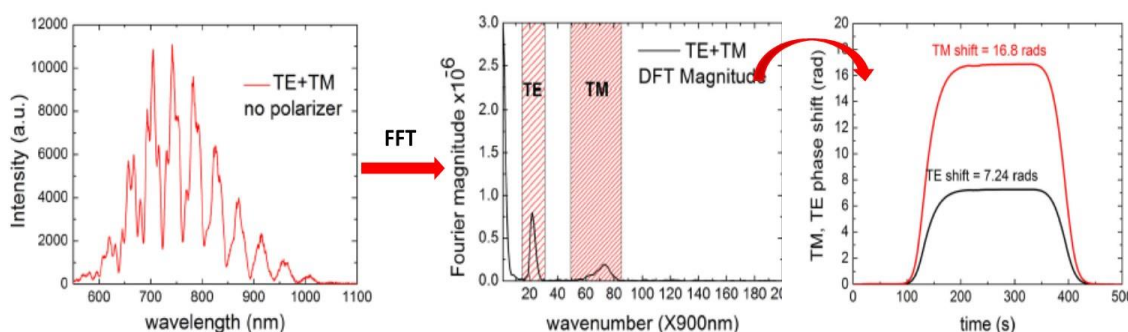


Figure 5.2 Demonstration of the BB-MZI signal recording and analysis. The spectrum of a BB-MZI containing two distinct frequencies is shown on the left. After the FFT is performed the two frequencies are separated (middle) and the observables in time become the phase of each frequency (right). The transition shown at right is the real-time change from a water to a 16.66% v/v water-propanol (1 solution volume of isopropanol to 5 volumes of water) and back to water. The spectrum was recorded with a typical spectrometer (Maya Pro 2000, Ocean Optics) and the BB-MZI had a sensing arm of only 600µm.

This in its turn allows for the instantaneous deconvolution of multiplexed polarizations and enables large spectral shifts and noise reduction through filtering in the Fourier Transform domain. Due to enhanced sensitivity, optical systems can be designed that employ portable spectrum analyzers with nm range resolution without compromising the sensor analytical capability. Furthermore, another dimension is introduced into the observables, namely, the instantaneous and independent measurement of the phase signal for the two polarizations over a range of wavelengths, while noise due to thermal drift effects are cancelled out. An additional advantage of BB-MZI is that it allows for the real-time monitoring of bioreaction kinetics that are essential for protein quantitation and kinetics

experiments in analytical laboratories. Therefore, it can also be employed to detect the presence or absence of active proteins and identify specific proteins in complex solutions, to measure protein concentration without labelling, to quantify proteins and antibodies even in complex matrices, to get rate and affinity constants for binding interactions (k_a , k_d , K_D), and to monitor the effects of changing conditions on binding interactions in real time helping improve immunoassays and pinpoint best antibody-antigen pairs.

In the case of GOHYDRO, instead of monitoring the two polarizations, one monitors the collective signal of two BB-MZIs that are contained onto the disposable chip. The two BB-MZIs are designed to have different frequencies in the FFT domain and hence the output signal is exactly of the same nature –from a mathematical point of view- as the one depicted in Figure 6 and the analysis follows the same logic. One of the MZIs is used as a reference giving the background signal, while the second is appropriately biofunctionalized to capture a specific analyte. **The observables are the time evolution of the phase peaks of the Fourier transform measured in units of angle (radians) as well as the real-time spectral shifts and evolution of the transfer function.** The processed signal is a continuous recording of $\varphi_{baseline}(t)$ and $\varphi_{sensing}(t)$ the difference of which $\Delta\varphi(t) = \varphi_{sensing}(t) - \varphi_{baseline}(t)$ or in some other cases (depending on the analyte) the gradient comparison between $\frac{d\varphi_{sensing}}{dt}$ and $\frac{d\varphi_{baseline}}{dt}$ corresponds to a concentration of the targeted analyte (in case of qualitative answers) or a range (in case of semi-quantitative answers) or a value over a set threshold providing a YES/No answer (in case of qualitative determinations). In the case of GOHYDRO it is speculated that the variations in the nutrient contents of the microgreens will affect in a distinct manner the cover medium refractive index and hence affect the real-time development of the recorded spectra. These in their tune will be correlated through the developed AI-component to the nutrient content.