MoleNet: A Wireless Sensing Platform for Teaching and Research in the Internet of Things

Jens Dede, Faruk Kollar, Daniel Helms, Asanga Udugama,
Andreas Könsgen, Saurabh Band, Shadi Attarha, Jennifer Horstmann,
Luis Hageman, Anna Förster
University of Bremen
Bremen, Germany
Corresponding Author: jd@comnets.uni-bremen.de

Abstract

MoleNet is an open-source sensor platform developed to support teaching and experimentation in environmental monitoring and embedded systems. Built around the ESP32-S3 microcontroller, it introduces students to key concepts in wireless communication, low-power design, and real-time data acquisition. The system supports the SDI-12 protocol, enabling integration with industry-standard environmental sensors, and includes power-saving features such as deep sleep and selective peripheral control to maximize battery life. MoleNet combines practical, field-ready teaching of the Internet of Things (IoT) principles and applied low-power environmental science in both classroom and outdoor settings in one open-source hardware.

CCS Concepts

• **Computer systems organization → Embedded systems**; • **Hardware → Sensor applications and deployments**.

Keywords

Wireless Sensor Networks, Internet of Things, IoT, WSN, Underground Sensing, Smart Farming, MoleNet

1 Introduction and Motivation

At the Sustainable Communication Networks group of the University of Bremen in Germany, our research and teaching activities are strongly aligned with the United Nations Sustainable Development Goals (SDGs), with a particular focus on smart agriculture and environmental monitoring. Several of our teaching modules and the majority of our student projects focus on various aspects of the Internet of Things, including communication technologies, sensing architectures, machine learning on the edge, general software and hardware development, and many more. In our research, we emphasize integrated monitoring of key environmental domains – soil, water, and air – as essential pillars of sustainable development. These topics not only provide a rich foundation for applied research but also offer highly relevant and motivating learning experiences for students.

A major challenge we have consistently faced in both research and teaching contexts is the limitation of existing hardware platforms. Available solutions frequently lack the required diversity of interfaces or rely on restrictive communication technologies. Furthermore, these platforms often suffer from short product lifecycles, leading to frequent discontinuation and long periods of unavailability. Minor or unforeseen changes in components can require complete revisions of software stacks – an especially burdensome issue in educational settings, where course materials must be stable and reproducible over time. In order to cater for these requirements, in 2015 we started developing our own hardware platform for the Internet of Things, called MoleNet. First, it was targeted more towards research in underground sensing. Later, we extended it to a more general platform, focused on very low power and on a variety of interfaces – both, for communication and sensors.

Our platform allows students and young researchers to actively participate in the co-development of system components, including sensor drivers, transceivers, and real-time clock modules. This hands-on experience encourages student engagement, results in outputs that can be directly published or applied, and contributes meaningfully to students' academic and professional portfolios. Moreover, our platform has proven to be an excellent basis for international cooperation and student exchange. Through existing partnerships in Thailand, Sri Lanka, Kenya, Cameroon, Italy, and Switzerland, we have developed a growing number of internship opportunities and external thesis projects. These collaborations enable students to work on tangible, locally relevant problems – such as smart farming in Sri Lanka – through small, manageable projects that can be tackled individually or in teams. This international, problem-oriented, and research-driven framework fosters deep learning and promotes global citizenship in line with the SDGs.

In this paper, we first discuss our platform and present its design rationale in Section 2. Next, we compare it with other IoT hardware platforms often used in teaching in Section 3. In Section 4, we present our outdoor testbed located on the campus of University of Bremen, where we can conduct various real-world experiments. Sections 6 and 7 present examples of MoleNet based student projects and lab assignments, as we use them in our teaching modules. Section 8 discusses our next steps and challenges, and Section 9 finally concludes the paper.

2 MoleNet Hardware Platform

When we began developing MoleNet in 2015, our motivation stemmed from soil science and reforestation: to measure subsurface soil parameters – particularly volumetric water content and temperature. Subsurface placement allows devices to remain hidden from animals and people and offers partial protection from vehicles. The design was guided by four key requirements rarely met by off-the-shelf hardware: (1) an SDI-12 interface for high-quality environmental (soil) sensors. (2) ultra-low power consumption enabling multi-year battery life. (3) a Sub-GHz transceiver suitable

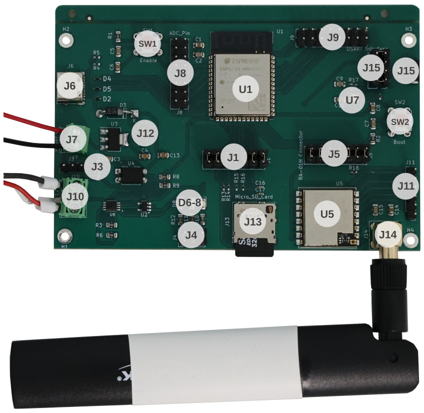

Figure 1: A PCB of the latest generation MoleNet v6 node with labels on the main components. Details of the individual labeled components are provided in Section 2 and more detailed in our git repository[1].

for underground communication. And finally, user-friendly setup, maintenance, data retrieval, and repair.

The first version of the MoleNet platform was built in 2016, initially as an ATMEL ATMEGA-based breadboard prototype [3], followed by a PCB version [13].

Over nearly a decade, we have continually updated MoleNet to align with advances in hardware, always balancing low power consumption, component availability, algorithm and library support, and – crucially – accessibility for students and international partners. The current version maintains the core requirements: SDI-12 interface, low power operation, and ease of use. Additionally, based on teaching experience, we integrated the on-board BME280 sensor to provide beginners an accessible introduction to embedded systems. We also upgraded to a LoRa-compatible transceiver, enhancing communication capabilities. The current version of MoleNet (6.3) is available in our GitHub repository[1].

The detailed setup of the current generation node is shown in Fig. 1. The current board has a size of 10×7 cm, which is ideal for research and teaching and simplifies handling. The core component is the ESP32 microcontroller (labeled as (U1) in Fig. 1), which is clocked with frequencies up to 240 MHz. The microcontroller has built-in WLAN and Bluetooth interfaces, therefore, an antenna is integrated into the copper plating of the PCB (top of U1). The LoRa communication is provided by the SX1276 transceiver (U5), which connects to the microcontroller through an SPI interface. The power and SPI pins of the LoRa chip can be disconnected from the circuit by jumpers (J5), which allows debugging and measurements of the current intake. It also allows an easy connection of different hardware for further experiments and evaluations. The LoRa antenna is connected externally (J14). The general I/O pins of the LoRa chip are accessible through headers (J11), which allows for debugging the state of the LoRa communication. For flashing the firmware like MicroPython, button SW2 which switches the microcontroller into boot mode. Another pushbutton (SW1) is used to reset the microcontroller. A MicroSD card reader (J13) is provided to allow for an extension of the storage space. This is useful to collect large amounts of data when the node remains in a field test for an extended period of time, in particular when the radio link is unavailable because of bad weather conditions. The extra storage is also useful to keep large amounts of debugging data which can then later easily be read by a computer. All available microcontroller pins are accessible through headers on the PCB for experiments with various types of sensors. There are headers, respectively, to connect to analog and digital pins (J8, J9). The currently used version of the ESP32 allows flexible binding and remapping of the GPIOs, i.e., the available GPIOs can be configured to act as analog pins, input, output, UART, I²C, SPI etc. This allows us to connect all sensors and actuators relevant to us to the current MoleNet board. Further details about the hardware, used GPIOs and further components can be found in the `doc` directory of the git repository[1].

For debugging purposes, three LEDs (D6-8) are provided which can be disconnected from the circuit by removing the jumpers (J4), in order to save battery power in field tests. One LED indicates whether power is available, the other two are connected to GPIO pins and can be arbitrarily programmed.

For programming and debugging the node, a USB-C connector (J6) is used to connect to a computer. When connected to a USB port, the power for the board is then also provided via it, so that no additional power supply is needed in this case. When the board is used in the field, the power is connected by the screw terminal (J7) and controlled by a low-drop and low quiescent current voltage regulator of type TLV76133DCY. This unit converts an input voltage between 4.6V and 16 V to 3.3V as required by MoleNet. The voltage regulator allows powering the board e.g. by four rechargeable or three non-rechargeable AA size batteries with cell voltages of 1.2V and 1.5V, respectively.

The battery lifetime depends on the power drawn in operating and sleep mode, as well as the amount of duty cycling. The shorter and the less often the device is woken up, the longer the battery will last. Here, many factors like the used sensors, the application, data transmission and logging highly effects how long such a device can survive. To give an example of the maximum lifetime, i.e., the best case for MoleNet, we measured the lowest power consumed using a Joulescope energy analyzer[2]. The results in Figure 2 show that we can go down to 15 µA. Assuming a rechargeable battery with 2000 mAh capacity will ideally lead to a battery lifetime of more than 15 years. Of course, such a duty cycle of 0% (only sleeping) is not of relevance for any practical application. Depending on the real application (attached sensors, measurement interval, number of transmissions, radio technology, type of the used battery etc.), this time will be reduced drastically: A duty cycle of 1% is realistic depending on the application scenario. Still, in most applications, a real-life application of several months or years is possible.

3 Related Works

To effectively prepare students and engineers for working with Internet of Things (IoT) technologies, hands-on experience is essential. Learning through real-world experiments with connected sensors, data processing, and embedded devices helps build a practical understanding that goes beyond theory. As IoT continues to shape areas like smart homes, industrial systems, and environmental monitoring, it is important that education also evolves, offering

[1] https://github.com/ComNets-Bremen/WUSN, accessed 2025-06-18

[2] https://www.joulescope.com/, accessed 2025-06-18

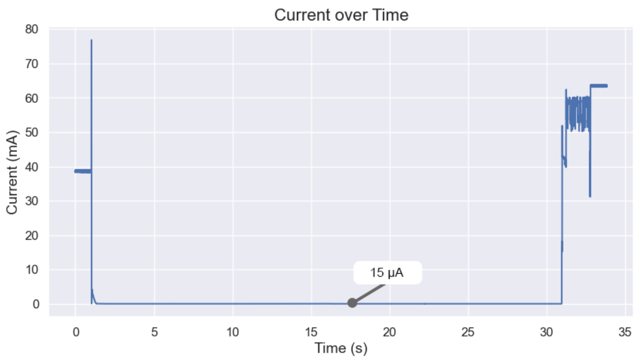

Figure 2: Power consumption of the MoleNet v6 board: The board starts the Python interpreter, goes to sleep mode (around second 1) and goes into deep sleep mode. There, it requires just 15 µA. After 30 seconds, the system starts again and continues operation.

tools and projects that reflect how IoT is used today, including aspects like edge computing, cloud services, energy harvesting, intermittent computing, and intelligent data handling. This also makes the usage of real IoT hardware necessary.

IoT hardware platforms generally fall into two main categories: single-board computers (SBCs) and microcontrollers (MCUs). SBCs, such as those running Linux, provide relatively powerful computing capabilities in a compact form factor, but are typically not optimized for low power consumption. In contrast, MCUs operate in highly resource-constrained environments, lack traditional operating systems, and instead, run lightweight, task-specific firmware. Their main advantage is their low energy usage, making them well-suited for power-sensitive applications. In this section, we have reviewed several commonly used boards for teaching IoT concepts in educational contexts, beginning with MCU-based platforms and followed by SBCs.

Table 1 offers a high-level comparison of some commonly used platforms. SBCs are excluded from this comparison, as their relatively high power consumption and lack of support for energy-constrained operation make them unsuitable for our focus on low-power IoT applications. All of the presented platforms have been broadly used not only for research, but also for teaching, for example in the TinyML book [10] or in the Network of Things Engineering (NoTE) Lab Guide by Jukan et al. [4].

From this comparison, the MoleNet platform stands out by combining a range of features tailored to both educational and research use. Its jumper system enables users to isolate and debug individual components, offering the level of transparency and control that is essential for hands-on learning and rapid prototyping. For environmental monitoring, MoleNet includes native SDI-12 support – rare among educational platforms – facilitating the integration of professional-grade sensors. It also features a built-in digital sensor for immediate use without requiring external wiring, and an SD card interface for reliable long-term data logging, even in the absence of network connectivity. Connectivity is further enhanced through integrated LoRa, Wi-Fi, Bluetooth, and BLE, enabling deployment across a variety of network conditions. To further support

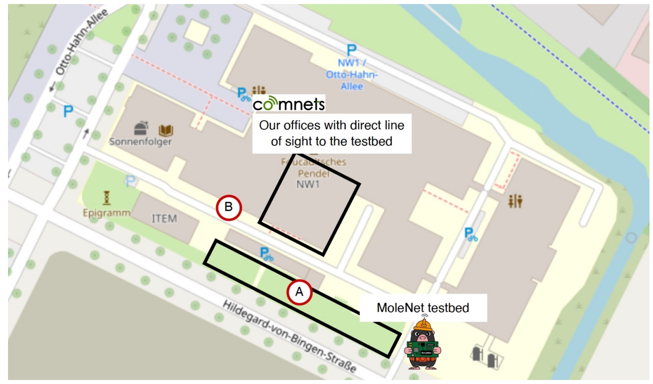

Figure 3: The outdoor MoleNet testbed at University of Bremen, Germany. (A) power box with WiFi, LoRa gateway, weather station, camera, etc. (B) water supply for experiments.

modularity, MoleNet incorporates a QWIIC interface[3], allowing seamless and low-effort connection to a wide range of I^2C sensors and peripherals.

To the best of our knowledge, no existing platform offers this combination of capabilities in a single board. Furthermore, unlike other platforms that are passively used, students are actively involved in the ongoing development of MoleNet, gaining experience in both using and building the underlying infrastructure. This makes MoleNet a uniquely open, flexible, and robust platform for teaching and advancing energy-aware IoT systems.

4 Outdoor Testbed

It is essential to test the developed hardware and software also under real world conditions. From the beginning of the project in 2015, we have been using various outdoor setups to test our hardware and protocols, such as private gardens, testbeds from other institutes at the University of Bremen, testbeds from cooperating partners, etc.

Since 2024, we have our university-owned outdoor testbed with an area of approximately 60×20 meters or 1200 square meters (see Figure 3). This allows us for even multi-hop communication experiments underground to underground. To better simulate various soil conditions, we have also access to water (B in Figure 3). Additionally, since some of our applications are for water monitoring, we can easily extend the experiments to the nearby water canals (seen in the top and on the right in the picture). The very close proximity to our offices and lab allows further control of the experiments and easy storage of tools.

5 Software Architecture

MoleNet is based on the widely used ESP32-S3, which is supported by a broad range of programming languages and operating systems tailored for constrained devices and IoT applications (see 1). In our teaching, we primarily focus on the popular MicroPython and Arduino. These platforms offer a lot of examples, libraries, and tutorials, providing an accessible starting point – particularly for

[3] https://www.sparkfun.com/qwiic, accessed 2025-06-18

Platform	Storage	Communication Interfaces	Programming	Accessible GPIOs	On Board Sensors
MoleNet v6.3	512KB SRAM, 16MB Flash, External storage: SD card reader	LoRa, WiFi, Bluetooth, BLE, USB	MicroPython, Arduino, C, RIOT, Toit	12	BME280 (humidity, barometric pressure, temperature)
senseBox MCU-S2 MPU [11]	520KB SRAM, 4MB Flash, External storage: built-in SD card	WiFi, Bluetooth, USB	senseBox-Blockly, CircuitPython, Arduino	22	6 axis accelerometer, brightness sensor; integrates with the OpenSenseMap platform
WiPy 3.0	520KB SRAM, 8MB Flash	WiFi, Bluetooth	MicroPython	24	N/A
LoPy 4	520KB SRAM, 4MB Flash	WiFi, Bluetooth, LoRa, Sigfox	MicroPython	24	N/A
NoTE	2KB SRAM, 32KB Flash	WiFi, USB	Arduino	20	DHT11, HC-SR04, HC-SR501
Arduino Nano 33 BLE	32KB SRAM, 256KB Flash	Bluetooth, USB	Arduino, MicroPython	22	3-axis Accelerometer, 3-axis Gyroscope, 3-axis Magnetometer, Digital Microphone, APDS9960, Pressure, Temperature
STM32F746G	320KB SRAM, 1MB Flash	Ethernet, USB	MicroPython, Arduino, C	168	Digital Microphone
SparkFun Edge	384KB SRAM, 1MB Flash	Bluetooth, USB	Arduino, C	21	Digital Microphone, 3-axis Accelerometer, 3-axis Gyroscope

Table 1: Selected embedded systems used in teaching.

newcomers to programming and embedded systems. We also support more advanced embedded operating systems such as RiotOS[4] and Toit[5]. Their modular architectures and accessible codebases facilitate performance evaluations and comparisons with existing implementations, making them suitable for research-oriented use.

6 Sample Applications and Student Projects

In order to illustrate the variety of possible project, thesis and internship opportunities that MoleNet (and similar projects in general) offers, we present here some of the most recent ones.

Hardware Selection One typical student project topic is the selection of a particular hardware component, e.g., a sensor or a LoRa transceiver. This topic is usually ongoing, as currently used components disappear from the market or do not get supported any more by firmware updates. In 2021, Justin Kleihauer conducted a bachelor thesis [6] to identify which soil moisture sensors currently on the market are most suitable for our applications. Relevant parameters included the cost, the precision, the working principle, the interface, and some more.

Communication Driver Implementation LoRa is our main communication technology used for MoleNet. Here, we use the community-driven *The Things Network* (TTN)[6] that requires a special driver to join and operate. One of our students currently implements such a driver (formally known as LoRaWAN) for Semtech's SX1262 and SX1276 transceivers in pure MicroPython.

Applications Throughout the years, many applications emerged for MoleNet, mostly initiated by our international partners. Examples include rubber tree farming with soil monitoring in Sri Lanka [1], monitoring of miners' safety in South Africa [12], monitoring onion smart farms in Senegal [8], reforestation monitoring in Cameroon [3], aquarium monitoring in Namibia [7], tea fermentation monitoring in Kenya [5], counting mosquitoes in Thailand [9], and some more. Of course, not all projects, theses and internship topics resulted in scientific publications.

Implementation of a software back-end for sensor data gathering and analysis A rather untypical example that shows the variety of possible project topics is a recent master thesis of Giada Ferrario from SUPSI, Switzerland [2]. The main objective of this project was to develop a versatile web platform capable of seamlessly accommodating various sensor configurations supported by the MoleNet IoT system independent of the exact sensors used (soil, water, air, acceleration, etc.). It was designed to help, especially other students and researchers, efficiently visualize, interpret, and analyze the gathered data. Furthermore, it incorporates machine learning functionality, enabling users to upload models to perform advanced data analysis, thereby improving the ability to extract valuable insights from environmental information. Another handy function is to define the parameters of the used sensors in a general way, such as the type of data and a correction function.

	Completed	Ongoing	Papers	Papers under submission
Bachelor projects (8 ECTS)	-	2	-	-
Bachelor theses (30 ECTS)	4	1	-	-
Master projects (18 ECTS)	5	3	1	-
Master theses (30 ECTS)	5	1	1	-
PhD theses	3	2	15	-
Internships (all levels)	11	1	4	1
Student jobs	6	3	1	1

Table 2: Number of projects and theses at MoleNet from January 2016 to May 2025, with resulting peer-reviewed publications.

An overview of the numbers of completed and ongoing theses and projects, together with resulting peer-reviewed publications is shown in Table 2.

7 Sample Lab Assignments

We are actively using MoleNet in our modules *Internet of Things* and *Edge Computing Lab* at University of Bremen. Generally speaking, those modules combine various topics from the IoT domain, such as communication technologies, system architectures, energy consumption, and many more. The syllabi of these courses and the teaching methodologies behind are out of scope for this paper. However, on GitHub we have shared some of our lab assignments

[4]https://www.riot-os.org/, accessed 2025-06-18
[5]https://toit.io/, accessed 2025-06-18
[6]https://www.thethingsnetwork.org/, accessed 2025-06-18

that are fully based on MoleNet. Currently, these include three lab assignments with their corresponding presentation slides, manuals, hardware setups and solutions: (1) Using the MoleNet platform to send environmental data over WLAN with Arduino IDE, (2) Sending data over LoRa with MicroPython, and (3) Energy measurements and a simple energy consumption model. More labs and projects will be added in the near future.

8 Discussion and Future Steps

MoleNet provides a flexible and energy-efficient platform for environmental monitoring and teaching, with a special focus on modularity and ease of use. The current version is well tailored to our applications, but also reveals limitations, particularly for long-time tests with non-technical customers. A key weakness is the lack of a dedicated battery for the real-time clock (RTC): timekeeping during power loss as caused by a battery change is not possible. Addressing this will require a complete PCB redesign, as the current architecture does not support adding an RTC battery.

As a more general aim, we plan to extend MoleNet into a modular hardware ecosystem without reinventing existing standards. Adopting the QWIIC connector is a first step, allowing easy integration of I^2C sensors. Supporting standardized modular formats (e.g., hats or shields) will further turn MoleNet into an extensible, open-source platform for education and environmental sensing.

The price of the platform also plays a role, especially because for teaching one needs several dozens of nodes. The MoleNet platform is available as open source and can be produced on demand for approx. 70 € per node[7], including the LoRa transceiver and a sensor. This combination of low price and open source availability makes the biggest difference and allows also low-resource communities and countries to use it.

9 Conclusion

In this paper, we introduced MoleNet, a low-power and open-source IoT platform designed for both teaching and precision agriculture, as well as environmental monitoring. Unlike existing platforms, MoleNet is tailored to critical challenges such as underground communication, long-term battery operation, and support for field-deployable interfaces like SDI-12. We briefly described its design, classroom use, and trade-offs, highlighting its ease of setup, reliability, and versatility. More importantly, MoleNet allows students to actively develop and extend the platform itself – building sensor drivers, add new components and optimize the entire ecosystem – rather than just using a prebuilt solution.

By combining hands-on learning with real-world relevance, MoleNet empowers students to explore agricultural and environmental IoT applications, contribute to the SDGs, and produce work that can be published or applied. We have open-sourced both the MoleNet platform and its teaching material and invite educators, researchers, and developers to adopt, adapt, and contribute to MoleNet 's ongoing evolution.

[7] Prices are approximate and as per June 2025

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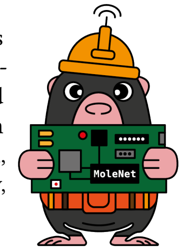

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A Online Resources

The design of the MoleNet platform is available under github.com/ComNets-Bremen/WUSN. The sample lab assignments can be found under github.com/ComNets-Bremen/MoleNet-Labs. More information about ongoing projects and use cases are under molenet.org.