An educational distributed Cosmic Ray detector network based on ArduSiPM

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Abstract. The advent of high performance microcontrollers equipped with analog and digital peripherals, makes the design of a complete particle detector and a relative acquisition system on a single microcontroller chip possible. The existence of a world wide data infrastructure such as the internet, allows for the conception of a distributed network of cheap detectors able to elaborate and send data as well as to respond to setting commands. The internet infrastructure enables the distribution of the absolute time, with precision of a few milliseconds, to all devices independently of their physical location, when the sky view is accessible it possible to use a GPS module to reach synchronization of tens of nanoseconds. These devices can be far apart from each other and their relative distance can range from a few meters to thousands of kilometers. This allows for the design of a crowdsourcing experiment of citizen science, based on the use of many small scintillation-based particle detectors to monitor the high energetic cosmic ray and the radiation environment.

1. Introduction

Outreach and education programs can greatly benefit from the incredible advances in technology. Regarding photon detection, in recent years, a range of very small and relatively cheap solid devices has become available: the SiPM (Silicon Photon Multiplier) [1], also known as MPPC (multi pixel photon counter) [2]. The SiPM/MPPC is a solid photon multiplier with single photon detection ability. This device consists of an avalanche photodiode (APD) array placed onto a common Si substrate. Each single element works in Geiger mode. When a photon hits the silicon, it produces a photoelectron in one of its microcells, through the photoelectric effect. With respect to the classical Photo Multiplier, the SiPM is more compact, robust and does not require a bias voltage of the kV order (which would be difficult to manage with such a compact design). In the past, the need to use expensive and fragile Photo Multipliers (PM) as photon detectors limited the use of scintillation materials as radiation detector handheld devices. This favored the use of Geiger tubes. The first modern scintillator detector for alpha particles was built by Curran and Baker in 1944, using a Zinc sulphide screen as a scintillator, and a photo multiplier coupled together. Their work was described in a classified report in 1944, and disclosed in 1948 [3].

Nowadays, scintillation counters are used extensively, in nuclear and particle physics, to build up detectors such as fast triggers, calorimeters, trackers and time-of-flight detectors. The idea of coupling a scintillator and a modern SiPM started in the early 2000s. Its first application came up in 2006 [4] for small animal positron emission tomography. The acquisition of a single Silicon Photomultiplier can require many electronic modules such as: preamplifiers, discriminators, bias voltage power supplies, temperature monitors, scalers, Analog to Digital Converters and Time to Digital Converters. Since 2011 our group has started to build a conceptually simple system to acquire and control SiPM photodetectors.
with the aim of creating a handy particle detector. The idea was to utilize one of the best off-the-shelf microcontrollers, making use of all chip peripherals and an external fast electronics for signal conditioning. We have developed a system based on the Arduino DUE [5] development board and a specific shield, the so called ArduSiPM [6]. The first targets of this particle detector were a scientific instrumentation for health probes [7] and a trigger for the CERN experiment UA9 [8]. The use of Arduino DUE, a well-known platform in the educational environment, and the potentially low cost of the system have led the aim of this project towards an outreach and educational purpose.

In this paper we report the implementation of our device describing how we equipped the ArduSiPM with a very low cost external network processor, able to communicate by IoT technology such as the MQTT (MQ Telemetry Transport) protocol and the NTP (Network Time Protocol) in order to build up a crowdsourcing experiment of citizen science.

2. The ArduSiPM hardware
The ArduSiPM consists of the following components: an Arduino Due Board, an ArduSiPM Shield, a Silicon Photomultiplier, a scintillator and an external Wi-Fi interface (Figure 1). Arduino DUE is an open source hardware and software development board based on the Atmel SAM3X8E ARM Cortex-M3 CPU. It is an off-the-shelf board, widespread in the community of developers and education, that provides a free integrated development environment (IDE). Due to an easy-to-use programming language it is widely used for the development of educational platforms. All the details, specifics, and documentation about both the platform and the development software are freely available on the internet.

The ArduSiPM Shield is our custom designed board. It provides a whole electronic interface for Arduino DUE and with a SiPM photodetector. The ArduSiPM Shield plugged into the Arduino DUE represents an easily transportable device which includes both the Front-end electronics and the data acquisition system. The global architecture of the system is displayed in Figure 2. The SiPM and the temperature sensor are externally connected, whereas the digital controlled bias supply, the voltage amplifier, a fast discriminator with programmable threshold, a peak-hold circuit, a set of LEDs for monitoring and all outputs from both the analog circuit and the digital controls are connected to the Arduino DUE.
The following is a description of the main components of the ArduSiPM Shield:

2.1. **SiPM Power Supply adjustment circuit**
A DC-DC converter uses the Arduino 5 V to supply a bias voltage in the range of 30-100 V. Once we fix the nominal voltage, it is possible to alter the voltage by a few Volts with 8 bits resolution. In combination with the temperature sensor, we can compensate for the typical gain variation in real-time.

2.2. **Analog circuit: Voltage Amplifier and Fast Discriminator**
The voltage amplifier fits the signal for the Arduino Analog to Digital converter. Moreover, it is fast and linear such that it follows the SiPM response and covers the whole voltage range. The noise is lower than a single SiPM pixel signal. For monitoring purposes, a replicated output of the amplifier is available on the external analog connection. The SiPM output Signal is very short (few ns). A fast (7 ns) discriminator is used to discriminate the over threshold signals and to count them thanks to the Arduino DUE counters. We can digitally control the threshold level and its value is monitored by the internal ADC. The width of discriminator output can be programmed in order to avoid after pulse counting and to control the death time of the pulse acquisition. A replicated TTL output of the fast discriminator is available as the output, so that it can be used as the trigger for the external acquisition system.

2.3. **Peak height measurement**
A precise circuit with a fast peak detector is used as the peak-hold. When the SiPM signal exceeds the discriminator threshold, the peak-hold circuit is activated to measure the maximum of the short pulse coming out of the detector. The pulses are stretched up to 1 μs in order to match the dynamics of the SAM3X8E ADC (1 MSPS, 12 Bits). A programmable digital signal controls the fast discharge circuit to reset the peak hold circuit and to rearm the system for a new acquisition.
3. The ArduSiPM network interface

The ArduSiPM Shield communicates via serial RS232. On the first prototype we chose a simple RS232-WI-FI interface to transmit data over the network. In the meantime, the availability of powerful and cheap microcontrollers with a Wi-Fi interface gives us the possibility to expand the networking feature of ArduSiPM (Figure 3).

Figure 3: The ArduSiPM detector connection to ESP8266 network processor. The RS232 sends data and receive settings to the ESP8266. During time synchronization the ESP8266 sends a reset signal to synchronize one sec ArduSiPM internal clock with NTP time.

ESP8266 also has 16 GPIO pins, SPI and I2C interface and a UART for RS232 serial communication. The chip came out in 2014 with a Software development Kit and, from April 2015, there is a free porting of the firmware to run Arduino codes. The availability of the Arduino IDE for ESP8266 gives us the possibility of benefitting from a wide range of freely available and open source codes developed for Arduino, especially regarding the Internet Of Things (IoT), the Network Time Protocol (NTP) and the webserver.

3.1. Use of MQTT protocol with ArduSiPM ESP8266 module

MQTT (Message Queue Telemetry Transport) is a "lightweight" messaging protocol to be used with the TCP/IP protocol. MQTT was invented in 1999 by Andy Stanford-Clark (IBM) and Arlen Nipper (Arcom, now Cirrus Link). Their goal was to create a protocol to interface sensors to a SCADA system with minimal battery loss and minimal bandwidth connecting oil pipelines over satellite connections. The protocol became an ISO/IEC standard in 2016 (ISO/IEC 20922:2016)[10]. It uses a publish/subscribe architecture in contrast with HTTP and its request/response paradigm. Publish/Subscribe is event-driven and enables messages to be pushed to clients. The MQTT is a light messaging protocol and also light in terms of the processor time required. There are different versions of the MQTT library for the Arduino ESP8266, and a full protocol library is not yet available. We chose
the Adafruit MQTT client library that covers the main parts of the protocol. Every second the ArduSiPM provides the number of events and the time of each event relative to a second lap (20 bits) in microseconds. The ESP8266 builds up an MQTT event packet adding the serial number of ArduSiPM (2 bytes) to the NTP seconds from the internal real time clock. The 4 byte second fractions are built using the 20 bits time from ArduSiPM as MSB. The 12 LSB bits are forced to zero but are available in case of a better time reference such as GPS (Figure 4). The MQTT rate data packet is built with 2 bytes for the ArduSiPM serial number and 2 bytes for the data rate. Other MQTT messages are built using sensors connected to the ESP 8266 (temperature, humidity, pressure…) and transmitted at lower rates.

3.2. NTP protocol with ArduSiPM ESP8266 module
The Network Time Protocol (NTP) is a networking protocol for time synchronization between computer systems, over packet-switched variable-latency data networks. The NTP was designed by David L. Mills of the University of Delaware [11]. The NTP is intended to synchronize all participating computers, within a few milliseconds, of Coordinated Universal Time (UTC). A simplified version of the NTP protocol is the SNTP. This protocol is easy to implement over the ESP8266 processor. Using SNTP the ArduSiPM ESP8266 module receives the time with precision of a few milliseconds from the internet. In synchronization with the leap second, the ESP8266 sets the time and sends a hardware counter reset to ArduSiPM. In this way the one second counter inside the ArduSiPM is synchronized with the NTP time (Figure 3). The NTP system is cheap and comes for free using the ESP8266. Nevertheless a better time synchronization, at tens of nanoseconds level, is possible using a Global Position System (GPS) receiver with one Pulse Per Second (1 PPS) signal. The use of GPS presupposes a sky view availability or a long connection between ArduSiPM and the GPS module.

3.3. WEB server and configuration interface
The tasks managed by the ArduSiPM ESP8266 module are: Wi-Fi connection and communication, Management of NTP time and ArduSiPM clock synchronization, MQTT client data formatting and transmission and readout of environment sensors. A simple web interface runs in the module to set variable parameters such as: Wi-Fi hotspot, MQTT Broker and NTP Server.

4. The MQTT broker
The central communication point in the MQTT protocol is the broker (the server in MQTT). It is in charge of handling the publish/subscribe protocol. A broker can handle up to thousands of connected
MQTT clients at once. The broker is primarily responsible for receiving all messages, filtering them, deciding who is interested in what and then sending the message to all subscribed clients.

![MQTT broker diagram](image)

**Figure 5:** MQTT broker connected to MySQL server for data storage. The data can be accessed from HTML5 web application using a Web Service.

We choose Mosquitto [12] as MQTT broker installed in a Linux server. Mosquitto is an open source (EPL/EDL licensed) message broker that implements the MQTT. Each ArduSiPM, using its username and password, sends the data to the MQTT Broker thanks to a Python plugin program which communicates and records all data from any ArduSiPM inside a MySQL database. A web service interfaced to the database, can access the data and publish it using an HTML5 web application (Figure 5). The idea is to provide a subset of the data or the whole dataset to the ArduSiPM community for visualization and elaboration.

5. **A cosmic ray and environment radiation crowdsourcing experiment of citizen science**

The first observation of a cosmic ray particle with an energy exceeding $1.0 \times 10^{20}$ eV (16 J) was made by Dr John D Linsley and Livio Scarsi at the Volcano Ranch experiment in New Mexico in 1962. This event has opened a new frontier in the research of Ultra High Energetic Cosmic Rays (UHECR) [13]. The size of the shower at ground level is linked to the primary cosmic ray energy. This implies the construction of detectors extended over a large area to sample the cosmic shower. Using the infrastructure described above, it is possible to create a citizen science experiment covering a large area. Each ArduSiPM would publish online the number of events per second and the absolute time with a precision of a few milliseconds for each event in case of NTP timing, or tens of nanoseconds in case of GPS timing (Figure 6). This infrastructure does not claim to be competitive with modern large area cosmic ray experiments such as Auger (Argentina) and Telescope Array (Utah) but provides a project to offer students the opportunity to understand how detectors, data acquisition and Ultra Energetic cosmic ray research work. The detector can also be used as an environment radiation monitor. By changing the scintillator type, it would be possible to detect other types of radiation as described in [14].

6. **Conclusions**

We have described the use of the small scintillation detector ArduSiPM to build up a citizen science experiment for Ultra High Energetic Cosmic Rays and environment radiation monitoring. The whole experiment architecture involving data acquisition, timing distribution, data storage using the internet to connect different devices, is described. Since 2016 the ArduSiPM device has been commercially
available through an Italian company [15] under the INFN license. This can potentially create a widespread use of the device especially for schools, universities and non-professional scientists.

Figure 6: Scheme of the ArduSiPM crowdsourcing citizen science experiment for the research of Ultra High Energetic Cosmic Rays and radiation monitor

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