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PUBLISHED BY IOP PUBLISHING FOR SISSA MEDIALAB

RECEIVED: *November 12, 2013*
ACCEPTED: *December 11, 2013*
PUBLISHED: *December 23, 2013*

AMIGA at the Auger observatory: the telecommunications system

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ABSTRACT: AMIGA is an extension of the Pierre Auger Observatory that will consist of 85 detector pairs, each one composed of a surface water-Cherenkov detector and a buried muon counter. Each muon counter has an area of 30 square meters and is made of scintillator strips, with doped optical fibers glued to them, which guide the light to 64 pixel photomultiplier tubes. The detector pairs are arranged at 433 m and 750 m array spacings. In this paper we present the telecommunications system designed to connect the muon counters with the central data processing system at the observatory campus in Malargüe. The telecommunications system consists of a point-to-multipoint radio link designed to connect the 85 muon counters or subscribers to two coordinators located at the Coihueco fluorescence detector building. The link provides TCP/IP remote access to the scintillator modules through router boards installed on each of the surface detectors of AMIGA. This setup provides a flexible LAN configuration for each muon counter connected to a WAN that links all the data generated by the muon counters and the surface detectors to the Central Data Acquisition System, or CDAS, at the observatory campus. We present the design parameters, the proposed telecommunications solution and the laboratory and field tests proposed to guarantee its functioning for the whole data traffic generated between each surface detector and muon counter in the AMIGA array and the CDAS.

KEYWORDS: Data Handling; Large detector systems for particle and astroparticle physics; Trigger concepts and systems (hardware and software)

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doi:10.1088/1748-0221/8/12/P12014

Contents

1 Introduction: AMIGA and the Pierre Auger Observatory

The Pierre Auger Observatory [1] was built to detect the highest energy cosmic rays known in nature with two distinctive design features, a large size and a hybrid detection system, in an effort to observe a large number of events per year with minimum systematic uncertainties. The southern component of the observatory is located near Malargüe, in the province of Mendoza, Argentina. It spans an area of 3000 km^2 covered with over 1600 surface water-Cherenkov detectors (SDs) [2] deployed on a 1500 m triangular grid with 24 fluorescence detector (FD) telescopes [3] grouped in units of 6 at four sites on the array periphery, each one with a $30^\circ \times 30^\circ$ elevation and azimuth field of view.

With the Auger baseline design described above, the surface array is fully efficient for cosmic ray detection above $\sim 3 \times 10^{18}$ eV and in the hybrid mode this range is extended down to $\sim 10^{18}$ eV, which does not suffice to study the galactic to extra galactic cosmic ray sources transition, assumed to occur at lower energies. To lower this limit, Auger has two enhancements: AMIGA ("Auger Muons and Infill for the Ground Array") [4–7] and HEAT ("High Elevation Auger Telescopes") [8, 9]. AMIGA only covers a small area (23.5 km^2) since the cosmic ray flux increases rapidly with decreasing particle energy. On the other hand, the detectors are deployed at smaller spacings in a denser array, since lower energies imply a smaller air shower footprint. Under this framework, AMIGA consists of an array of detector pairs comprising 61 detectors spaced 750 m apart plus 24 extra detector pairs spaced 433 m apart. All 85 pairs are placed within the main 1500 m Auger SD array. This group of SDs is referred to in this paper as the graded infill array, or simply the infill.

The present paper is organized in the following way: We present a concise description of the telecommunications requirements for AMIGA, in terms of bandwidth, timing, signal to noise ratio, frame error rate and synchronization. Then we propose a WiFi system that would satisfy these requirements, including a hardware implementation. We describe the laboratory and field tests designed to evaluate the system, and their results. We describe in detail the AMIGA network as it was implemented for the engineering array, its performance and hardware characteristics. Finally we propose a telecommunications system as an extension of the one already installed and functioning for the AMIGA engineering array, that can be used for the whole AMIGA and infill array.

2 AMIGA telecommunications requirements

In this section we aim to explain the data flow during the functioning of AMIGA and the infill in order to establish the requirements for a telecommunications system that can cover the AMIGA requirements and how these requirements reflect in the application, network, MAC and physical layers of the system.

The Pierre Auger Observatory can be viewed as a large, sparse coincidence detector. The detector is comprised of a large number of surface detectors capable of precisely determining the moment at which a particle passes through them. These detected particles are cascade sub-products of the collision of a high energy particle with the Earth's atmosphere components. It is the coincidence between three or more surface detectors what may indicate a high energy particle event. The infill is a subgroup of the Pierre Auger Observatory surface detectors. Each surface detector of this subgroup will have a local buried muon counter connected that will determine the number of muons that reach the detector every time a surface detector detects a particle on the surface. Each pair of surface detector and muon counter that integrates the infill is part of the AMIGA enhancement to the Pierre Auger Observatory, and as such it requires a new telecommunications system in order to avoid overloading the original Pierre Auger Observatory system. AMIGA generates data that are similar to that of the Pierre Auger Observatory except that some extra information is sent when an event is detected.

The coincidence detection is performed in a Central Data Acquisition System (CDAS) and, because of that, some data must be transferred to this centralized facility in order to evaluate the coincidence. The majority of the data currently being transported by the Pierre Auger Observatory communications system comprises of a list of time stamps of potentially interesting events, called T2 [10] in the Auger system, which corresponds to a trigger in the surface detector. The conditions for T2 are either one of the following:

1. Threshold: a signal above 3 VEM (Vertical Equivalent Muon) in 3 photomultipliers in the surface detector with a rate of $\sim$100 Hz
2. Time Over Threshold: a signal over 0.2 VEM during 12/120 bins with rate of $\sim$0.2 Hz

Each surface detector sends every second a list of T2 time stamps, those data are then used at the CDAS to identify events that occurred simultaneously in three or more surface detectors, a situation that indicates that the event comes from a particle with enough high energy. The detailed data for the event is then requested to each involved surface detector for cosmic shower reconstruction. The T2 time stamp is a 20-bit number representing the microsecond within the current GPS second, plus 4 bits of additional data, which the AMIGA telecommunications system should be able to transport from each surface detector to the Auger Observatory central campus in Malargüe,

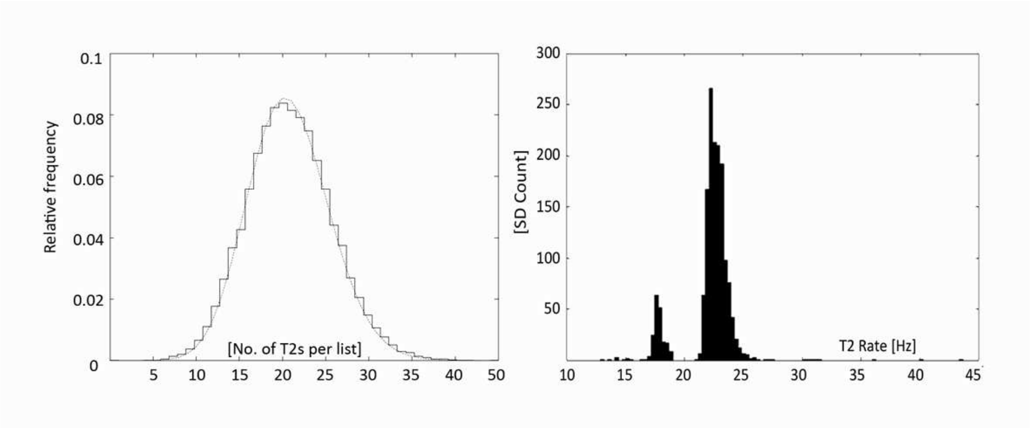

Figure 1. Measured rate and length of T2 time stamp lists in the AMIGA infill. The left panel shows the histogram of the distribution of number of T2s per list, while the right panel shows the histogram of the rate of occurrence of T2 sent to the CDAS.

at the application level and at a rate of 1 Hz [10]. The amount of data transported in T2 lists is variable and a measurement of the traffic using the already existing telecommunications system for the observatory was performed. The measured length and rate of the T2 lists is shown in figure 1.

Besides the T2 lists, every 15 minutes on average, an extra amount of data is sent with information on every T3 occurrence [10]. The occurrence of a T3 trigger event is determined by the CDAS from the recollection of all the T2 lists from all the surface detectors in the Auger array. A T3 occurs when a GPS time stamp from three or more adjacent surface detectors is found within all the T2 lists of all the surface detectors. In that case the CDAS sends a request for extra data from the detectors that represents the measurements of the analog to digital converters on each of the 3 PMTs in the surface detectors involved in the event. On top of this we must also take into account the muon counter information, which is fixed in size at about 64 kbits for four scintillator modules, for every T3 request. It should be noted that these data take into account a compression factor of 1/4 that can be done without loss of information. The compression ratio is usually greater, but in order to have a safety margin a value of 1/4 is used. This process can take up to 20 seconds (the time CDAS takes to evaluate the occurrence of a T3). AMIGA is being designed to have 85 stations but, allowing for extra detectors to be added in the future for calibration purposes and a safety factor of 2 in the total data traffic, for 90 subscribers we have a total throughput for the whole AMIGA array of 20160 bytes/sec.

As established from the above calculations, and from the previous measurements of traffic in the Auger array, at the application layer, a data loss of 0.01% of the T2 time stamps lists is allowed for a correct functioning, which means an almost zero data loss of the T3 requests. Concerning the network requirements, the AMIGA project has an available bandwidth of 27 Mbps to provide for all the stations and a maximum delay between subscriber coordinator of 500 msec/station. There are no requirements specified for the MAC and physical layers. As for the hardware is concerned, the equipment has a power budget of 5 W and the interconnections between the sicntillator modules of the muon counters has to be done using an Ethernet Local Area Network (LAN). The interconnection with the surface detector hardware has to be minimized and the AMIGA telecommunications system has to work in parallel with the Auger telecommunications system during the testing phase until it is proven that it can replace the actual system, at least for the detectors within the infill.

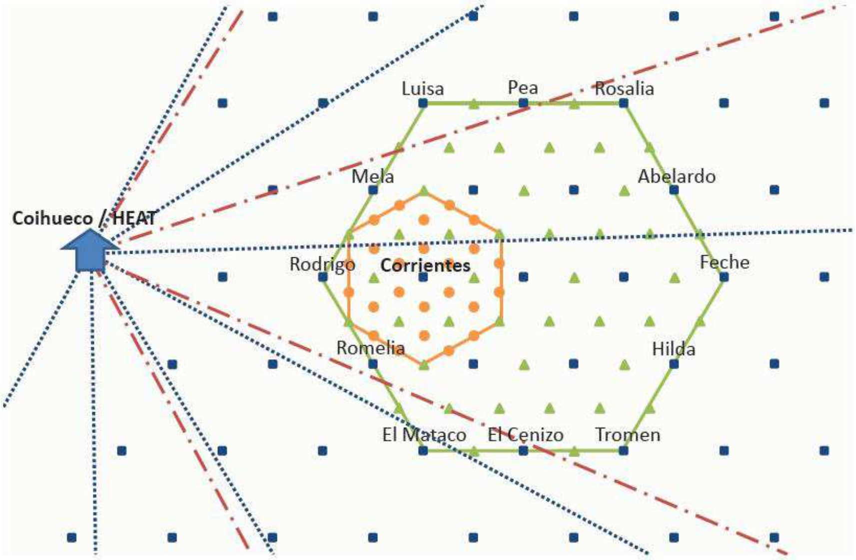

Figure 2. Map of the AMIGA infill. The green hexagon indicates the part of the Auger array where the AMIGA detectors are being deployed. The large blue arrow indicates the Coihueco HEAT/fluorescence detector site, where the three AMIGA coordinator radios are deployed.

Concerning the signal to noise ratio, there are no specifications besides the ones required for the proposed wireless standard which, as we will show in the following sections, is fulfilled.

3 Proposed wireless standard for AMIGA

In order to satisfy the requirements of the AMIGA data flow for the telecommunications system established in the previous section, a wireless network using standard 802.11 from the IEEE is proposed. To have a correct functioning of the network, several factors must be taken into account to minimize response time and bit rate problems, as well as assuring reliability. As a consequence low power consumption and industrial grade WiFi radios working with Transmission Control / Internet Protocol (TCP/IP) are used for this purpose, as AMIGA has one 802.11 channel assigned for the project in the 2.4 GHz wireless band.

The network structure can be seen in figure 2.

At the time of this article, the coordinator located at Coihueco consists of three radios with their corresponding antennas, each of 17 dBi gain and 60^o aperture, with an output transmit power of 23 dBm. As they are installed now, each antenna has enough aperture to communicate with any detector in the array. One of the three radios is used to communicate with each of the subscribers in AMIGA, one is used as a backup, and the third one is used to monitor the spectrum looking for any possible interference in the AMIGA WiFi channel. There are two kinds of coordinators installed in Coihueco: 2 router boards RB493, each with an R52nM radio from Mikrotik (one of them used as the main coordinator and the other one for backup); and a Rocket M2 from Ubiquity (used for spectrum monitoring), all three of them work at 1/2 of the maximum bandwidth available for the assigned WiFi channel, 10 MHz.

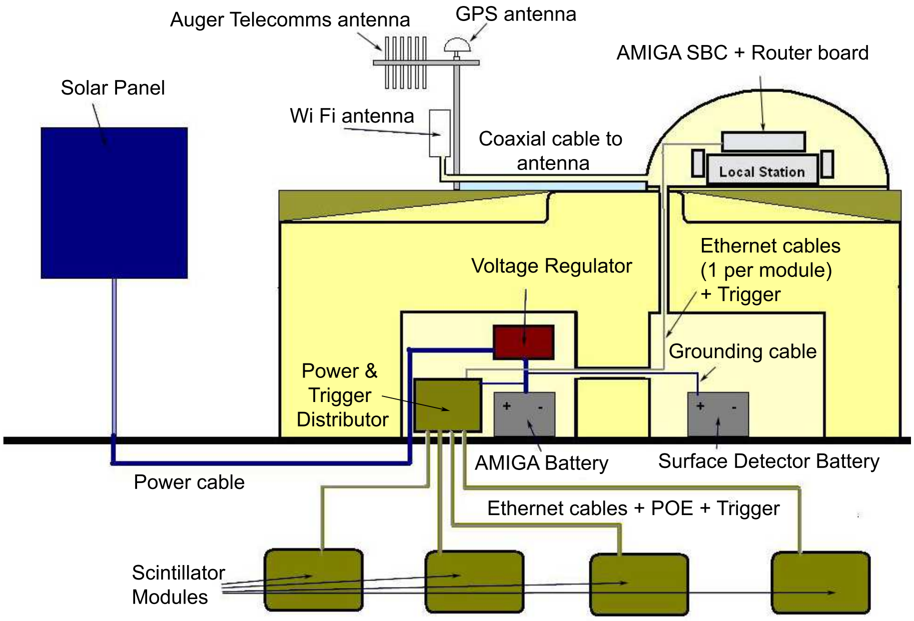

Figure 3. The AMIGA interconnections general layout. Also indicated are the SD antenna, the SD local Station and the SD battery, as it was originally installed for the observatory. The only physical interconnections between the SD electronics and the AMIGA electronics occur between the AMIGA SBC and the Local Station (for T1 requests and the radio sniffer) and the grounding cable that connects the AMIGA and SD batteries.

3.1 General description of the AMIGA hardware and software interconnections

The muon counters are composed of three (four in the engineering array) scintillator modules of 64 scintillator strips each with an optical fiber glued to them that collects the light generated in the strips by impinging cosmic particles (most of them assumed to be muons since only they can penetrate the shielding provided by the soil above the module). The fibers guide the light to a 64 channel photomultiplier tube (PMT) (Hamamatsu UBA H8804-200MOD). Such PMTs transform light into short ($\sim$ 3 ns to 5 ns) current pulses that are then amplified, digitized and sampled into digital zeros and ones by a buried data acquisition system [6]. The buried electronics all communicate with surface electronics that handles the communications with the coordinators in Coihueco, as seen in figure 2. Each muon counter and its surface electronics, including the radios, are powered by batteries charged by 24 V DC solar panels of up to 50 W (depending on the number of scintillator modules connected to one surface detector). Figure 3 shows the general layout of the whole system.

AMIGA surface electronics is divided into three functions: communications, control and distribution. Communications is achieved with a WiFi module that provides a maximum of 23 dBm of TX power connected to a 20 dBi, 2.4 GHz subscriber antenna. The subscribers in the AMIGA engineering array are implemented by a router board RB493 with a low power R52nM radio from Mikrotik in the surface detectors known as Kathy Turner, Los Piojos, Yeka, Toune, Heisenberg, Tierra del Fuego, Corrientes and Phil Collins. The power consumption used for telecommunications is at least 3 W per station.

The RB493 router board has 9 ethernet ports and it can be used to interconnect up to 8 scintillator modules and a TS7260 Single Board Computer (SBC) from Technologic Systems. In the original engineering array design, the TS-7260 SBC uses a CAN bus for interconnection with the buried scintillator modules [11], but this configuration is no longer used. The hardware version implemented at the time of this article for the engineering array uses the ethernet router in the RB493 that provides a LAN with the buried modules to be accessed by the SBC. A serial port from the SBC connects to the hardware of the surface detector, called a Local Station, and a second serial port is connected to the RX pin of the Auger current radio to receive the information of a T3. The function of the SBC is to handle the data transfer to the buried modules, the interconnection to the local station and the interconnection with the Auger radio of the surface detector. The local station front end FPGA software was modified to send a serial peripheral interface (SPI) signal of the time stamp lists to a digital port, where the digital signals are transformed to differential signals and sent via a differential pair cable to the AMIGA SBC. The time stamps are received in the SBC and stored in a 2048 line circular buffer. The complete surface electronics interconnection is described by the schematics in figure 4.

The surface and buried electronics receives T1 time stamps [10] from the Local Station, while the buried electronics transmits the muon counter data to the observatory campus via the WiFi radio. An independent transmission line from the local station to the underground electronics is implemented in an auxiliary board installed on the Front-End board of the local station. It provides the T1 pulse and a local time stamp to trigger the underground detector. The time stamps and the T1 signals are sent from the local station to the AMIGA surface electronics using differential transmitters connected to the local station front end, and receptors connected to the AMIGA surface electronics. The T1 signal is transformed to TTL standard and retransmitted in differential mode to a distribution board in the battery box. A UTP cable carries T1 data transmission between the surface and buried electronics. The power source for the AMIGA electronics is provided by the AMIGA batteries, therefore a second separate cable must connect the battery box with the electronics dome in the SD. With a different UTP cable, a LAN is established to interconnect the particle detectors within a counter using power over Ethernet, providing both data and power connections using only one cable. When a T1 trigger takes place in the surface detector, some microseconds later, a local time stamp and the T1 time stamp are transmitted from the local station to the to the SBC using a SPI protocol, as mentioned in the previous paragraph. Therefore each event recorded by the muon counter can be synchronized with a surface detector event at T1 level.

The request for T3 triggers arrive through the Auger telecommunications system for the prototypes in the AMIGA engineering array. The SBC used to coordinate the AMIGA data flow between the buried scintillator modules and the WiFi radios is listening to all the messages sent by the Auger radio to the Local Station through the Rx_LS and the Tx_PPS pins of the Local Station radio serial port. That means that the SBC is working as a sniffer, to decode all the radio messages and act accordingly whenever there is a trigger from the surface detector. The AMIGA telecommunications are handled in parallel in the 2.4 GHz band through an ethernet port to the router board and there after to the WiFi radio. Every AMIGA radio message is channeled through its own WiFi radio. This is a temporary setup to have both telecommunications (the Auger and the AMIGA ones) working in parallel until the AMIGA setup is officially adopted for the infill surface detectors by the technical board of the Pierre Auger Observatory. Until then there can be no interference between them. These data is going to Coihueco and eventually to the Auger campus.

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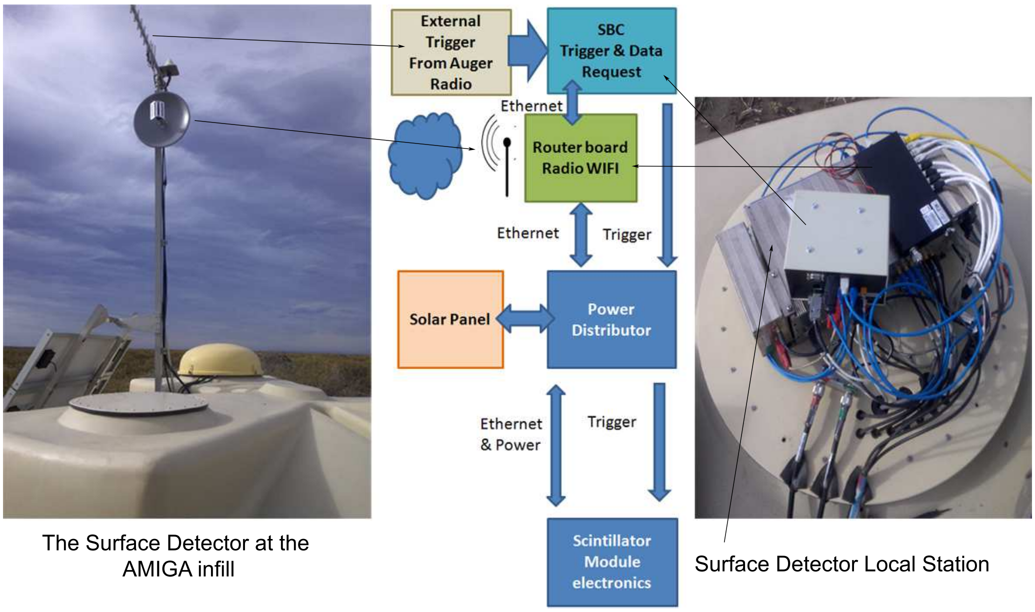

Figure 4. The general layout of the AMIGA interconnections on a surface detector.

AMIGA data consists of the digital output from the AMIGA front end, which is sampled at 320 MS/s by a Field Programmable Gate Array (FPGA) that continuously acquires digital signals into a circular buffer. When a T1 signal trigger arrives, an active buffer is stored on a static RAM memory with the trigger time stamp. Data requests are received by the SBC that transforms the requested time stamp to trigger time stamp and broadcasts both time stamps to all the modules. Upon reception of this packet, each module sends its event information to the data storage system. Each data frame for an event consists of the event identifiers (Data request ID, Detector ID and Module ID), the PMT channels with signal pulses and the corresponding time-bin number within that channel that detected a signal pulse (time-bins with no signals are not transmitted as part of our compression algorithm) and the prefixes for the relative temporal positions of each time-bin. The network as it is configured for the engineering array and currently working in the field as shown in figure 5.

3.2 Summary of the AMIGA data flow

The digital output from the scintillator module's front end is sampled at 320 Msps by a FPGA that continuously acquires digital signals into a circular buffer. When the surface detector electronics generates a T1 time stamp, this information is transferred via an independent transmission line from the local station to the underground electronics through an auxiliary board installed on the front-end board of the local station, which provides the T1 pulse and a local time stamp to trigger the underground detectors. The local time stamp and the T1 time stamp are also transmitted from the local station to the to the SBC using an SPI protocol and stored in a 2048 line circular buffer. Therefore each event recorded by the muon counter can be synchronized with a surface detector event at the T1 level, the lowest trigger level of them all. The T1 trigger signal and time stamps are transferred to the buried detectors through a distribution board in the battery box that broadcasts to all of them. In the underground scintillator module, when a T1 trigger arrives, the contents of the

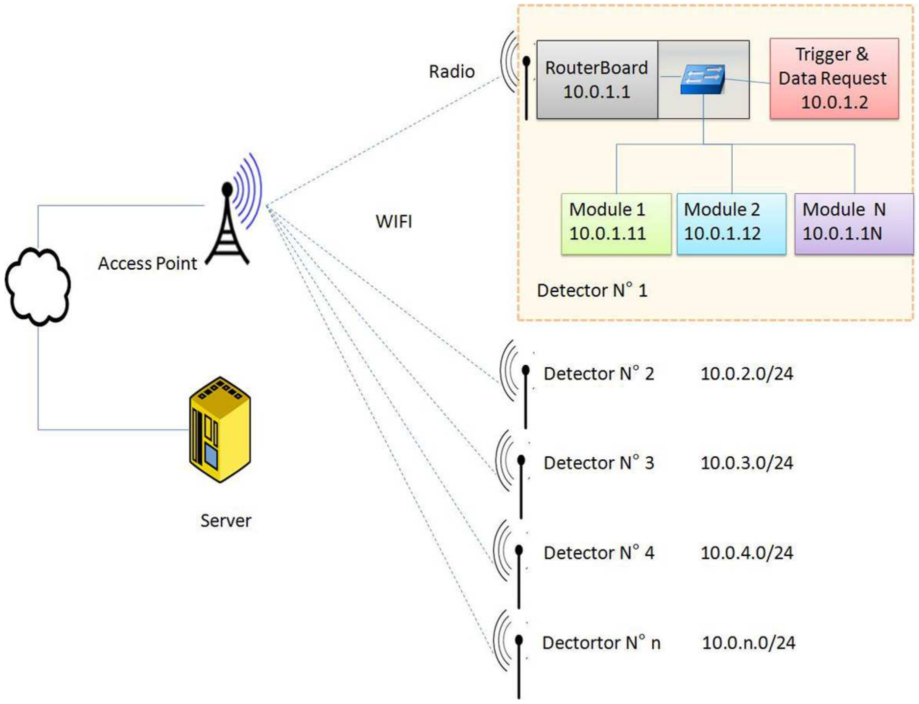

Figure 5. The AMIGA network as it is installed in the field. n represents the number of installed muon counters, currently $n = 8$. The second 0 in the detector IP address can also increment to allow a number of muon counters greater than 255.

circular buffer are stored on a static RAM memory together with the trigger time stamp. When a T3 trigger coincides with one of the T1 time stamps being stored in the SBC, each module sends the contents of the RAM memory directly to the CDAS.

3.3 Radio link calculations

In order to demonstrate that the WiFi link using the antennas and coordinator chosen can support the maximum distance between the furthest tank from the AMIGA array (that is, detector Feche) and Coihueco, we calculated the radio link for three SDs (Feche, Rosalía and Tromen), that represent the furthest locations from the coordinator to a subscriber in the AMIGA network. For these calculations we are simulating the following equipment: radio Ubiquiti RocketM2 with a 120° panel and 15 dBi gain for the coordinator and radios Ubiquiti AirGrid with 20 dBi directional antennas for the subscribers. The same measurements of transmitted and received power calculated in the radio link were performed in the field. Results are shown in figure 6, generated with the airLink Outdoor Wireless Link Calculator [12].

The closest station to the coordinator at the top of the Coihueco hill is about 3 km away. The farthest detector (Feche, SD number 0736) is about 9 km away from the coordinator. The calculations were performed for tanks Rosalía and Tromen as well, as those are the tanks at the farthest locations to the north and the south respectively. All RX power calculations give results of -68 dBm at the coordinator and -61 dBm at the subscriber, with the exception of Feche that has -69 dBm and -62 dBm respectively. As the hardware we are using for the system, which we

Figure 6. The map indicates the location of the coordinator at the Coihueco FD site and the subscriber at detector Feche. On the lower panel it is shown the terrain profile and the different Fresnel zones for the radio link.

described in the previous sections can work with up to -90 dBm of RX power [13], we believe the link represents no challenge for the AMIGA telecommunications needs.

4 Laboratory and field tests

Several tests have been performed in the laboratory and in the field. These are listed as follows:

Signal to noise ratio tests: Signal to noise ratio values measured on site with the 8 deployed stations (even though 7 of them have scintillator modules installed, the 8th station also sends dummy information emulating muon data) has a mean value of around 30 dB. This value decreases drastically in the presence of interference, and the system was tested using an interference that reduced the signal to noise ratio up to 15 dB without affecting the throughput or the data loss rate. These results are shown in the first panel of figure 7.

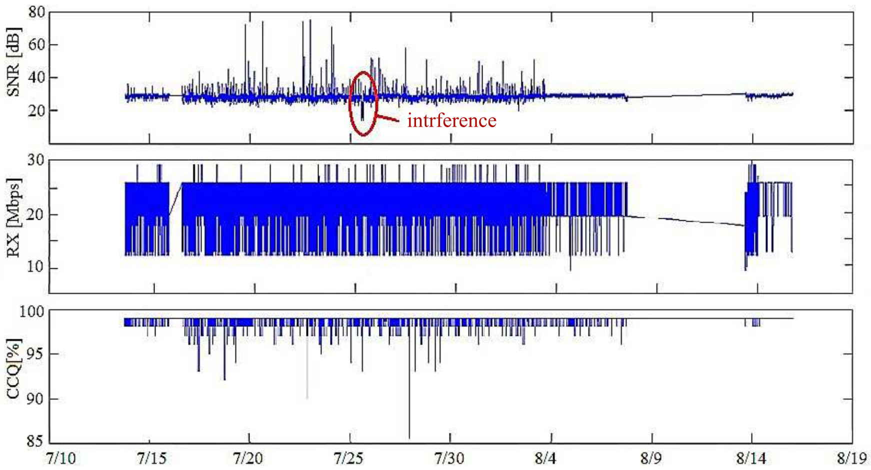

Figure 7. Field test results recorded during July and August 2012. The first panel shows SNR in dB, the second panel shows received throughput in Mbps and the third panel shows CCQ. Even though this figure correspond to measurements performed in detector Kathy Turner, all 8 detectors tested showed similar results.

Throughput tests: throughput tests were performed on the laboratory with the equipment mentioned in the previous section, using one station and one coordinator. Occupying one WiFi channel at half of its capacity, 90 packets of 200 bytes were sent contiguously every second during 2 hours. This setup tries to emulate a scenario where 90 muon counters are sending simultaneously data. The results for this test showed a maximum delay of 2.2 msec. The throughput used during this test was ~ 25 Mbps. During July and August 2012, similar tests of throughput were also performed. Using the 8 stations already deployed on-site, the data generated by each of the 8 stations was sent 12 times to emulate a similar scenario as the one performed in the laboratory with one station and one coordinator. The throughput obtained during this period of time produced results very similar to the ones in the laboratory: ~ 25 Mbps per station and a delay of up to 6 msec. This result was performed using a coordination system based on a Distributed Coordination Function (DCF) as described in [14]. These results are shown in the second panel of figure 7.

Data loss and Frame Error Rate tests: in order to test the Frame Error Rate, and since the protocol used to transmit data (TCP/IP) assures the transfer of data by retransmissions, to quantify any amount of data loss we measured the Client Connection Quality (CCQ) that is a weighted average of the ratios $T_{\rm min}/T_{\rm real}$, that are calculated for every transmitted frame, where $T_{\rm min}$ is the time it would take to transmit a given frame at the highest rate with no retries and $T_{\rm real}$ is the time it took to transmit frame in real life (taking into account necessary retries and transmit rate). The results obtained with 8 stations and using a DCF access were between 98% and 85%. This does not mean that any data is lost, but using a DCF coordination system, some of the data must be retransmitted. This fact will be reviewed in the Network coordinator test. These results are shown in the third panel of figure 7.

Power consumption tests: even though the hardware used has a base consumption of 3 W, this value increases as each of the Ethernet ports in the router board are used. For 6 ports in use, the power consumption is 4.8 W and at maximum capacity, for 9 ports used, the power consumption is 5.7 W. Therefore up to 5 scintillator modules and a SBC can be connected to the router board without exceeding the power budget.

Uptime tests: the hardware has been working on-site since May 2012 until the time of this article (October 2013) without any failure. The gap in the data observed between 8/8 and 8/14 in figure 7 correspond to a failure of the link from Malargüe to the Coihueco building, during which time no data were transferred to the Auger campus. The AMIGA telecommunications hardware resumed the data transfer after the link was restored.

Network coordinator tests and its effect on data loss: the network coordinator system was tested under two modes of operation: mode 802.11g that uses a carrier sensing system [14] to detect when the channel is being used, a DCF (Distributed Coordination Function) system; and mode 802.11n that uses a polling system [15] to assign exclusive use of the channel to each subscriber during a given time frame, a PCF (Point Coordination Function) system. To compare both DCF and PCF systems, a field test was designed in order to have a similar situation to the one that would be encountered under normal operation with 85 or more detectors working simultaneously in the field, using the 8 available detectors today. In order to emulate a worst case scenario, when a group of detectors send their muon data trying to access the channel at the same time, every time a T3 trigger request is received at a given detector, a massive data transmission is sent repeating 12 times the muon information to be sent. This allows us to emulate with 8 stations a situation that would be encountered with 96 stations in total. The resident daemons in each station SBC were modified in order to do this under the User Datagram Protocol (UDP), sending 12 consecutive 150 bytes packets of information for every T3 occurrence on a given station. The UDP was chosen in order to allow for loss of packets and consequently compare both access systems using this parameter. The final packet size considering all protocol layers was 192 bytes. This test was performed for a week for each system and all the UDP packets were dumped on a computer located on the Auger campus in Malargüe. Finally the data transmission efficiency E_{ff} was calculated from equation (4.1) as the ratio between the number of packets received N_r and the total number of packets sent N_{tot}:

$$E_{\mathrm{ff}} = \frac{N_r}{N_{\mathrm{tot}}} \tag{4.1}$$

The results for these tests are presented in figure 8. As can be seen the PCF based system displayed in the top panel has an $E_{\mathrm{ff}} = 100\%$ while the DCF based system in the bottom panel shows some degree of data loss in all the stations. This result shows that the PCF system can assure a successful coordination under TCP/IP, solving the hidden node problem. A DCF system would lead to retransmission due to collisions in the use of the channel, leading to a possible collapse of the network with a large amount of subscribers. This situation could not happen with a PCF system that dedicates an exclusive use of the channel to each subscriber for a finite time much less than the delay allowed for the T2 and T3 triggers data transfer.

5 Conclusions

We present and test a telecommunications system to be implemented for AMIGA using a point to multi point network with one WiFi channel used at half of its capacity. The proposed telecommunications system works in the 2.4GHz band, using off the shelf hardware under IEEE WiFi standard

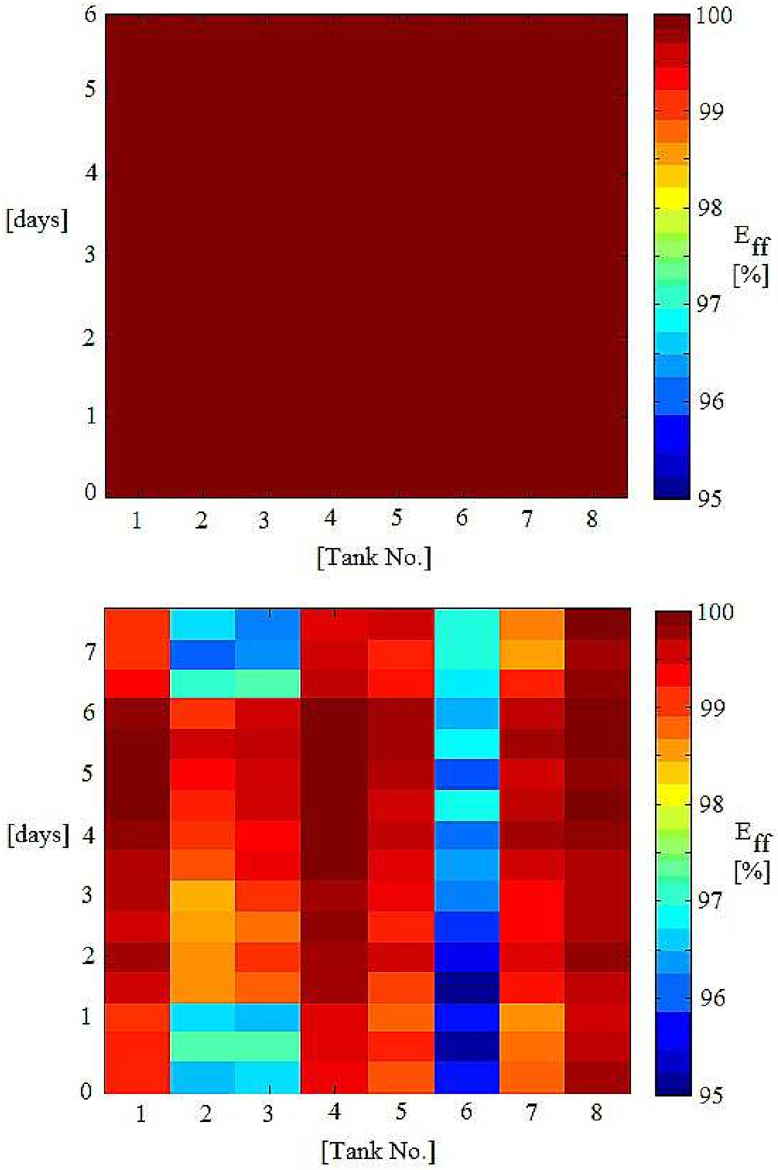

Figure 8. Plots of E_{ff} for the 802.11n IEEE Standard PCF access system (top panel) and the 802.11g IEEE Standard DCF access system (bottom panel). The y axis is the time elapsed during the test, the x axis is the station number. The color scale is E_{ff} in %.

802.11 (n and g). The hardware proved to work without failure during 1 year of testing under outdoor field conditions found in Malargüe, and the use of standard 802.11 proved to be enough for AMIGA requirements. The hardware presented in this paper worked without problems under this norm and it proved to interchangeable, which is a desired result for AMGA. Results show that the IEEE standard 802.11n is the most suitable to transfer muon data from the scintillator modules to the CDAS with a muon data transfer efficiency of 100%. Tests of signal to noise ratio, throughput, power, data loss and uptime show that the hardware works within requirements, and proves to be a possible viable option for future enhancements of AMIGA and the Pierre Auger Observatory.

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