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 m^2 and is made of scintillator strips with doped optical fibers glued to them, which guide the light to 64 pixels photomultiplier tubes. The detector pairs are arranged at 433 m and 750 m array spacing. In this paper we present the telecommunications system designed to connect the muon counters with the central data processing system at the auger 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 fluorescent 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 dete0ctors to the central at the Auger campus, or CDAS. 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: muon counters, methods techniques and instrumentation

1 Introduction: AMIGA and The Pierre Auger Observatory

AMIGA (Auger Muons and Infill for the Ground Array) [1], [2], is one of the enhancements of the Pierre Auger Observatory [3] designed to study the galactic to extra galactic cosmic ray sources transition, assumed to occur at lower energies than the ones Auger was designed for. It consists of an array of 61 detector pairs (a surface detector + a muon counter) spaced 750 m apart plus 24 extra pairs spaced 433 m apart. All 85 pairs are placed within the main 1500 m Auger surface detector array. This group of surface detectors is referred 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 signal to noise ratio, throughput, allowed data loss (related to allowed frame error rate) and synchronization. Then we propose a WiFi system that would satisfy these requirements, including a hardware implementation following IEEE standards. Finally we describe the lab and field tests designed to evaluate the system and their results.

2 AMIGA Telecommunications requirements

The Pierre Auger Observatory is a large, sparse coincidence detector that is comprised of $\sim$ 1600 surface detectors capable of determining the moment at which a particle passes through them [3]. In the infill, each surface detector has a connected and synchronised buried muon counter. Each surface detector and muon counter pair in 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 Auger original system.

The coincidence detection is performed in a Central Data Acquisition System (CDAS). Every surface detector sends a list of T2 [4] time stamps that are used by the CDAS to identify possible cosmic ray events. The T2 time stamp is a 20-bit number representing the microsecond within the current Global Positioning System (GPS) second the T2 trigger occurred, plus 4 bits of additional data, which the AMIGA telecommunications system should be able to transport from each muon counter to the Auger Observatory central campus in Malargüe, at the application level and at a rate of 100 Hz [4].

Besides the T2 lists, every 15 minutes an extra amount of data is sent with the information of every T3 [4] occurrence. 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, and it occurs when a GPS time stamp from three or more adjacent surface detectors is found. In that case the CDAS sends a request for the measurements of the analog to digital converters on each of the 3 photomultiplier tubes (PMTs) in the surface detectors involved in the event. This process can take up to 20 seconds, which is the time CDAS takes to evaluate the occurrence of a T3. The data flow during a T3 trigger also includes the muon data, an extra amount of 64kbits for every T3 request (this data takes 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). 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 previous measurements of traffic in the Auger array, at the application layer a data loss of 0.01% of the T2 time stamp lists is allowed for a correct functioning, which means a data loss of 0% of the T3 requests. Concerning the network requirements, the AMIGA project has an available throughput of 27 Mbps to provide for all the stations and a maximum delay between subscriber and coordinator of 500 msec /station. There are no requirements for the MAC and physical layers. Concerning the hardware, the telecommunications equipment has a power budget of $5W$ and the interconnections between scintillator 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, at least during the testing phase. Concerning the signal to noise ratio, there are no specifications besides the ones required for the wireless standard proposed for the system which, as we will show in the following sections, it is fulfilled.

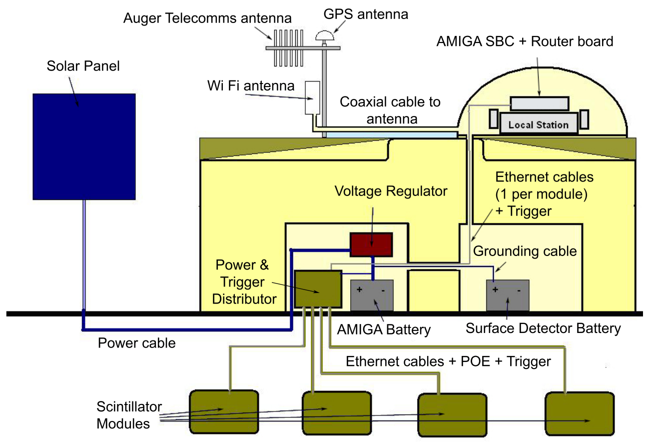

Figure 1: The AMIGA muon counter interconnections general layout. This is the subscriber station.

3 Proposed wireless system for AMIGA

In order to satisfy the requirements of the AMIGA data flow for a telecommunications system established in the previous section, a wireless network using standard 802.11 from the IEEE is proposed. Low power consumption, 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 observed in Figure 1 of [2]. 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 26 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: A Rocket M2 from Ubiquity (main coordinator), working at 1/2 of the maximum throughput, 27 Mbps; and a RouterBoard RB493 with two R52nM radios from Mikrotik (used for backup and spectrum monitoring).

3.1 General description of the AMIGA hardware and software interconnections at the subscribers

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 PMT (Hamamatsu UBA H8804-200MOD). Such PMT transforms 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 [2]. Every scintillator module communicates with a surface electronics that handles the data flow with the coordinators in Coihueco. Each muon counter and its surface electronics, including the radios, are powered by batteries charged by 24V DC solar panels of up to 50W (depending on the number of scintillator modules connected to one surface detector). Figure 1 shows the general layout of the whole system.

AMIGA surface electronics is divided into three functions: telecommunications, control and distribution. Telecommunications is provided by a WiFi module connected to a 20 dBi, 2.4GHz subscriber antenna that provides a total transmit power of 20 dBm. There are 2 types of subscribers in the AMIGA engineering array at the moment: An AirGrid M2 from Ubiquity in surface detector Corrientes; and a RouterBoard RB493 with a low power R52nM radio from Mikrotik in surface detectors Kathy Turner, Los Piojos, Yeka, Toune, Heisenberg, Tierra del Fuego and Phil Collins.

The RB493 RouterBoard 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 TS7260 SBC uses a Controller Area Network (CAN) bus for interconnection with the buried scintillator modules, and this configuration is still used in surface detector Corrientes. The rest of 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 the local station, and a second serial port is connected to the RX pin of the Auger radio to receive the information from T3 requests. The function of the SBC is to handle the data transfer to the buried modules, the interconnection with the local station and the interconnection with the Auger radio of the surface detector. The local station front end Field Programmable Gate Array (FPGA) software is modified to send a serial peripheral interface (SPI) signal of the trigger 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 SBC. The trigger signal is retransmitted in differential mode to all the scintillator modules via a distribution board located in the battery box. The same Shielded Twisted Pair (STP) cable carries data transmission (either CAN for the Corrientes station or Ethernet for the rest of the stations) and a grounding cable. A LAN interconnects the scintillator modules within a muon counter using power over Ethernet, providing both data and power connections with only one cable.

3.2 General description of the AMIGA data flow

The data flow can be described as follows: The digital output from the scintillator modules 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 [4], 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 1024 lines circular buffer. Therefore each event recorded by the muon counter can be synchronized with a surface detector event at T1 level, the lowest trigger level of them all. T1 trigger signal and time stamps are transferred to the buried detectors through a distribution board in the battery box that broadcasts both to all of them. In the underground scintillator module, when a T1 trigger arrives, the contents of the circular buffer are frozen and stored on a static RAM memory 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 to the SBC in the surface, to be transferred back to the CDAS. Every data frame in this exchange of information consists of an event identifier (Data request ID, Detector ID and Module ID), the high bits corresponding to the PMT pixels with signal pulses and their corresponding time-bin number (time-bins with no signals are not transmitted as part of our compression algorithm) and the prefixes for the relative temporal positions.

The request for T3 triggers arrive through the Auger telecommunications system. The SBC is listening to all the messages sent by the local station to the Auger radio, working as a sniffer to decode all radio messages and act accordingly whenever there is a T3 request that matches a T1 trigger from the surface detector. The AMIGA data transfer back to the Auger campus is handled in parallel through the 2.4GHz WiFi band using an Ethernet port to the router board and the WiFi radio. Data is transferred back to Coihueco and eventually to CDAS at the Auger campus. Every AMIGA radio message is channeled through its own WiFi radio, there can be no interference between the Auger and the AMIGA telecommunications system.

4 Laboratory and Field Tests

Several tests have been performed in the lab and in the field, which are being enumerated 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 can be observed in the first panel of Figure 2.

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

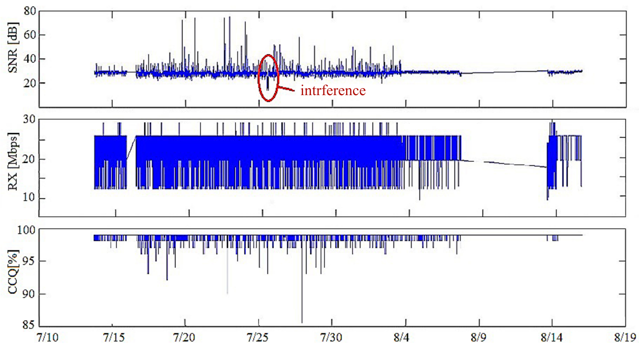

Figure 2: Field test results recorded during July and August 2012. Fist panel shows SNR in dB, second panel shows received throughput in Mbps and third panel shows CCQ. Even though this figure correspond to measurements performed in detector Kathy Turner, all 8 detectors tested showed similar results.

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 amount of data was sent 12 times to emulate a similar scenario as the one performed in the lab with one station and one coordinator. The throughput obtained during this period of time threw results very similar to the ones in the lab: ~ 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 [5]. These results can be observed in the second panel of Figure 2.

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_{min}/T_{real}, that are calculated for every transmitted frame, where T_{min} is the time it would take to transmit a given frame at the highest rate with no retries and T_{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 can be observed in the third panel of Figure 2.

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

Uptime tests: The hardware has been working on-site since May 2012 without any failure. The gap in the data observed between 8/8 and 8/14 in Figure 2 correspond to a failure of the link from Malargüe to the Coihueco building, during which no data was 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 [5] to detect when the channel is being used, a DCF (Distributed Coordination Function) system; and mode 802.11n that uses a polling system [6] 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 during 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} is calculated from equation (1) as the ratio between the number of packets received N_r and the total number of packets sent N_{tot}:

$$E_{ff} = \frac{N_r}{N_{tot}} \tag{1}$$

The results for these tests are presented in Figure 3. As is observed the PCF based system displayed in the top panel has an $E_{ff} = 100\%$, while the DCF based system in the bottom panel shows some degree of data loss in all the stations. This result shows that only a PCF system can assure a successful coordination under TCP/IP, since a DCF system would lead to retransmissions due to collisions in the use of the channel leading to a possible collapse of the network with a large amount of subscribers, a situation that 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. Results show that it is suitable to transfer muon data from the scintillator modules to the CDAS with a muon data transfer efficiency of 100% using a WiFi system under the 802.11n IEEE standard. Tests of signal to noise ratio, throughput, power, data loss and uptime show that the hardware works within requirements.

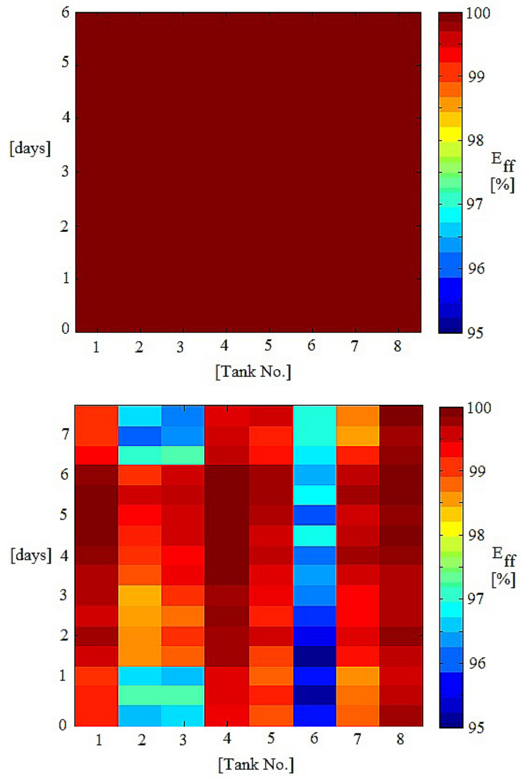

Figure 3: Plots of E_{ff} for the 802.11n IEEE Standard PCF access system (top panel) and the 802.11g IEEE Standard DCF access system (bottom panel). The y axis is the time elapsed during the test, the x axis is the station number. The color scale is E_{ff} in %.

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