Creating a large scale wireless network with SCIFI

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Abstract

One year after progressing from a research project to become the technology driving the wireless network at UFF, SCIFI Magalhaes, 2013 has grown. SCIFI (an acronym which stands for Intelligent Controller for Wireless Networks in Portuguese) started as a software controller to allow the use of inexpensive hardware in large wireless deployments, costing a fraction of a similar installation using enterprise controllers and access points. Although the core technology (Balbi, 2012) remains the same, the lessons learned from running a growing wireless network composed currently of 320 access points (APs), with more than 50000 unique users led to changes in network architecture, to the deployment of multiple SSIDs to allow visitors to self-register, and to the creation of an automated system for installing new APs. This paper presents the new, segmented network architecture that creates two planes, a control plane that connects all APs and the controller in a single VLAN, and multiple data planes, that isolates data traffic from each campus. It also presents the automated system for installing new APs, that prevent errors that were plaguing the network as faulty communication between the installation teams and operations caused misconfigurations and even network failures. To illustrate this we discuss the post-mortem of a denial-of-service "attack" caused by a simple mistake while installing new APs. Throughout the paper, we show how the monitoring tools that have been incorporated into the SCIFI installation (nagios (Josephsen, 2007), mrtg (Oetiker, 1998and monitorix (Monitrix, 2014) play a key role into understanding what is happening in the increasingly complex infrastructure.

Keywords: software controller, Wi-Fi, wireless networks, monitoring

1. Introduction

Universidade Federal Fluminense (UFF) is a large University located on the State of Rio de Janeiro, Brazil, with 15 campi and 94 buildings in its main centre in Niteroi, and campi at several other locations both in the State of Rio de Janeiro and in other States of Brazil, with 35,599 undergraduates students and 11,675 graduates, 4,005 staff and 2,852 professors. UFF has its own fiber network connecting its campi in Niteroi, and chose SCIFI as the solution for installing a wireless network (Wi-Fi-UFF) to span all its campi.

In this last year, the SCIFI project at UFF has undergone many changes, to overcome challenges that appeared as the network grew. SCIFI is an acronym is Portuguese for "Intelligent Control System for Wireless Networks", and started as a work group funded by RNP, the Brazilian NREN. The objective of the project is to create an Enterprise Grade wireless network using inexpensive, off-the shelf, generic wireless routers. It does that by coupling OpenWRT, an open source linux distribution for wireless routers with a software controller, which was also made open source and can be found at github.com/Sci-Fi. More information about SCIFI can be found at Magalhaes, (2013), Balbi, (2012 a, 2012b)

In many Universities in Brazil, wireless access is being offered in an ad-hoc manner. As the price difference between an Enterprise solution, such as those offered by Cisco, Motorola, Aruba, Ruckus and other vendors, and standalone SOHO routers such as those by TP-Link, D-Link, Buffalo and others is so large, users started bringing in their own equipment and connecting to the University wired network. This brings a host of security, management and operational issues, and is highly inefficient in terms of spectral use, so the final bandwidth available to users is lower than that of any Enterprise system. SCIFI bridges that gap. By endowing inexpensive routers with characteristics that only Enterprise routers have, it is possible to have the best of both worlds, secure and efficient operation at a low cost.

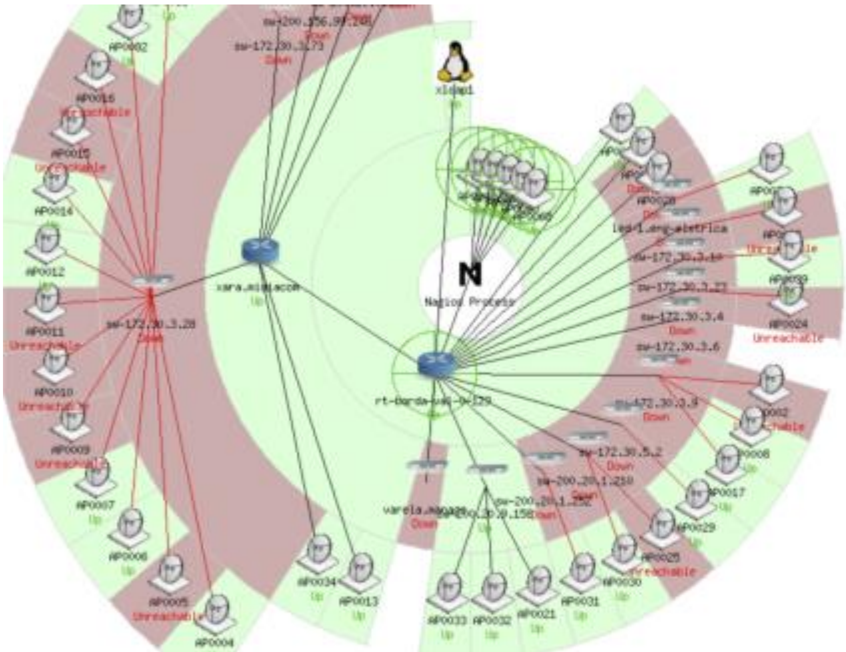

Figure 1: Number of APs and switches in the beginning of 2013

RNP funded the pilot project at UFF. Twenty two routers were installed at natural gathering points (libraries, study halls, cafeterias). Figure 1 shows an early NAGIOS (Josephsen, 2007) map, after adding twenty more routers to the pilot. Although the SCIFI controller has a nice map based on the google maps API, and shows the location of the routers with a color code that says if they are working, turned off or presenting problems, we decided that we could add value to the system by incorporating existing management platforms. NAGIOS allows the operator to see at a glance if things are not working, and also the underlying network infrastructure, which is absent in the controller interface. As we found out, most of the problems came from two sources, the wired network and the installation process. Those will be discussed in sections 2 and 3.

People familiar with NAGIOS will see that the map pictured in figure 1 is faulty. There are routers that are working although they should be unreachable because the switch they are connected is marked as down and there are routers not connected to a switch. This is the result of a lack of communication between the IT department at the University and the group that is installing SCIFI. NAGIOS maps are created with information configured in files, and if this information is not accurate, the map will not reflect the network. There are tools, such as NetDOT (NetDOT) that automatically create a NAGIOS configuration using discovery tools. We have installed NetDOT, and are converging on this objective.

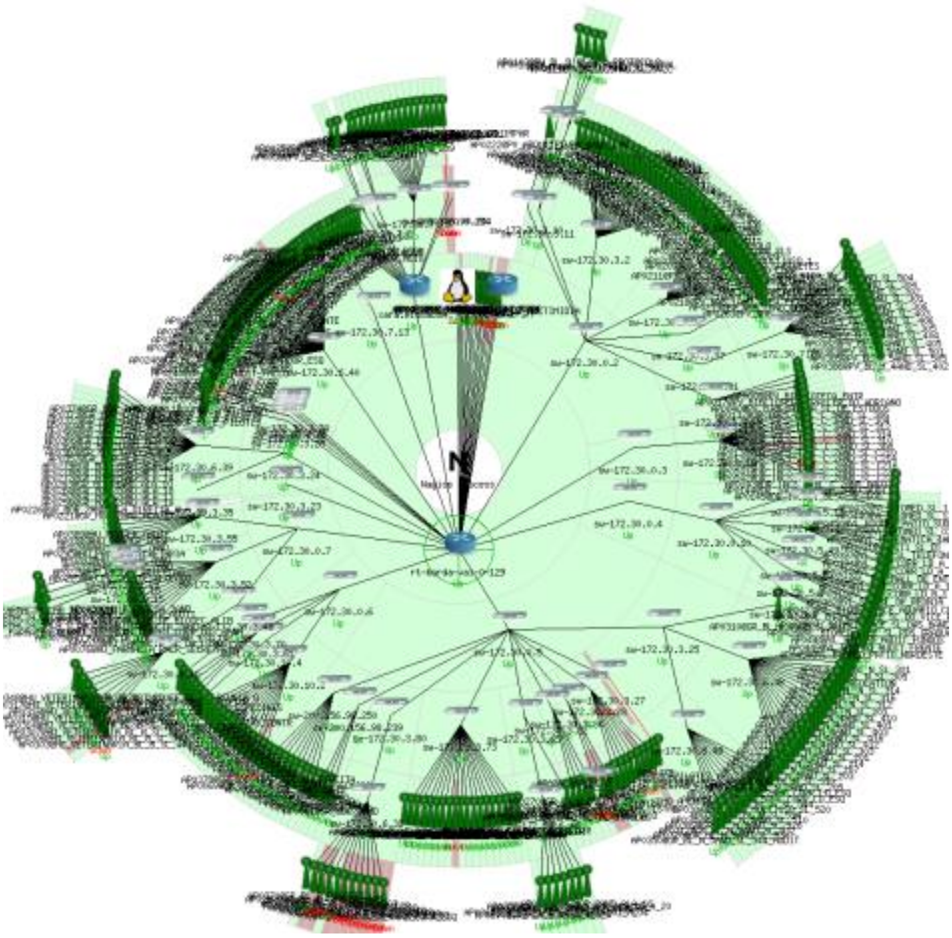

Figure 2: NAGIOS map on October 2014

Figure 2 shows the NAGIOS map that reflects the network growth in a year and a half. There are now more than three hundred and twenty nodes. This map is no longer current because five more nodes were installed since this snapshot but this will happen continuously, as the objective is to ramp up to installing 20 new APs a week, so the network grows by a thousand nodes each year.

This NAGIOS map has grown too large to read. We mainly use the map as a visual tool to see if there are problems with the infrastructure, when a whole slice of the graph will turn red. We changed the icon that represents the routers as the previous was too large, and print the location of the router on the label, because with 300 nodes it is no longer possible to know where each AP is without some aid. We do use the grid view and NAGIOS allows the exclusive display of nodes that are down, so we can dispatch the teams that fix the network.

In the week from 19 to 26 of October, we had 1,600,834 association requests, from 18,111 unique MAC addresses. As we will explain in section 2 below, each AP now advertises four different SSIDs, and we will show the breakdown of how many association requests each SSID had. But most of the association requests (1,255,471) were for EDUROAM (Florio, 2005 (Muchaluat-Saade, 2013. EDUROAM is an international, federated system for authentication and authorization, and allows members of the federation to access freely the wireless networks in other federated institutions. The authentication request is routed to the home network of the user. UFF decided to adopt EDUROAM as its main network (SSID) but other architectures are possible, such as using one main SSID (eg. WIFIUFF) and deploying EDUROAM at selected Access Points.

The rest of this paper is structured as follows: section 2 deals with network architecture, and shows how SCIFI went from a single VLAN that incorporated data and control information and a single SSID (EDUROAM) to separate VLANs for control, self-registration and a "visitors" network, and one data VLAN for each campi, and separate SSIDS for self-registration, visitors and a special, local SSID for management functions, keeping EDUROAM as the campus wide SSID for general access; section 3 deals with the problems that plagued the network because of faulty installation, and the system that was developed for installing new nodes, finally, the paper ends with the section on future work, which describes the plans for active monitoring and what was learned from the work done so far.

2. Network Architecture

When the number of APs installed at UFF reached one hundred, the system was considered stable enough so it could be handed over from MidiaCom Labs, where it was being developed, to the University IT services. The task of the Laboratory became of doing second and third tier support, with the understanding that second tier would also be moved to IT services, and to community building. Most of the development in this phase was the creation of an installer, a large script that installed the many packages that compose the system so it could be installed by people with less expertise.

The handover proved to be a mistake. IT services did not have a stake on the project, and was also at pressure to install a large number of APs. This led to the problems that are described in section 3. Before those catastrophic problems, though, shortcomings in the current architecture had become apparent, and a new network architecture was developed to its place. In a nutshell, the problem was that a single LAN cannot support a large number of stations. When the number of APs grew over 100, and the number of simultaneous users grew over 500, we had a single LAN (composed of many LAN segments connected through a VLAN) with over 600 stations. The broadcast traffic was swamping the network, and performance suffered.

This was not completely clear, because as a University UFF was growing at a fast pace, and it has become now the University with most incoming students in Brazil. Thirty new buildings were being finished, and the network infrastructure was suffering growing pains. As incidents were being reported, such as inability to get IP addresses from the network, monitoring was being expanded, and it became clear that the network had to be segmented. From a single VLAN connecting everything, it was decided to go to an architecture where control would still be centralized, using the old VLAN, but data would be segmented into different VLANs, with a DHCP/NAT server for each large group of stations (normally mapped to a campus).

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Figure 3: Monitorix interface

One of the tools that helped see what was happening in the server was Monitorix. Monitorix allows the inspection of many aspects of the server, such as the load, the CPU usage, the network and filesystem usage. Figure 3 shows the Monitorix web page for the main server. We can see that it is still heavily loaded. Ironically, this is caused by MRTG, another tool that collect information. Currently, NAGIOS and MRTG are used for daily tasks. NAGIOS tells us what is broken, and MRTG allows us to see the history and correlation between events and breakdowns.

The way we currently have MRTG set up it creates new "daily" graphs every 5 minutes, "weekly" graphs every 30 minutes, monthly graphs every two hours and yearly graphs once a day. For the number of APs we have, this creates a large consumption of disk and CPU, as can be seen by the regular peaks on the system load graph on Figure 3.

One of the best features of the new architecture is that it made possible for a gradual move from the old, single VLAN architecture, to the new, segmented architecture. In fact, it is even possible to APs belonging to both architectures to co-exist, but this is not recommended as it has side-effects that will be explained below.

As can be seen in figure 4, that are five VLANs connected to "Controle", the control server. Each of the segmentation servers ("Trabalho"- work) is connected to three VLANs. The five VLANs connected to the control server are:

1. Control. VLAN number 200. To make transition easier, the VLAN that carried data and control information became the VLAN that carries control information. This VLAN will stop carrying data when all APs are migrated to the new architecture, but there are still APs connected solely to this VLAN. The IP addresses in this VLAN are in the range 172.24.0.0/16 for APs, and 10.0.0.0/16 for stations.
2. Monitor: Control data for switches have a separate VLAN. As the wireless network is dependent on the wired infrastructure, we asked to monitor the wired infrastructure to be able to understand where the problems were located. The IP address range for switches is 172.30.0.0/16

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3. Registration: This VLAN, numbered 203, carries data for the self-registration feature of SCIFI. This feature allows visitors to register to use the network. This feature will be described below. The IP range for this VLAN is 192.168.0.0/17.
4. Visitors: This VLAN, numbered 204, carries data for visitors. The IP range for this VLAN is 192.168.128.0/17
5. External link: this VLAN leads to the Internet, and has the external world valid addresses (200.20.0.0/24).

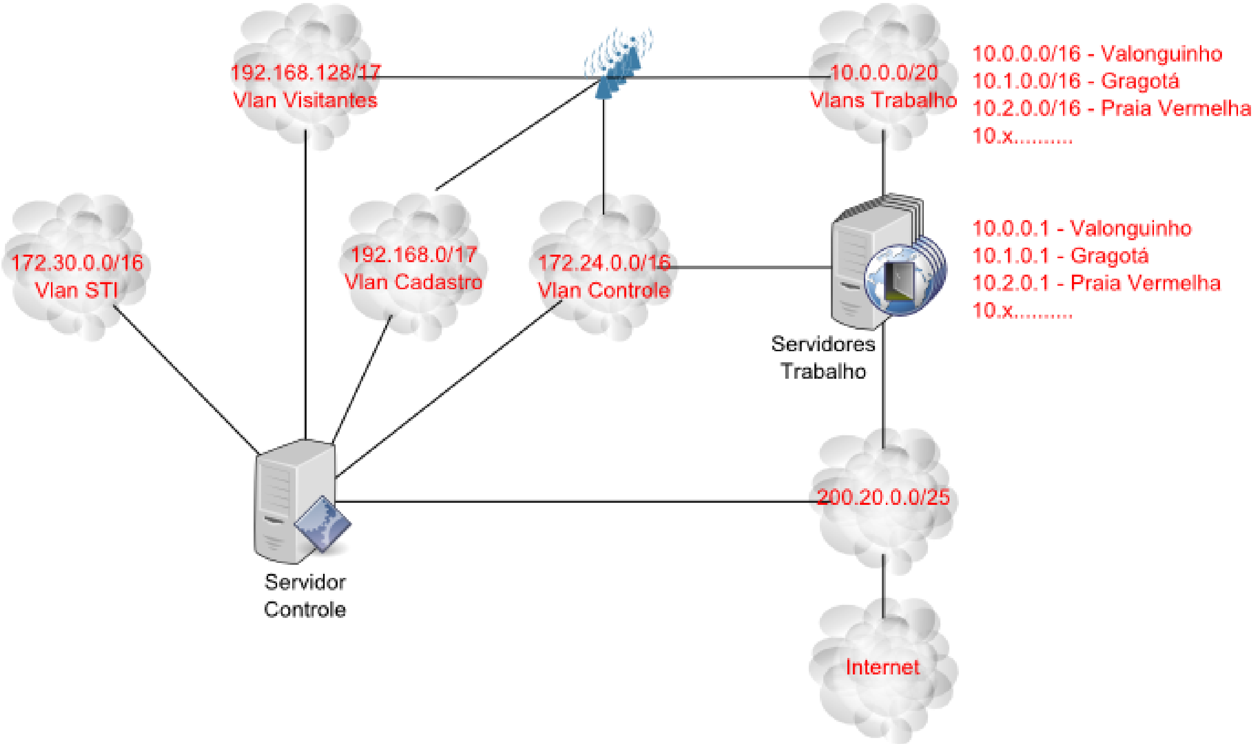

Figure 4: The new network architecture

The three VLANs connected to the work servers are:

1. Control: The same VLAN described above
2. Data. VLANs number 205 & 206. Only the two larger campi have been "segmented". Praia Vermelha uses VLAN 205 and Gragoatá uses VLAN 206. The station IP address range for each VLAN are respectively 10.1.0.0/16 for Gragoatá and 10.2.0.0/16 for Praia Vermelha.
3. External link: this VLAN leads to the Internet, and has the external world valid addresses (200.20.0.0/24).

In the old architecture, it was possible for a station to "see" an AP. Now there is isolation on the IP level, and stations will no longer able to communicate on the APs control plane, when segmentation is finished. Because we had used some APs as switches to increase the number of available ports on some switches, they had to carry tagged Ethernet frames. Unfortunately we found out that OpenWRT supports only VLANs with 4 bit tags. This led to the coexistence of segmented and non-segmented APs in the same vicinity, which creates the following problem: if a device switched from on segmented AP to a non-segmented, or vice-versa, it would not ask for a new IP, because it was still on the same network (given by the SSID EDUROAM). At this moment communication would fail, because its IP (and NAT table entry) was for a different network. The mapping from VLANs to SSIDs is explained below.

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In the APs, the VLANs map to different SSIDs. There are four SSIDs in each AP: EDUROAM, CADASTRO (registry), VISITANTES (visitors), and APXXXX, were XXXX is the AP number. This last maps to the same VLAN as EDUROAM (200, 205 or 206 depending on the location of the AP), but is used only for testing. As it is the user device that chooses the AP, it would be impossible to connect (and stay connected) to a specific AP if the only SSID was EDUROAM. The device could choose to connect to a different AP than the one you were trying to test, or switch to a different AP in the middle of the test. Although the network architecture was designed specifically to allow roaming, sometimes that characteristic is undesirable.

CADASTRO maps to the registry VLAN (203) and VISITANTES maps to the visitors VLAN (204). CADASTRO is the only SSID that is open, allowing anyone to get an IP address without a login/password or a pre-shared key. On that network only web accesses are allowed, and any web access is redirected to a site that has two functions: for students, professors and staff at UFF it has the manual on how to connect to the network; for visitors it leads to a step-by-step guide that allows the user to register to the network, and connect to the visitors network.

We have two metrics that allow us to gauge the usage of the wireless network. One is the number of associations, which tells us how hard the APs are being hit. The other is the number of successful DHCP requests (which resulted in an IP address being handed out). Not all association requests will result in a DHCP request, as if authorization does not complete there will be no DHCP request, and if the user is roaming (changing from one AP to another) it will keep the same IP and will not make a new request. Table 1 shows the number of associations per SSID in the week from 19 to 26 of October of 2014.

Table 1 shows that devices are associating with more than one SSID, as the total of unique MACs is lower than adding the number of unique MACs for each SSID. Table 2 contains the number of successful DHCP requests.

SSID	**Number of association requests**	**Number of unique MACs**
EDUROAM	**1,255,471**	**12,443**
CADASTRO	**260,886**	**8,856**
VISITANTES	**69,217**	**1,254**
APXXXX	**15,260**	**526**
Total	**1,600,834**	**18,111**

Table 1: Association Requests and Unique MACs per SSID

SSID	**Number of DHCP requests**	**Number of unique MACs**
EDUROAM (Praia Vermelha)	**161,344**	**4,288**
EDUROAM (Gragoatá)	**195,998**	**4,396**
EDUROAM (non-segmented)	**105,035**	**4,833**

CADASTRO	**177,735**	**7,764**
VISITANTES	**23,031**	**459**

Table 2: Successful DHCP Requests and Unique MACs per SSID

By comparing the information on the two tables it is possible to infer that not all association requests are resulting in successfully getting an IP address. This is more critical for the "CADASTRO" network, because by being open there should be no obstacle for a device to get an IP address once it connects. The other networks require a login and password, and there may be authentication failures. On the other hand, we have seen that most of the device population is made up of cell phones (smartphones), and those tend to change access points frequently, and retry a number of times before "latching" to an access point. If the user is moving while this happens it may not be successful in getting an IP address, and this may explain the discrepancy.

3. Growing Pains

Federal Universities in Brazil have rigid rules on how to acquire equipment. The growth of the wireless network is governed by those rules. The first one hundred nodes were bought with personal and project funding, but then the next four hundred nodes were subject to public bidding, which took a long time. When the APs arrived, University IT services became responsible for tagging the APs, uploading the new image which was custom made by MidiaCom Labs, and physically installing the APs. The tag, location and other data would then be relayed to the SCIFI group at MidiaCom for adding the new APs to the controller and monitoring system. An installation manual was produced together with an installation sheet, containing all data that should be filled in for each AP.

There was a large backlog of requests for wireless installations, but because most of the installations required new cabling, which is a work intensive, lengthy task, it was agreed that IT services should concentrate on places where resources (cabling and switch port) were available, and new buildings.

The first one hundred installations had not gone without a hitch, but the knowledge gathered from the experience and mistakes were concentrated on the manual, and on the installation sheet. We were secure that if procedure was followed then few mistakes would happen. On October of 2013 IT services took over.

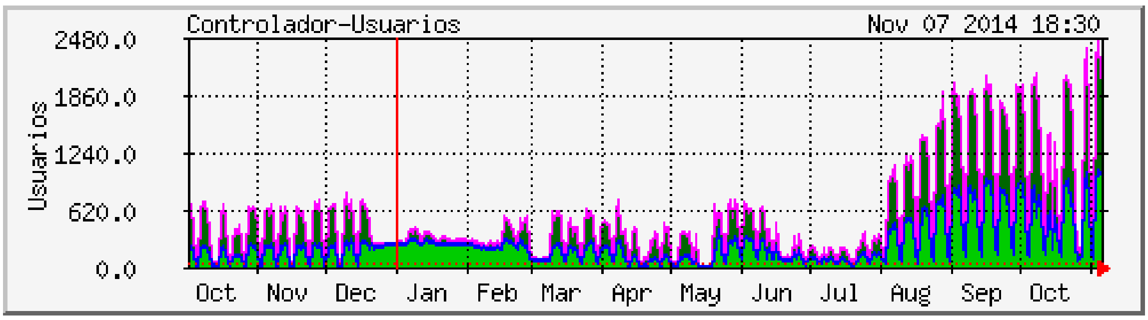

Figure 5: Growth in the number of simultaneous users over the year

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Figure 5 shows the MRTG graph of the sum of associated users in all APs installed. The number of APs grew from less than one hundred in October 2013 to more than two hundred and fifty at the end of February 2014. But the number of associated users declined. It should be noted that December, January and February are summer vacations, so it was expected that the numbers would not be as high as during classes. But when classes resumed in March the SCIFI group was mystified that with double the number of APs we were getting less users than before. We started combing the network for problems.

It should be noted that an open-source, free system is seen with reservations by some IT professionals. The TCO (total cost of ownership) calculation has to consider that support many times is not a phone call away, but done voluntarily by people on their own time (or by paid subscription, when it becomes more like paid software). So the failures that were seen were blamed on the low-cost routers and faulty software.

As we investigated the problems, we found many practices that were causing problems. Two were especially destructive. The first was taking installed APs down to install somewhere else, due normally to urgent request for connectivity in events. If done correctly, this multiplies the effort of installing one AP by 3. This practice also messes all the location tables and if not returned to their original places, APs become "lost". The second deleterious practice was installing the APs and powering them up, but not connecting them to the network. That ranged from not configuring the VLAN to not connecting the AP physically. The problem in this case is that not only the AP did not work, but that the AP advertises the SSID (EDUROAM), so users would switch to them and lose connection, although they had a radio link.

The other problems were not turning in the installation sheet, or turning it in with incomplete or inaccurate information, duplicating tags, and installing APs without uploading the custom image first, leaving the original firmware. Sometimes, to compound this mistake, instead of connecting the AP to the network using the blue (WAN) port, the AP would be connected using the yellow port (LAN). The original firmware has a DHCP server active by default, so it would start responding to requests from users. But the final problem that led to changing the image on the APs is depicted on Figure 6.

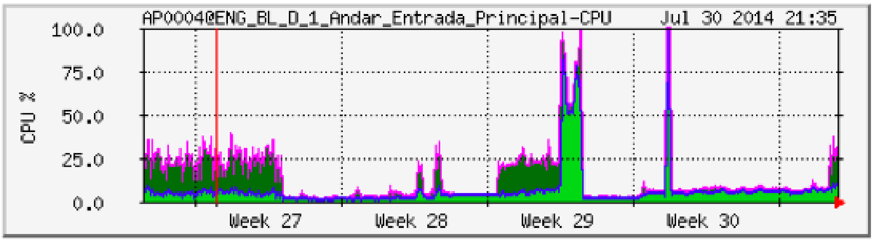

Figure 6: CPU usage on AP0004

Figure 6 shows, on week 29 and week 30, the MRTG graph of CPU usage on the AP going to 100%. In some APs, this caused the APs to reboot. Some were left in a failure state, unresponding. All the APs on the network show a similar graph. AP0004 weathered both events. We captured network traffic while the second event was happening, and saw 20Mbps of "gratuitous ARP". This is what happened: two APs with original firmware were installed in a new building (block P). In addition, the APs were connected through their LAN port, instead of the WAN port. When an AP is connected, it sends a gratuitous ARP advertising its address, in this case, 192.168.0.1. The problem is that with two APs connected simultaneously to the same LAN, both were contending for the same address. When

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receiving the gratuitous ARP from the other AP, it would respond with its own gratuitous ARP requesting the address back.

This was before the network was segmented, so all APs were receiving 20Mbps of gratuitous ARP. The problem with that is every time a gratuitous ARP is received, the AP has to update its ARP table. That uses CPU, and with so many ARPs (with changes), some APs could not keep up and simply rebooted. At the incident investigation, we saw that the new building that had the misconfigured APs was connected to the network on a Thursday around 14:00. Chaos ensued. On Friday at 17:00 the IT staff left, and switched off the network. The same happened on the next Tuesday, when we located the problem, and asked the APs responsible to be taken off the network.

We think that there is intelligence in the network that should be able to filter out that flood. UFF has firewalls in place that should be able to do that. But as this falls beyond the administrative domains of the wireless network, we took the following actions:

- unconnected APs do not advertise the SSID associated with the missing VLAN. For instance, if VLAN 203 (registry) is down, the SSID CADASTRO is taken down. We continuously monitor the VLANs and switch off and on the associated SSIDs according to their state
- we isolated the data VLAN for different campi. This was needed by performance reasons, but makes the network more robust to this type of "attack"
- we made a new installation image, that will be described below, that collects the data that used to be written on the installation sheet on a web form, and sends this info to the installation server. This diminished the time it takes to percolate the information, and prevents users to associate with an unconnected and unconfigured AP.

At the end of this process, the installation and operation of the wireless network was returned to MidiaCom Labs. A permanent workgroup was created with six undergrads and a PhD student that are now installing and running the wireless network. This happened at the end of July. By solving the problems and fixing up the APs that were in place but not working, the number of simultaneous users quickly topped 2000 from the previous 600 high water mark, as can be seen on Figure 5. We are now having peaks of near 2500 simultaneous users.

It should be noted that most of the problems we still have now are due to installation and environment. Only four APs failed since we started the project, two of those outdoor APs that after three years had the rubber gasket failing which caused water to reach the network connector, corroding it. Two were indoor APs with failure on the wan port - we retired those because, although they could still be used, it would not be a standard installation. We have on average two APs stopping responding each week. Some of those failures are due to physical problems, such as one case of a user disconnecting the power block from the socket to charge her cell phone (on a network rack), or disconnecting the AP to use the network socket. We tag those problems as installation problems, because some of these problems can be avoided with more judicious installations. Other problems are due to the low power quality in some campi, which causes brownouts that can leave the APs in an unresponding state. Because SCIFI is meant to work with a very high degree of overlapping coverage areas, we believe that with less than 1% failure rate the wireless network coverage will be satisfactory with our current maximum response time of one week.

The automatic system configuration was designed for an adverse installation environment. The idea is that the AP may be installed and its installation not reported, and the AP may not be configured. So the software that runs in the AP is in "survival mode". It advertises its presence by broadcasting an SSID with config-<MACADDRESS>, eg: config-00:12:34:56:78:99. If connected to a network, it will try to send messages to the configuration server, and those messages will vary corresponding to its state. The state machine that was

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implemented has six states: unconnected & unconfigured, connected & unconfigured, unconnected & configured, connected & configured, server informed and changes in configuration.

Basically, the system has nine steps:

1. it starts with the physical installation of the AP
2. once turned on, the AP advertises an SSID named config-MAC.
3. To set up the AP the admin connects to this SSID with any web-enable Wi-Fi device (smartphone, tablet or laptop) and enters the address 192.168.0.5. This leads to a web page stored inside the AP, The configuration page is shown in Figure 7.

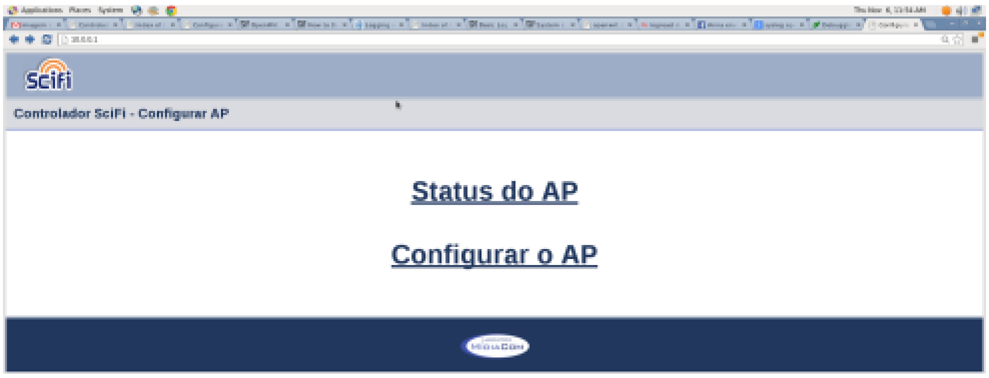

Figure 7: The configuration page hosted on the AP

4. The page allows the admin to check the status of the AP, or configure the AP. Status is its IP address, which shows if it is connected to the right VLAN. The Status page also allows the user to run ping commands to test connectivity. If the second (configure the AP) option is chosen, the form on figure 8 is shown, allowing the admin to fill out the relevant data that will be used to configure the AP (AP tag number, AP location, network socket number, switch port and so on)

Figure 8: AP configuration web form

5. Every 15 minutes the AP sends a file containing its IP and MAC to the configuration host. Both the client and server were built using nc (netcat).
6. The server uses this information to copy the configuration file from the AP using SCP. This two step process was used to prevent spoofing attacks.
7. Using the data in the configuration file, the server generates a script for each AP and stores these scripts in a folder called "APs ready." The server could execute the script and configure the AP, but as an added security measure an admin has to review the script.
8. The admin executes the script which configures the AP, and adds the AP to the controller and monitoring system.
9. The last step is to update the AP to the current version, and restart it so it can be used.

4. Conclusion and Future Work

In the last year, SCIFI has grown and evolved due to the experiences of running a growing operational wireless networks that serves one of the largest Universities in Brazil. There is a constant feedback from the problems found on the field and the development of the software and the new network architectures that are being deployed to be able to cope with the growing active user base.

Monitoring has become fulcral to the development of SCIFI. Early choices, like MRTG, have fallen short because the amount of resources that it uses as the network grows. As moving away from this has becoming necessary, there is a central question of which tool to use, how much should be developed in-house and how to leverage development made elsewhere. As SCIFI is environment-aware, it seems logical that monitoring should become more intermeshed with its fabric, instead of being an external add-on. On the other hand, using time-proven tools shorten the development cycle and allow rapid deployment with tested code.

We are looking specially at two tools: NetDOT and Zabbix. NetDOT can help with documentation and automatic generation of NAGIOS configuration. The Zabbix model of agents can be used to lessen the footprint that monitoring has on the APs, network and monitoring server. Active monitoring is also being deployed, so the underlying network and the authorization infrastructure can be monitored, and problems reported.

Finally, as the network continues to grow it may be necessary to segment the control VLAN. We think we still have a road to cover before we get to that, but we expect to have a solution that allows this segmentation be as smooth as the first, with no service interruption and low configuration overhead.

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Michael Stanton is Director of Research and Development at RNP. After a PhD in mathematics at Cambridge University in 1971, he has taught at several universities in Brazil, since 1994 as professor of computer networking at the Universidade Federal Fluminense (UFF) in Niterói, Rio de Janeiro state. Between 1986 and 2003, he helped to kick-start research and education networking in Brazil, including the setting-up and running of both a regional network in Rio de Janeiro state (Rede-Rio) and RNP. He returned to RNP in 2001, with responsibility for R&D and RNP involvement in new networking and large-scale collaboration projects.