# The RUCA Project and Digital Inclusion


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***Abstract* - The XO (OLPC's "one hundred dollar laptop") is under evaluation by the Brazilian Government as a possible educational tool and also as a means of promoting digital inclusion. The laptops would be distributed to school children to use during classes and to take home. The RUCA Project was created to validate the network capabilities of the XOs. In this paper we focus on one particular aspect of these tests, namely the feasibility of the XO as a digital inclusion aid device. The premise to be tested is the following. If children take their laptops home would they be able to communicate to each other and with the school? Will the novel 802.11s implementation (the first implementation of the IEEE draft) be successful in forming a mesh network to interconnect children in a low cost, infra-structure free environment? Will its performance suffice? Here, we present some answers that indicate that although further testing is still required, the results are encouraging.**



***Keywords-component*; Measurement, Wireless mesh networks, IEEE 802.11s, digital inclusion, OLPC's XO.**


## I. INTRODUCTION

Mesh networks are a good low-cost solution for distributing network access to areas with poor infra-structure. UFF's Midiacom Lab is involved in two different mesh projects: the ReMesh project, which has installed a pilot mesh network around UFF's Engineering Campus to provide free Internet access to students that live around it, and is being tested by the Ministry of Planning to be used as a means for distributing access in small towns, and the RUCA project, which is testing the mesh network implementation of the OLPC's XO laptop in two different scenarios: inside the classroom and distributed across town, for when the students leave school and go home. In the second scenario, the XO laptop can be used as a means for digital inclusion not only for the students, but for their entire family.

The two mesh networks use very different approaches. ReMesh uses a classical level 3 mesh, based on the Linksys WRT54G hardware and the OpenWRT [2] operating system, with local improvements on the metric used by the OLSR [7] protocol. ReMesh approach will be presented briefly in section 2, along with related work in mesh networks. The RUCA Project will be introduced in section 3.

The XO mesh network is a level 2 implementation based on the IEEE 802.11s draft. The highlights of the current IEEE 802.11s draft and the particular details of the OLPC´s implementation of the draft will be presented in section 4.

The RUCA project conducted extensive tests on the XO network features. Although the XO is a beta hardware with alpha software, the main results for digital inclusion, namely the maximum distance in which two laptops can still communicate and the performance of the network in a sparse scenario, where communication will transverse multiple hops, are presented in section 5.

This paper ends with the discussion of what tests are planned, in section 6, and with the conclusions that can be inferred on the performance of the XO laptop, and the feasibility of using mesh networks for digital inclusion, in section 7.

## II. THE REMESH PROJECT

The ReMesh project bases its architecture on the OpenWRT linux distribution. It is composed of routers placed on top of buildings in weather-proof boxes with high gain antennas, a Power-over-Ethernet solution and a captive portal (WiFiDog [20]) for authorization. Clients can connect to the mesh via wires (as the signal usually is not strong enough in the vertical axis to be useful more than two floors below the mesh router) or wirelessly. A picture of ReMesh architecture can be seen in Figure 1.

An improvement made by ReMesh was a new metric for OLSR, the minimum loss (ML) metric, which uses as the metric value the product of the link quality instead of the sum used by OLSR-ETX [21].

The project also developed management tools that allow real-time visualization of wireless link quality. The tools help troubleshooting the network by pinpoint problems on the wireless links and help network maintenance. Figure 2 shows an example of the network topology that was active while this paper was being written.

The project offers free Internet access to students that live around the Engineering Campus, and it is being expanded towards other campi to increase the number of students served.

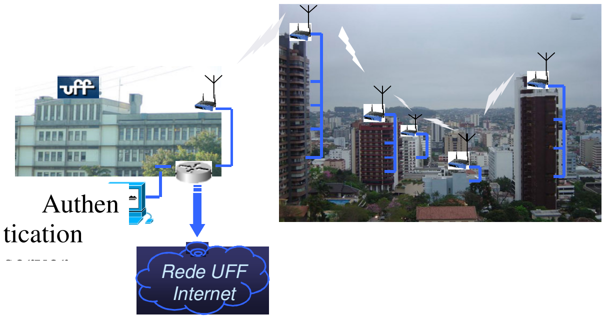


**Figure 1 - Remesh Architecture**

At the same time, as the pilot has been tested, and the project comes into full production, there is a discussion on which models an be used to make the network self-sustaining, the cost of Internet interconnection being covered by the University.

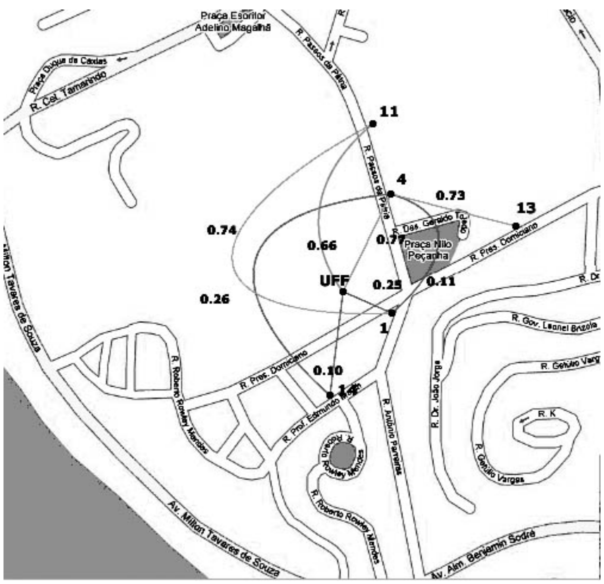


**Figure 2 - UFF`s ReMesh Network Topology**

## III. THE RUCA PROJECT

The RUCA project is funded by the Brazilian Government and administered by RNP (Rede Nacional de Pesquisa). It encompasses five Universities in Brazil and its main goal is to test the OLPC XO's network capabilities. In the first phase of the project many test routines were designed and performed by the Midiacom Labs, at Universidade Federal Fluminense (UFF). The project is now entering phase two where the validation tests will be repeated by each one of the five Universities. This paper focus on the design phase and also on these first tests performed at UFF.

The tests were designed to evaluate a series of isolated aspects of XO network performance to generate a set of results that when analyzed in conjunction, would help decision-makers in the Brazilian Government in their task of deciding whether XOs are to be implemented in Brazilian public school system.

This decision process obviously involves more than the networking capabilities of the laptops. There are, for instance, many educational implications, and discussions on the propriety of using public funds for that purpose, just to name a few. But these and other important topics are being discussed on other forums by other institutions and Government Agencies. They are outside the scope of the RUCA project which focus is to validate the following premises:

(1) XOs must work in the dense environment of a school, where hundreds of XOs will be spread over a building and dozens of them will be packed inside a relatively small indoor environment – the classroom. And all of this must work with inexpensive infra-structure (costumer grade access points);

(2) That children will take their XO home and once distributed on a community they will easily form a mesh network with its neighbors. This may also extend Internet connectivity to this community since some of the XOs will be accessing an antenna placed on the top of the school. Those connected nodes will act as Mesh Portal Points and further extend Internet connectivity to other nodes in the mesh cloud, as we will further explain (see Figure 3).

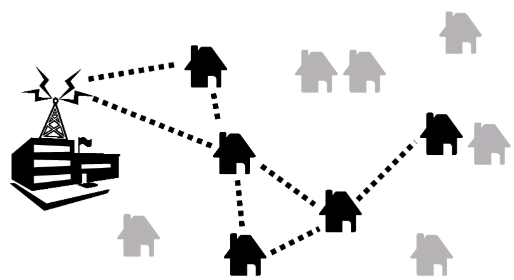

**Figure 3 - mesh connected to school**

In the present paper we are mainly concerned with the second goal and we describe the tests designed to check this capabilities and the results collected so far. In other words, we describe the tests and results trying to answer to the question: Will a working mesh network be established automatically? And will the mesh network be able to connect to Internet?

If we consider the above questions we will easily see that the first capability to test is related to distance. The effectiveness of connecting to another XO and also to reach the school's antenna from home is directly connected to the distance at which XOs are able to communicate with each other and to access points, among other variables such as topology and radio noise.

The distance between the children homes and their school or connected neighbor is clearly unknown. According to INEP [8], in 2001 there were more than 159.000 primary public schools in

Brazil (more than 60% in rural areas) and the population density, topography and radio noise will vary significantly from community to community. That is why the RUCA project should not pursue a universal answer, but instead should be able to provide baseline data which can be used to determine if the mesh network will work in one particular school/community instance. What is the maximum practical distance? How far can a XO be from each other or from the school?

These tests should take into account that, as previously mentioned, it is very likely that no extra infra-structure will be deployed - all that can be counted on are antennas on the top of the school.

The second capability to test is related to multi-hop networking. Many authors [9][10][11] fear that wireless mesh networks throughput could be low due to characteristics of 802.11 MAC layer and also because of the overhead, imposed to each node, of having to forward other nodes` frames. So, the question to answer is “will the XO and its novel 802.11s tier 2 routing effectively and efficiently allow for a mesh network to spread over a community?”

In section 5, we will describe the tests and preliminary results of the project. The RUCA project also simulated the dense environment of a classroom but this data is currently under analysis and will be presented in another opportunity.

## IV. IEEE 802.11S AND OLPC

By the time of this writing the IEEE 802.11 Task Group S is working on the draft version 1.0 of its Extended Service Set Wireless Mesh Network proposal - the future IEEE 802.11s standard. OLPC´s XO is an early adopter of the proposal, the first actually, and follows the 802.11s draft “when possible” [12]. In this section we will highlight some aspects of 802.11s giving special attention to the OLPC’s implementation of the draft.

### *A. 802.11s Architecture*

According to the 802.11s draft, nodes in a mesh network fall into one of the four categories (see Figure 4):

Client or Station (STA) is a node that requests services but does not forward frames, nor participate in path discovery (described bellow)

Mesh Point (MP) is a node that participates in the formation and operations of the mesh.

Mesh Access Point (MAP) is a MP who has an attached access point (AP) to provide services for clients (STA)

Mesh Portal Point (MPP) is a MP with the additional functionality to act as a gateway between the mesh and an external network like the Internet, for instance.

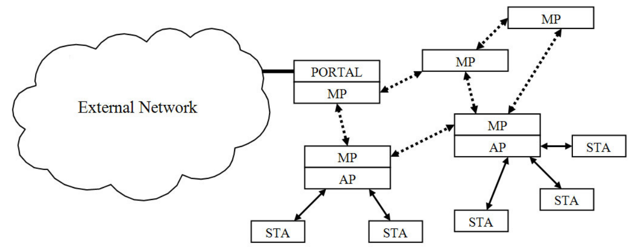


**Figure 4 - mesh network architecture**

XOs have one single radio and so one physical layer (PHY) but the wireless driver implements two interfaces: eth0, the main interface which is used for infrastructure traffic and msh0, for the mesh traffic.

Therefore they can perform as an STA or a MP. They can also perform the MPP role and forward traffic in and out the mesh. There are two methods of turning an XO into a MPP. The first is to connect the XO to the wired infrastructure using an external usb-ethernet adapter and forward the traffic between the wireless mesh and the wired network. The second method uses scripts [13] that take advantage of the virtual interface schema, associating eth0 to an access point and forwarding traffic between msh0 and eth0. In this case, both interfaces should operate on the same channel as there is actually a single PHY in use. Presently, both options – the adapter or the MPP scripts, will need extra software and configuration.

One last issue concerning MPPs is that stations should be able to find them and to choose between them if there is more than one. On section 4.3 (Routing) we will briefly describe OLPC´s solution to this.

### *B. XO radio subsystem design*

The XO’s radio subsystem is composed by a Marvell 88W8388 chip, an onboard ARM 9 processor (plus ROM and RAM) and an 802.11b/g interface. Its two rotating bunny ear antennas provide diversity and are quite effective if compared to the usual concealed commercial laptop antennas.

The radio system is connected to the main cpu (an AMD Geode processor) by a Universal Serial Bus. This brings important implications to throughput, since all the IP traffic will be transferred through the USB, from the cpu to the radio and vice versa. Because of this architecture, the maximum throughput we could register in out tests, was 13,9Mpbs, using the iperf tool [15] to generate an UDP flow. On the other hand, this allows for operation of the mesh even with the main processor in sleep mode.

### *C. Routing*

Currently, 802.11s’ mandatory routing protocol is the Hybrid Wireless Mesh Protocol, or HWMP [16], which uses elements of Ad hoc On-Demand Distance Vector (AODV [14]), and also concepts of tree-based routing. The draft also allows the use of the RA-OLSR, which is based on OLSR [7].

AODV is an IP routing protocol, which exchanges routing messages via UDP datagrams. In contrast, HWMP is a layer two protocol. As we will demonstrate next, the choice of layer two for the mesh implementation brings some advantages.

Because of the laptop architecture (described in B), all the layer two processing is handled by the radio subsystem, relaying only the TCP/IP processing to the main CPU - an AMD Geode LX-700. The main CPU and the radio are connected via Universal Serial Bus, which imposes a limit in performance, not because of USB's speed, which is quite adequate, but because of constraints on the subsystem that manages USB.

One of the design goals of the XO is enabling a node to forward frames and routing information even when the main processor is turned off. And this is possible not only because the radio and layer two processing is detached from the main CPU but also because the layer two network subsystem needs no more than 0.5 watts to operate. This way another important premise – low power consumption – is not violated.

The OLPC mesh implementation is based on version 0.1 of the 802.11s draft and its routing protocol is a simplified version of the HWMP. Currently, XOs implement only on-demand route discovery and no proactive routing mechanism, i.e. no tree-based routing.

The path selection mechanism is also based on HWMP. When a XO (A) needs to discover a path to another XO (Z) it broadcasts a Route Request Mesh Management Frame (RREQ). Upon receiving this frame intermediary nodes will further broadcast it until it eventually reaches Z which will in turn respond with a Route Reply Mesh Management Frame (RREP).

Each node who broadcasted the original RREQ has learned the "reverse route" to A and this reverse path will be used to route the RREP up the chain via unicast transmissions. Also, when forwarding the RREP back to A, intermediary nodes will learn a "forward route" to Z and the cycle is complete.

Forward routes are used to send data frames from A to Z, while the reverse path is used only for mesh management. When Z needs to send A some data, it starts another path discovery cycle. One obvious consequence is that forward paths from A to Z and from Z to A may be different.

Another fact to be noticed is that broadcasted frames are not acknowledged in 802.11. So, lost RREQs will not be retransmitted. In order to improve robustness of the schema, and also as a means of metrics establishment, XOs send out many copies of the RREPs. They do so by varying the transmission rate and associating different metrics to each one of the RREQs. For requests broadcasted in 54Mbps, for instance, the metric will be lower (better) than the consecutive try, in 36 Mbps, and so on.

Frames transmitted at lower rates have higher probability to succeed but their associated metric is higher (worse). If a choice exists, the protocol tends to select the higher throughput path. However, the choice for higher performance links must take the number of hops into account. In terms of airtime, energy savings and aggregated cpu cycles, one slow hop can be more effective than many fast hops. We are yet to know if the OLPC developers will find a good compromise between link rates and number of hops.

Route Error Frames (RERR) are used to indicate that a frame could not be delivered to the next hop thus enabling predecessors on the path to mark the route as lost. Also, because routing information is supposed to be soft state, the XOs will periodically "forget" the route and restart the path discovery cycle. At present this refresh time is set to 10 seconds and presents another protocol tuning point to be investigated.

Another difference from OLPC´s routing protocol and HWMP comes from the fact that RREQ/RREP is the only mechanism a XO uses to find its neighbors. XOs do not probe actively or passively for neighbors as prescribed in HWMP.

The RREQ/RREP mechanism is also used to discover and select a Mesh Portal Point. Whenever a station wants to find a MPP – for instance, if it has internet traffic to send – it sends an RREQ to a special address (C0:27:C0:27:C0:27). Each Mesh Portal Point present will answer to that request (sending a RREP). If the STA receives more than one answer, it will select the MPP with the lower cost path.

## V. RUCA TESTS AND RESULTS

In the following subsections will be describing the procedures and the respective results for each of the two capability tests previously mentioned, namely (1) the results for the distance tests which are concerned with the communications between the involved nodes (XOs and AP) and (2) sparse mode tests which were designed to test the performance of multihop forwarding. But before we dive into the details we will briefly mention some challenges this category of tests impose as this might be useful information for other institutions wishing to perform similar tests.

### *A. Challenges*

Measurement tests are difficult to perform when compared to simulations. In a simulation, after the programming is finished, changing the scenario is a question of altering some parameters on a script file, and simulations run under the same parameters will give the same results. In real tests the research team must deal with many practical issues and must try to control the environment, which is a difficult task if you are testing radio devices in real scenarios, i.e. outside anechoic chambers or special projected shielded containers. What follows is a short list of specific challenges the RUCA project had to cope with, beside the inherent difficulties of radio testing:

*Alpha software* – XO's are running alpha software. Although the progress in each successive version is noticeable, OLPC was tuning or even building some of the functionalities as the RUCA project progressed. In terms of software there are three components that have to be kept up to date during the tests. The first is the flash image containing the customized Linux kernel; the minimized version of Fedora Core 6 Linux distribution; and all of the companion software, including kernel drivers to the XO devices. The second part consists of the firmware to the main board, and the third is the Libertas firmware responsible for controlling the Marvell radio subsystem.

During the tests there were ate least five updates to each of those pieces of software. Although all of the three would affect the operation of the tests, the most important of them in relation to the RUCA project was the Libertas firmware. Because, in short, whenever a new version of the firmware was released the behavior of the radio would be tuned or improved and the tests had to be repeated.

During the tests some issues had to be addressed by the OLPC team. Iperf hanged during TCP tests and some access points would not work properly in the presence of the XO mesh frames. These and other minor issues were usually solved simply by updating the firmware some days later and regression bugs were not absent nor abundant.

*Beta hardware* - Hardware issues were also of some significance for the tests, particularly those who affected the battery cycle and charging. First versions of the main board firmware would not properly charge the five-cell NiMH battery. Fortunately car batteries could be employed to power the XOs during long field tests. Other hardware problems included intermittent keyboard malfunction and also radio interfaces that would not initialize after a reboot, though the last one was rare. Some of those seemingly hardware issues are actually software issues and also tended to be addressed as new releases came by.

The RUCA project equipment includes 10 B1 XOs and 14 A-test motherboards. The motherboards' radios are not shielded and using them on tests had to be done with special attention since they would radiate and capture more noise than the XOs.

*Test beds* – As we will detail further in this article, test beds are not easy to find. Especially if close to ideal sites are to be found in order to establish the best possible results. Distance benchmarking tests are not easy to perform if you have obstructions or competing wireless networks on the site.

*Difficulties inherent to Radio* – Radio measurements are hard to take. Radio conditions change during the test because of the unpredictability of the interference sources. Particularly in a non-regulated band as the 2.4GHz ISM, where other sources can not be controlled.

Other effects such as multi-path losses and fine antenna positioning are also hard to track and radio ranges (interference and transmission) are almost impossible to determine in tests that take a long time. Thus, because of these varying conditions radio measurements must be repeated many times, which is not easy in the limited time available during field tests.

*Schedule constraints* – Because of schedule constraints the tests had to be planned, designed and also performed in a short period of time. This leaves no margin to errors and errors are inevitable if you do not have time to plan ahead. As there was no time to develop custom testing tools, third party software – like iperf - had to be employed – and they showed less then ideal to the Project goals. As tests were performed, better ways to make the measures were learned and the tests were redesigned.

### *B. Distance tests*

In this subsection we describe the tests performed to determine how distant can two XOs be in order to communicate (scenario A) and also how distant can a XO be from an access point to associate and effectively communicate (scenario B). Scenario A will provide important information regarding the practicalities of forming a mesh network in a community, while scenario B will provide validation for the idea of reaching the school network from a child's house.

As distance grows we expect degradation in performance due to Signal-to-Noise Ratio (SNR) degradation. If no strong and variable source of noise is present (a pre-requisite of the testbed), then the main cause of the degradations would be the weakening of the transmitted signal.

Path loss is a measure of the weakening of the radio signal due to propagation losses. It accounts for the effects such as absorption, refraction, diffraction, reflection and also for free-space loss. However, as path loss is strongly influenced by the environment (vegetation, terrain roughness, air temperature and moisture, etc) it is almost impossible to calculate precisely.

One major component of path loss is free space loss which measures the power loss of a radio signal as it travels from the transmitter to the receiver in "open space". An easy formula to calculate free space loss for the frequency 2.437 GHz (channel 6) is the following:

```
FSL = 20log(d) + 40
```

Where *d* is the distance in meters, and *FSL* is the free space loss, in decibels.

In order to account for the other components of the path loss – which together we will refer as attenuation – one simple approach would be to add an index *n*, as follows:

```
PL = n*10log(d) + 40
```

In outdoor environments, the *n* index, called loss exponent, will typically vary between 2 (for free space loss) and 4. So, for a 500 meters link, path loss (PL) would vary between 94 and 148 dB, for a loss exponent equals to 2 and 4, respectively.

With an estimative for path loss, we could perform link budget calculations and infer the feasibility of the radio link. For the link to be feasible the signal power at the receiver must be larger than the radio sensitivity. The following simplified formula expresses this condition:

```
ERP – PL > RS
```

Here, ERP stands for effective radiated power. This should consider not only the radio transmission power but also cable and connector losses, the harmful effect of the standing wave ratio (SWR) and also add the antenna gain.

The formula states that the effective radiated power subtracted by the path loss must be grater than the radio sensitivity where the latter is the minimum power the receiver needs to fully recover the signal. Of course, we should also take into account antenna gain at the receiver and attenuation due to cable and connectors. For the sake of simplicity, we consider this part of the radio sensitivity component.

For the XO the best number we have available are 17dbm for the ERP and -85dbm for RS. This means that for test scenario A, we should have no more than 102dB of path loss for the link to work. The best (least) path loss possible would equal the free space loss. The distance where free space loss equals 102 dB would, hence, be the maximum distance we could get on a test under ideal conditions. This distance is 1.26 Km.

The platforms used on the distance tests are 1.20 meters height. This is high enough to achieve 1.26 Km with an obstruction of the Fresnel Zone of 38%. The Fresnel Zone (Figure 5) is an imaginary region surrounding the line-of-sight path between the transmitting and the receiving antennas and its shape is an ellipsoid of revolution. It is a well know rule of thumb for microwave radio links that obstructions to the Fresnel Zone must be kept bellow 40% for the link to work.

In practice many links will stop working with less than 40% obstruction, because path loss will be too high, but a link will hardly work after this limit. The height of the cart built for the tests is sufficient not to reach the 40% limit if the tests are performed in distances shorter than 1,7 Km. This is almost 500 meters more than the limiting distance previously determined in our link budget calculations.

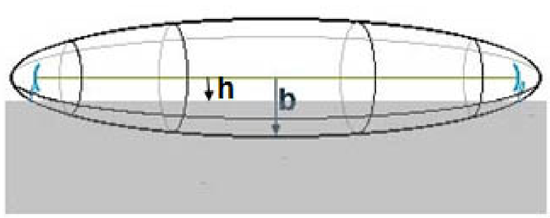


**Figure 5 - Fresnel zone partially obstructed (if *h* is smaller then *b* there is obstruction)**

We clearly could not expect distances that long, because there will be some amount of attenuation to consider in the real test site. But this does not mean that the height of the platform would not matter. Actually we could get pings at 750 meters distance, just by raising the XOs 2.70 meters above the ground. This is 200 meters more than we could obtain at the height of 1.20 meters.

Higher platforms would result in longer distances, but it would be difficult to operate the XOs if they were placed, for instance, at 1.50 meters from the ground, and it is improbable that XOs will be operated at this heights. Actually a table is typically 0.7 meters high and a windowsill is about one meter high.

Our goal was to get as near as possible to the best possible performance but using real measures instead of simulations. Although useful, simulations fail to capture the complexities of real deployment, especially if you are trying to test particular equipment, where the project and manufacturing process may pose performance limitations a model will not capture.

For these tests codification rate was fixed at 2 Mbps because higher rates would mean shorter ranges, and automatic rate adaptation would add one more variable to the tests (and retrain could happen during the measurement). Informal reports [17] and previous tests performed [1] showed that XOs would effectively communicate at distances of 300 to 500 meters, which also rule out higher rates. Last, 2 Mbps, or even a fraction of this rate is enough to provide most of the network services a user would require considering present applications.

In scenario A two XOs are used, one kept stationary at the base while the other is moved away in fixed steps. For scenario B, the same procedure is used, only the node in the base was a Linksys WRT54G Access Point instead of an XO. To test range, the two mobile XOs (scenarios A and B) were moved away from the base in fixed steps. At each stop the test scripts were executed.

A good test site must be flat, free of obstruction and as free of radio noise as possible. As previous calculations showed, the test bed also has to be long – about one kilometer or more. It comes out that this site is hard to find and while the team could not find such a place, preliminary tests were performed in less than ideal places.

These preliminary tests were an important opportunity to validate the test design itself. They allowed us to determine, for instance, if the equipment were appropriate and if the test scripts were correct and efficient. This is a short list of things we validated in the preliminary tests.

*Test the power sources.* In long field tests batteries would run off and extra power was needed. XOs are able to take DC input ranging from 5 volts to 25 volts to charge its 5-cell NiMH. So, car batteries, providing 12.6 volts, could be successfully employed. Proper cabling and adapters were built to connect the XOs to the batteries.

*Test scripts.* Shell scripts were built in order to configure the stations, run the commands and log the results. We needed to debug the scripts and check if they were flexible and practical enough.

*Test the measurements*. We needed to determine if the results generated by the scripts were meaningful. For instance, we needed to check if the parameters for the iperf tool were properly selected.

*Logistics*. Many practical measures, including crew transportation, shelter for the equipment, shade and radio equipment to allow easy communication between the team members.

*Team members training*. We needed to train our team members to perform the tests efficiently, within a short period of time and with a low occurrence of errors. If tests can be performed quickly, they can be repeated more often, and result in more data acquired.

*Test 802.11 monitoring*. Auxiliary laptops were used to monitor radio noise and 802.11 activity on the site. We used Wi-spy 2.4GHz ISM spectrum analyzer to monitor noise levels and the Netstumbler tool [18] to identify nearby wifi networks. To take iperf measures in scenario B, there was also a laptop cable-connected to the lan interface of the access point, running an iperf server. Unlike XOs, regular laptop displays are not legible outdoors and their batteries do not last as long.

*Test the gear and methodology*. We built a mobile platform to transport the XOs, car batteries and auxiliary laptops. We wanted to test the cart, other equipment and procedures, from the methods to mark the distance on the ground to the backing up of the test logs.

Two preliminary tests were performed in order to check the above items. The first preliminary tests are described in [1]. Some days after the second preliminary test, the first distance test was performed. The site location was an Air Force Base in Santa Cruz, Rio de Janeiro. The radio noise was low and the physical conditions were very good. We used a 2 km auxiliary taxiway, a test bed flat and free of obstruction.

The test results to the Santa Cruz tests are presented next along with some analysis of the data. The following measures were collected using iperf and ping. Each point represents a mean of two different set of measurements. Because of the limited number of measures and also because of the nature of radio tests some unexpected fluctuations were registered but the graphs show clear tendencies and the results are consistent with those of preliminary tests.

Figure 6 shows the mean results for iperf test executed under scenario A. An UDP flow of 1400 byte packets was generated at the rate of 2 Mbps.The graph shows good performance to the distance of 400 meters. At 450 meters we have about 20% packet loss and throughput drops to 220 kbps which is actually not a bad number in absolute terms but it represents only about 10% of the maximum throughput.

It is worth noting that in a wireless link, when applications like iperf, experiment 20% loss this actually indicates severe degradation of link quality, since 802.11 devices automatically retransmit unacknowledged data frames.

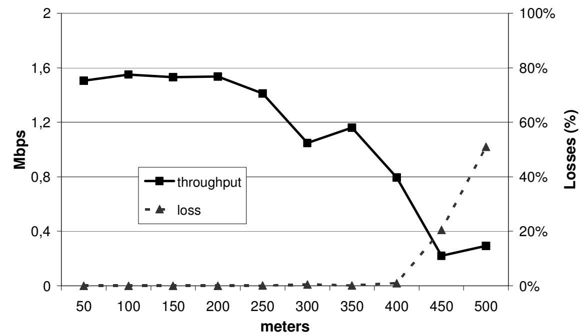


**Figure 6 - Throughput and losses given distance for scenario A**

Figure 7 represents the loss measures taken with ping and confirms iperf-udp results – insignificant losses to 400 meters.

For scenario B we have the following results. The link between XO and Linksys Access Point showed no more than 0,2% of losses on iperf udp tests. But after 350 meters the XO could not associate to the Access Point. For measures at 400 and 450 meters an external omni-directional antenna was attached to the AP, extending the range to 450 meters. The results are displayed in Figure 8.

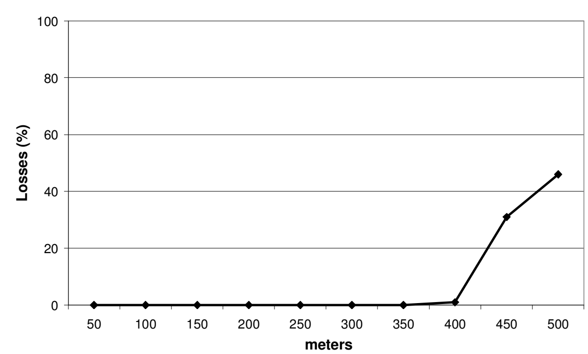


**Figure 7 - Packet loss given distance for scenario A**

At 500 meters, though, associating to the access point was not possible even with an external antenna. But it must be noted that the diagram of radiation of the omni-directional was unknown and we can not guarantee it was properly aligned. We believe that better results can be achieved by repositioning the antenna or using an antenna with a more forgiving radiation pattern (which would have lower gain).

Quick calculation would point out that if antenna gain was of 12dB considering losses on the cable, that would represent extending the distance to about 1km.

Although iperf did not register significant losses for the B scenario, ping tests revealed different results Figure 9 shows the loss

There is a consistent behavior in scenarios A and B. In both the 40% loss rate matches the maximum distance the tests could be performed.

Also, the tests indicate that in terms of distance XOs perform better when talking to each other than when associated to an Access Point. The same is not true when throughput is considered, tough. But these results still have to be validated by future tests, performed by UFF or by another university during the RUCA project.

*C. Sparse mode tests*

In most Brazilian communities children live close to their schools. Thus it is logical to envision a scenario where the children could take their laptops home and get internet access through an external antenna installed on the top of the school. This way, not only the child would get benefits, but also his/her family. One of the achievements of the aforementioned GT-Mesh [6] was to demonstrate that an antenna on the roof of a building, with an access point inside a weather resistant case, proper cabling and power-over-Ethernet costs less than five hundred Dollars in consumer grade equipment.

However, connectivity would be limited to few children if the only source of network connectivity were a direct link between the school access point and their laptops. A further and necessary step into digital inclusion would be the possibility of children who live farther from the school to get network access too. This is the point were mesh networks and digital inclusion meet. The child whose home is out of reach from the school access point can connect to the school (and to the world) through another child's laptop, if the latter is in contact with the school infrastructure or to another laptop which is connected to the infrastructure, recursively. Mesh network provides an easy and inexpensive way to provide connectivity, being a means to "cover" wider areas than a traditional BSS approach would alow.

The 802.16 "wimax" technology has been considered as an alternative to achieve higher distances. But it implies higher costs compared to 802.11. Not only chipsets are currently more expensive then wi-fi chipsets, its base station are one order of magnitude more expensive than the GT-Mesh roof kit, or any other based on 802.11. There is also the issue of licensing the spectrum which is not yet addressed in Brazil and even more important, 802.16 may improve distance, (particularly if premium bands are employed, like 700 MHz band, for instance) but not user density.

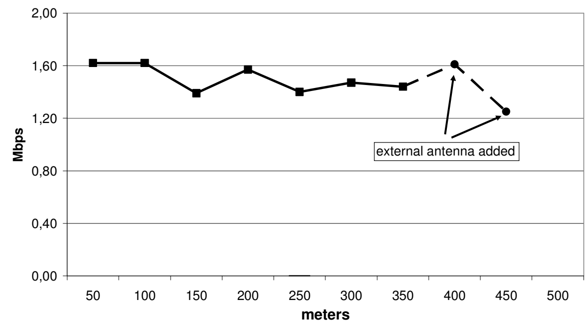


**Figure 8 - Throughput given distance for scenario B**

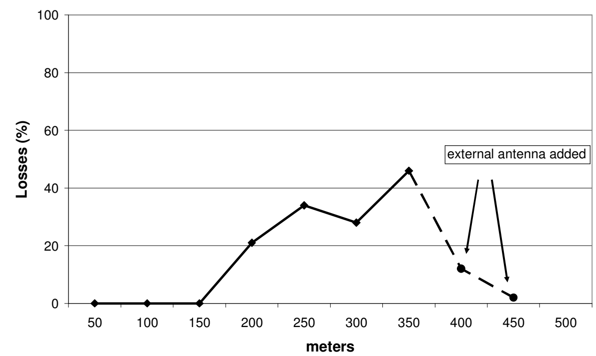


**Figure 9 – Packet Loss given distance for scenario B**

The distance tests, previously described, demonstrated that two laptops can effectively communicate at about four hundred meters from each other, and that this distance can be extended a few hundred meters more with the use of an external antenna.

At such distances, tough, any obstruction can disrupt communication, so distances between the nodes inside the houses would have to be shorter than that. Midiacom is conducting experiments in many different environments in order to determine how close houses must be, considering various conditions, such as the materials houses are build, the terrain and the weather conditions (more on these futures tests in section 6).

The first aspect studied in order to check the feasibility of this mesh model is the performance of the OLPC's 802.11s implementation in a multihop scenario. What follows is the description of these tests and the respective results.

The first test in this set was designed to measure the throughput degradation of a multi-hop chain of XOs. The main goal is to determine if communication will be possible after a long chain of hops. In this case, this number is nine hops, since we had ten XOs available.

In the present paper we have not defined what a useful link is. First, because there is not a canonical mix of applications to analyze what are the required network characteristics - the latency, throughput and admissible jitter is enormously different if we analyze file transfer, audio or video streaming, chat or internet browsing, for instance.

The second reason preventing the definition of what a useful link is comes from the digital inclusion premise of the project. Some bits per second are better than no bits per second at all. In other words, broadband is not a requirement. In fact, a 40Kbps link is equivalent to a dial up Internet connection, which is more than poor families in Brazil can afford because of the high price of the monthly fee to maintain service (in fact poor people in Brazil have to resort to high price per minute pre-paid cell phones).

Below we show the results of throughputs for UDP flows generated with iperf for an SCP File transfers. The latter simulates what a user would experience in an application running over TCP.

For this purpose XOs were put in a chain-like configuration where nodes could only communicate with their immediate left and right neighbors (nodes at the end of the chain had only one neighbor). As will be describe below, the blinding table mechanism was employed to force multihops in our test scenarios.

Two scenarios were implemented. In the first, ten XOs (A to J) were placed side by side, inside the lab. In the second scenario, five XOs (A to E) were distributed on the five floors of the School of Engineering.

OLPC´s XO is the first device to implement IEEE 802.11s, which is still in draft. One of the features it incorporates is the capacity of forwarding traffic on the link layer. Because of this feature, the intermediary hops, when operating in mesh mode, are able to forward frames automatically, without any special configuration or additional software.

In the first test bed, 10 XOs were placed in a row, 15 centimeters apart from each other. This scenario presents some advantages and some drawbacks in terms of network performance. All of the nodes are close enough so that the hidden node problem is negligible. However, this is a high contention environment as each of the ten nodes is trying to transmit simultaneously and all of them interfere with each other.

As the idea is to force frames through the intermediary hops (from A to B to C …) we should take some precautions to prevent frames of being delivered directly (from A to E, or from A to C, for example). This can be achieved through the blinding table.

The blinding table (BT) can be used to control which other nodes an XO can "see". It operates in two modes, "black list" or "white list". In the first we inform which nodes should be ignored. This means that frames coming from that node will be discarded. In the white list mode, the blinding table consists of a list of valid MAC addresses - frames coming from other source addresses will be ignored.

Through the use of BT entries we can assure that the XOs participating in the test will follow the multi-hop path as planned, i.e. frames will not be delivered to XOs that are not immediate neighbors, even if they are within the radio coverage area.

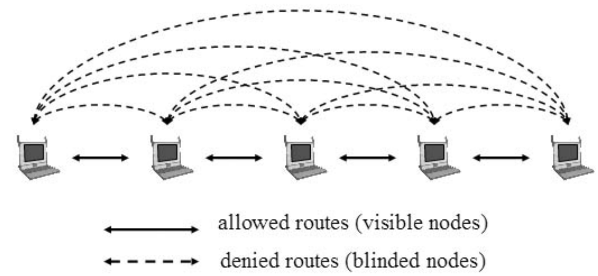


**Figure 10 - A chain of XOs and the Blinding Table**

For the first test bed, Figure 11 shows the results where an UDP flow was generated with iperf. Considering 13,9 Mbits/s as the maximum possible rate, we can see that after 4 hops the rate measured was still of about one third of the maximum, and after the fourth hop performance degradation was about 15% per additional node. Thus, the results show that even after 9 hops the rate achieved (2,09 Mbits/s) would be easily considered "broadband connectivity" in any developing country

Figure 12 shows the same results for a file transferred via SCP. One interesting point to note is that throughput was unchanged after 3 hops. This can be explained by the data rate of the intermediary hops being higher than the rate at the source. If nodes can forward frames at a codification rate higher than the source (54 Mbps has been observed on this particular test, compared to the maximum throughput of less than 14Mbps), the result is less contention and high efficiency. Of course this could not be observed if the applications were able to generate higher data rates, but this is not possible because of the USB system bottleneck. Only when the chain has five nodes or more the effects of contention could be observed, but even then, throughput degradation was not dramatic, and after nine hops measured throughput was higher than 1 Mbps.

In the second test scenario, five XOs were placed on each one of the five floors of the School of Engineering at UFF. Thus, each of the XOs was separated by more than four meters and a concrete floor. A blinding table was created again in order to force the traffic to hop on each of the intermediary XOs and the tests were performed from the first to the ground floor, from the second to the ground floor, and so on.

Figure 13 shows the results for a SCP transfer of the same file used in the lab scenario. The test was repeated five times and the graph displays the maximum and the average throughputs (with error bar) registered.

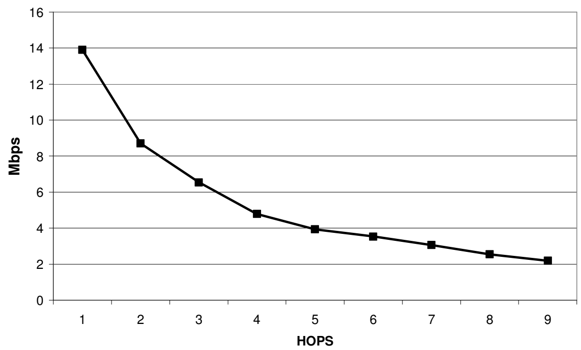


**Figure 11 - Throughput given chain length for UDP**

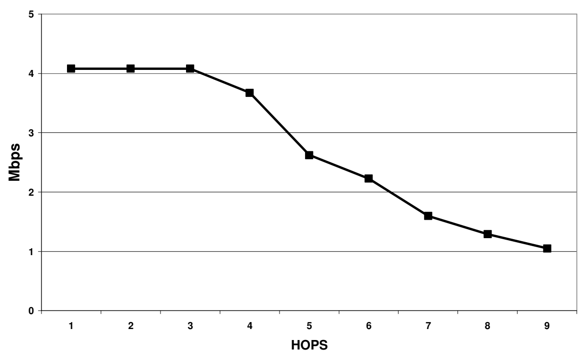


**Figure 12 - Throughput given chain length for SCP**

Similarly, Figure 14 shows the results for the iperf UDP tests. The average throughput for the top floor was 1,32 Mbps and the maximum was 2,09Mbps (43% of the lab result).

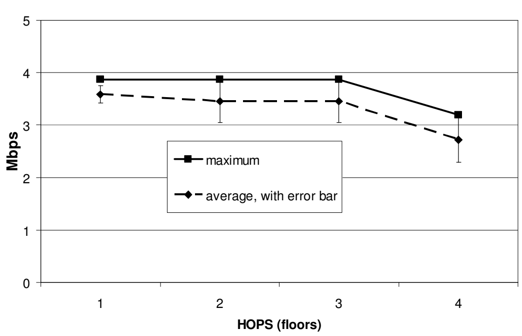


**Figure 13 - Throughput given hops (floors) for SCP**

As Figure 15 and Figure 16 show, the results are quite similar to the ones obtained in the lab test. In the SCP test, again, for the first 3 hops maximum throughput was the same (3,86 Mbps), and it was 95% the results registered in the first scenario.

Comparing the two scenarios (1) inside the lab and (2) the five floors setup; in the second scenario, XOs are subject to a noisier environment and the signal to noise ratio (SNR) is expected to be worse. Also this setup introduces the risk of having collisions caused by the hidden node problem.

If, on the other hand, we could expect less contention than in the previous setup, in practice, there is no reason to believe that we could actually get an advantage from separating the nodes. And that is for two reasons.

First, there is still a lot of contention to consider. In another test we checked that direct communication between the ground and the second floor (2 hops) was still possible, and this indicates that, although the XO on the ground floor was outside the transmission range of the XO on the top floor (four hops away), they were probably still interfering with each other transmissions, i.e. they were inside each other interference range. For this assumption to be true, it is enough to assume that interference range is, at least, the double of the transmission range.

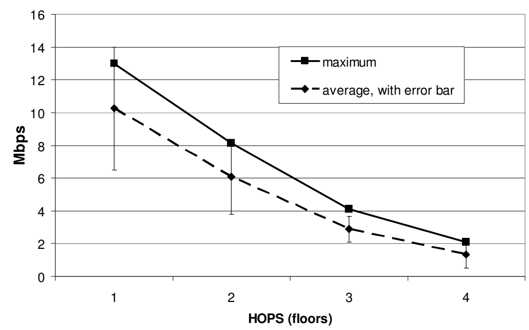


**Figure 14 - Throughput given hops (floors) for UDP**

The second reason comes from the fact that even if you could get parallel transmissions happening down the chain, for instance, a frame being transmitted from the ground to the first floor, at the same time a frame is transmitted from the third to the fourth floor, this would not compensate for the collisions caused by the hidden node problem.

So, because of the similar results in both tests we believe none of those influences (hidden node or less contention) played an important role. In general the throughput decreased, but not much, due to the degradation of SNR caused by the separation of the nodes.

## VI. FUTURE WORK

The Midiacom Lab had less than four months to perform the tests we just described. That included planning and designing the tests, training the team to perform then, performing them and analyzing the results. On April 20$^{th}$, the 10 B-1 XOs and 14 A-Test motherboards were shipped to the Federal University of

Paraíba and tests at UFF had to stop. Fortunately, OLPC has donated 20 B2-XOs to Midiacom. The laptops are currently waiting for bureaucratic procedures on Brazilian Customs. In the present section we will introduce some of the future tests to be initiated as soon as the B2 XOs arrive to our lab.

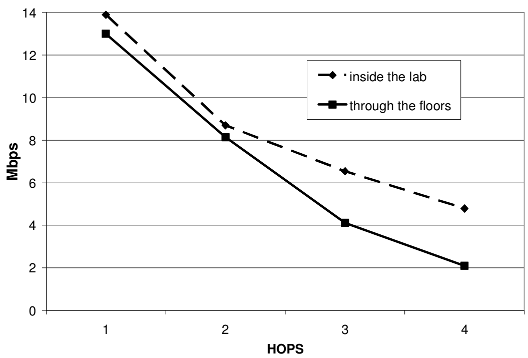


**Figure 15 - Comparison (inside the lab vs. five floors) for UDP**

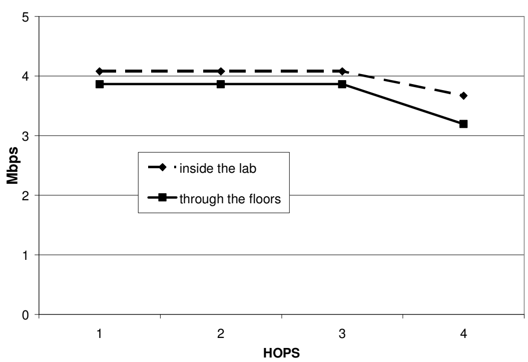


**Figure 16 - Comparison (inside the lab vs. five floors) for SCP**

First, further tests with external antennas must be performed. Antennas can be engineered to achieve the best performance in a given situation. The generic antennas used on the tests had unknown radiation patterns and added no more than a hundred meters to the effective communication range.

It will not be possible to customize every antenna to be installed on the schools around Brazil, but the RUCA project can recommend one particular antenna design that would be used if no customization is possible. High gain antennas reach distant places but at the cost of a more limited coverage. In an optimized installation, the main lobe in the radiation pattern should be pointing to children's neighborhood. The fact that directivity considerations also apply to omni-directional antennas are many times neglected.

Although the outdoor tests performed can provide us with a measure of maximum distance XOs could achieve, results in real world scenario are expected to be worse, particularly if an XO is placed inside a house and connects to another XO inside a neighbor´s house. This is because we are not dealing with the outdoor situation, where the signal faces less obstruction, nor the indoor situation, where the signal is reflected by the walls before reaching its destination. This is an indoor/outdoor/indoor scenario, which presents disadvantages of both indoor (obstruction) and outdoor (dispersion) scenarios.

Preliminary tests in a low radio noise neighborhood where houses are made of brick and mortar, with considerable foliage between them, show that communication is still possible if the houses are less than 20 meters apart. Some of these results are discussed in the next section.

During the tests it was clear that we could perform better with a customized testing tool. Most of our throughput measures were taken with iperf and although its use as a network performance measurement tool is widespread, iperf was not designed for wireless network tests. By the time of this writing we just finished writing new performance measurement programs suitable for wireless links and the first results will be available soon.

As we mentioned before, dense mode tests were designed to simulate a school classroom where many XOs are placed inside a room and associated with an Access Point. Those tests were performed with 10 XOs and 10 motherboards. Although some results are presently being studied, we plan to repeat the tests with 20 B2 XOs and experiment with different access points.

Part of the RUCA team visited the school Luciana de Abreu in Porto Alegre. This is the first school where children are actually using the laptops during class and the best place for the dense mode tests to be performed. The school principal is also making arrangements to install an omni-directional antenna in one building close to the school, so in the near future connectivity can be extended to children who live nearby.

Moreover, we are also studying fairness - the effects of competition between the XOs in infrastructure and mesh modes. Also, we are planning routing tests to be performed when the 20 B2 XOs get to our lab. Since we have already determined the efficiency of a multihop chain, we want to determine the efficiency of the metrics for path discovery and also the refresh times used in RREQ/RREP cycles.

XOs will be compared to commercial laptops and also with commercial mesh equipment. And, finally, Midiacom contacted Intel and Encore and offered to repeat the same tests with their equipment (Mobilis and Classmate), although none of them currently implement a wireless mesh network and only a subset of the tests could be performed on this equipment.

## VII. CONCLUSIONS

The tests performed so far showed positive results. That XOs could perform well in distance tests and multihop tests seem to indicate that the degradation in performance did not occur. XOs were able to communicate flawlessly at distances over 400 meters. And multihop tests showed that after 9 hops, the throughput of a file transfer was greater than 1Mbps inside the lab and 2Mbps could be achieved on the same file transfer in an indoor four hops scenario, where each node was placed in a different floor.

The hardware, software and firmware are evolving at a rapid pace. Early adoption of the 802.11s draft brings in additional challenges to the project, since it is an unknown terrain. But the features introduced by the mesh implementation are particularly important to the project goals.

However, we should note that XOs performed well but it is still an 802.11g/b device and must deal with some technical constraints. First there is the frequency issue. The use of unlicensed band brings obvious advantages but also one disadvantage: interference is almost inevitable. But in remote areas and developing regions this will probably not be an issue for some years.

The main disadvantage of the 2.4GHz ISM band when compared to “premium” bands, under 1GHz, comes from the propagating characteristics of microwares. At 2.4 GHz frequencies line of sight is very important. Penetration is limited and signal is not expected to pass through many walls or dense foliage.

Although flawless packet transfers at over 400 m (as reported by other sources) have been observed, these are outdoor results. As we previously underlined, when XOs are put inside children houses, it is not expected that they will connect easily to a neighbor XO if their houses are more than a few meters apart. But then, we must acknowledge that Brazilian low income neighborhoods present a very high population density.

Another issue related to distance is that if a child’s home is not close from school it will not easily connect to its network. Although the Brazilian Government does not consider any additional infra-structure, it may be needed in some scenarios.

One advantage of using 802.11 is that it is customer grade equipment. Inexpensive antenna projects are not difficult to find and mount and people creativity, particularly children’s spontaneous approach must not be underestimated, even more when scarce resources force them to improvise. Although the design of the XO does not allow for an external antenna, it may be possible to increase coverage by using inexpensive parabolic reflectors made of cardboard and aluminum foil– a great project for kids!

As we previously mentioned there are many additional tests to be performed at UFF and at the other participating universities. Many new issues concerning security and fairness are sure to arise and must be addressed by the OLPC team in the near future.

Finally one can also argue that digital inclusion is not a synonym to Internet access. We can think of a mesh of XOs running Voice over IP applications, of low demanding text chats, or new peer to peer services interconnecting the children through the XO.

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