The Design of a Wireless Solar-Powered Router for Rural Environments Isolated from Health Facilities

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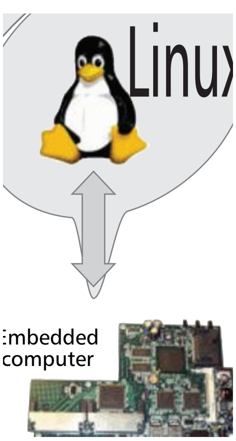

The authors present the development of an autonomous solar-powered wireless node for low-cost, static mesh networks. IEEE 802.11 is used for communication among nodes.

Abstract

Isolated rural areas often lack terrestrial telecommunication networks, especially in developing countries, which poses an important obstacle for offering health assistance of acceptable quality. On the other hand, low density and low concentration of population, lack of electricity in many areas, and accessibility problems make it difficult to propose realistic solutions based on conventional technologies. This work presents the development of an autonomous solar-powered wireless node for low-cost, static mesh networks. IEEE 802.11 is used for communication among nodes. The network is QoS-aware at the IP level, providing reliable VoIP services, and nodes contain a software PBX so that any two nodes in the network can establish a multihop VoIP communication.

Introduction

More than half of the population of the world lives in isolated rural areas, out of the reach of terrestrial telecommunication networks. This is particularly true in developing countries, where rural areas very often lack access to the public telephone network or even to electricity. Low density and low concentration of population make it difficult to afford the installation of permanent infrastructures that are expensive due to typical restrictions in power service, accessibility, maintainability, and security. Additionally, in developing countries, rural communities are usually extremely poor and cannot afford the cost of services if they are too high [1].

In the Enlace Hispano-Americano de Salud (EHAS) group [2], we are very concerned about isolated rural environments in developing countries and specifically, about health facilities and their communication with hospitals. In this work, we propose to use IEEE 802.11 mesh networks supporting voice and data communications as the most appropriate technology that makes it possible to use telemedicine applications and public health information systems in the rural areas of developing countries.

Mesh networks do not require a communication infrastructure. Nodes connect to neighbors as they discover them and can communicate with non-contiguous nodes or with other networks using other nodes as routers. Several aspects must be taken into consideration for applying IEEE 802.11 and the mesh networks paradigm in this project:

- IEEE 802.11 is a very well-known technology and extremely inexpensive, but originally designed for indoor environments. It requires some adjustments in order to be applied to long distances.
- Mesh networks reduce the price of communication infrastructures because user terminals permit themselves to extend the network scope.
- Network autoconfiguration is desirable to reduce the requirement for network administration. Using multihop, ad hoc dynamic routing protocols, nodes can organize themselves for routing packets if each node has a unique IP address.
- Minimal power consumption is a must. Nodes will be solar powered, so size and cost will be strongly related to consumption. Hardware must be optimized for low power consumption, and the network must collaborate to avoid useless transmissions when users do not require the system to be available.

All these considerations guided our design of an autonomous wireless mesh node; some units of the designed system could constitute a net-

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work just by putting them in different places and making sure that each node sees at least one neighbor.

Related projects were developed by the TIER group at the University of Berkeley [3], the RuralNet project in India [4], and some industrial groups, but none of them offers a complete self-configuring quality of service (QoS)-aware solution.

IEEE 802.11 Mesh Networks for Rural Telemedicine in Developing Countries

Isolated rural scenarios in developing countries have some common characteristics:

- Long distances of several tens of kilometers among "controlled" points
- Lack of fast routes that would make the movement between different points of the network easy
- Lack of an electric installation or if one exists, it is often unstable
- Shortage and high cost of qualified technical staff
- Extremely low incomes of rural inhabitants

These environmental characteristics determine the requirements that must be met by any telecommunication technology to be successful and sustainable in such scenarios. WiFi mesh networks have the following interesting properties that make them a candidate solution:

- The use of WiFi permits the production of very low-cost nodes that can establish long links. Because WiFi is a technology designed for short distances, the following important technological problems must be faced to obtain an optimal performance: restricted transmission power levels, propagation issues and signal reception at the physical layer, and the modification of some timing parameters (Slottime, Acktimeout) at the IEEE802.11 MAC layer [5].
- If we are able to obtain a self-configurable mesh architecture, nodes can be placed at strategic positions by any non-qualified person, whose only concern will be to assure the line-of-sight to neighbor nodes.
- Using low power hardware and optimizing the power consumption by several means, it is possible to produce compact autonomous nodes that incorporate a solar power subsystem, thus eliminating any restrictions regarding power sources.
- The fact that all nodes in mesh networks have the same functionality is also very positive for the extension and maintenance of the network.

The EHAS group has developed a mesh architecture as represented in Fig. 1. Actually, the three kinds of nodes represented in the figure can have the same functionality, but they are used differently; so it must be understood that client nodes, core nodes, and gateways are essentially the same thing; the only difference is the position and use of the nodes. One can think of this architecture superposed over rural telemedicine scenarios: core nodes would be deployed in strategic points in the area whose main characteristic is the visibility among them. The gateway node would be placed in the first establishment where we can have access to fix networks (i.e., the reference hospital), and client terminal nodes would be placed in isolated health facilities.

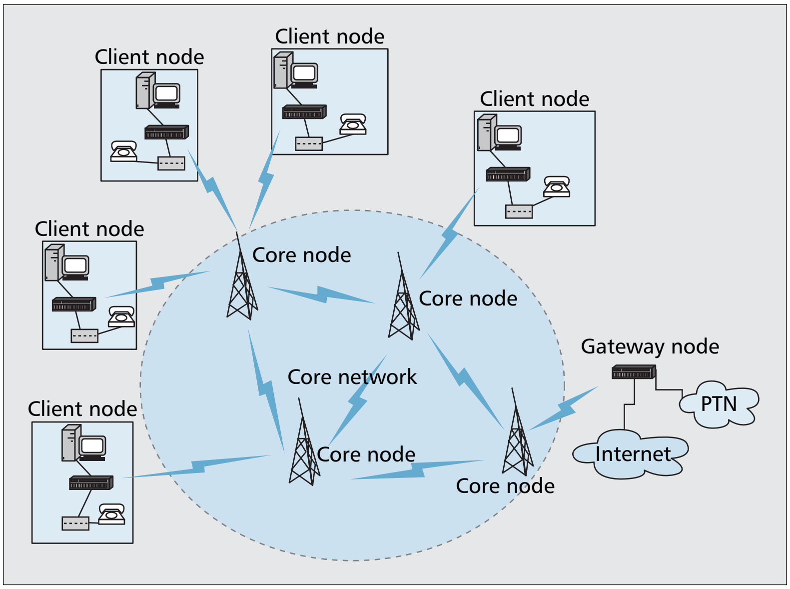

Figure 1. *Mesh network architecture.*

The main concern of this work is to develop a WiFi mesh node powerful and flexible enough to enable the building of this architecture with it. The core idea is that nodes automatically do everything after they are placed in the right positions. As a node is powered on, it discovers its neighbors, attributes itself a unique IP address, and then establishes the most appropriate routes to the rest of the network and to the world, taking into account the quality of the links. Nodes know about the different classes of traffic in the network and manage the QoS at the IP level. Additionally, each node has the required elements to make possible partial voice and data connectivity even if part of the network is provisionally not available.

The rest of the article describes in detail the design of the WiFi mesh node.

Components of the Wireless Solar-Powered Router

In this section, we study separately the hardware and the software of the wireless solar-powered router. The design presented in this section has been installed in two different isolated rural areas in Peru: Cusco (mountainous scenario) and Loreto (Amazon jungle).

Hardware

The hardware is composed of several subsystems:

Computer subsystem. The computer subsystem is the brain of the router and consists of an embedded computer that is optimized according to consumption and size requirements. As minimum power consumption is a must for our requirements, we compared some of the most

Board	Power (W)
Soekris net4521	1.9
WRAP.1E-1	2.04
MeshCube	2.16
Routerboard 532	2.28
Peplink SBC-Classic	2.34
Compulab SBX255	3
Compulab ATX255	3

Table 1. *Power levels of various boards.*

Components of the router	Total power per day (Wh)	Panel (Wp)	Battery (Ah)
Soekris+1SR2+2Proxim	155.75	62	105
Soekris+1CM9+2Proxim	149.78	59	100
Soekris+1SR2+1Proxim+1SRC	144.87	57	98
WRAP+2SR2	113.93	45	76
WRAP+2CM9	109.70	44	74
WRAP+1SR2+1CM9	107.97	43	72
WRAP+1SR2	80.96	32	54
WRAP+1CM9	75.01	30	50

Table 2. *Router components.*

popular boards available on the market. Results from this comparison are shown in Table 1. From these numbers, we chose Soekris and WRAP boards, based on x86 architecture for our prototype. Moreover, these platforms have other important design features, such as low-cost design, availability of at least two wireless interfaces, robustness against bad weather conditions, and a hardware watchdog.

Wireless subsystem. The wireless subsystem is responsible for communication with the rest of the network. It consists of WiFi interfaces, pigtails, low-attenuation cables, and high-power directional and omnidirectional antennas. We are currently working with wireless cards using Atheros chipsets: SR2 (400 mw mini-PCI b/g), SRC (300 mw Cardbus a/b/g), CM9 (80 mw mini-PCI b/g), and Proxim Orinoco Gold (80 mw PCMCIA b/g). Atheros Linux driver (Madwifi) enables one to tweak some MAC parameters (Acktimeout and SlotTime) that must be modified to obtain optimal performance on long distance links [5].

Solar subsystem. Our router will be installed in isolated rural areas, typically high in the mountains or in the jungle, where often there are no power sources at all. So nodes must have a solar power subsystem dimensioned so as to provide enough power in a continuous way. This subsystem will consist of all required elements to feed in DC our communication system: solar panel, batteries, charger/regulator, and cables. Depending on the number and model of wireless cards, we have sized several solar subsystems. The consumption of a node was estimated by measuring the average power consumption in three different states: idle, transmitting, and receiving (and transmitting and receiving simultaneously, in the case of nodes with two wireless interfaces). We estimated the time share of each state upon the observation of nodes in operational networks (see more details in the WiFisleep point of the next subsection). The energy required for powering a system 24 hours a day has been calculated, and the solar systems have been dimensioned based on the solar energy received during the worst month of the year in a tropical region (Table 2).

Software

The software part of the node is composed of an operating system and several applications that are discussed here.

Dynamic Routing Protocol — Static routing is stable and does not add any routing control traffic. This was the first approach taken in the Cusco network. However, this is neither a self-configuring nor a scalable solution.

For networks without loops (there is only one way to go from one node to another one), a protocol like open shortest path first (OSPF) can meet our requirements perfectly. Although OSPF was designed for wired networks, we have successfully tested it in the laboratory using a chain of seven WiFi nodes. For the test, we used quagga [11], an OSPF implementation for Linux. The next step will consist of its installation in a real network.

However, for the case of generic mesh networks, it is interesting to use a multihop ad hoc dynamic protocol with a QoS metric. Several multihop, ad hoc dynamic routing protocols (e.g., optimized link state routing [OLSR] [6]) were proposed for routing packets internally or between any node of the network and the exterior through a gateway node. In these protocols, the only requirement for an IP address in the network is its uniqueness. Related to the QoS metric, an MIT group proved in [7] that protocols that establish routes based on number of hops as a metric are not always optimum. This is because they do not take into account the relative quality of the links. De Couto et al. suggested a metric called the expected transmission ETX count [8] that considers the average number of retransmissions in every link.

We explored several mesh network protocols looking for stable implementations with QoS-aware metrics. The *olsrd* implementation of OLSR [12] was chosen due to its remarkable maturity and stability, as well as its support of the ETX metric. Our work in [9] mentions lab tests that enabled us to use the OLSR successfully in static ad hoc chains with one wireless interface per node.

QoS — IEEE 802.11 networks can offer a strong, suitable, and low-price solution to distribute voice and data communication. But if we want to propose real-time communications, we must ensure QoS under certain conditions. In our case, telephony communications are essential; voice is the most demanded service for communicating in isolated rural areas as was proven in the long-term evaluation of previous demonstrative projects of the EHAS group [2]. Additionally, if we could propose other real-time services, such as video-conference, it also could be interesting for telemedicine and e-learning applications, among others. Typical IP QoS architectures are IntServ and DiffServ. Both are standardized by the Internet Engineering Task Force (IETF), but generally, the second one is preferred because it is simpler and it scales better. The QoS at the IP level in DiffServ implies that different traffic classes can be identified in each router and be treated separately, with different priorities. An important handicap will be that the throughput of wireless links must be estimated to perform bandwidth sharing in a fair way, though the throughput may be variable due to the distance between nodes or to the presence of interferences. Some experiments made by our group with mesh node chains permitted us to demonstrate that a differentiated quality of service of voice, video, and elastic data could be guaranteed if it is possible to delimit the performance of the link [9].

Based on the previous considerations, a simplified DiffServ-like scheme was implemented with the following elements:

Classifying packets: First we must distinguish voice packets from data ones. Voice packets can either enter our private network from the Internet or be generated inside our network. They are easy to distinguish by looking into the destination User Datagram Protocol (UDP) port. (Asterisk, the application that manages them, always uses the same port.) We perform this using iptables software.

Marking: After voice packets are identified, we must mark them in order for them to be clearly recognized by the rest of the routers. IP protocol considers this idea, using a field in its header called ToS (type of service). We can mark voice packets by modifying this field properly. The gateway and the nodes generating voice packets are in charge of this task.

Queuing disciplines: Queues enable us to assign different priorities according to the type of packet. Our main concern is to give absolute priority to voice communications, which can be achieved with the priority (PRIO) queuing discipline. PRIO contains three simple queues for three different traffic classes and assures absolute priority to packets queued in higher priority queues. Voice packets are queued with the highest priority, followed by video, and finally best-effort traffic. As long as the voice queue has packets waiting to be routed, no data packet will be forwarded.

Network Management — A management system is advisable in our mesh networks for information about the availability and state of the nodes. We also can prevent future problems or failures in advance. EHAS has developed a management system based on electronic mail and Zabbix, an open source software that supports both polling and trapping techniques to collect data from monitored hosts or to execute some control tasks remotely. A flexible notification mechanism enables one to easily and quickly configure different types of notifications for pre-defined events. Two software packages, ehas-netman and ehas-router, were developed to install this management system in the router.

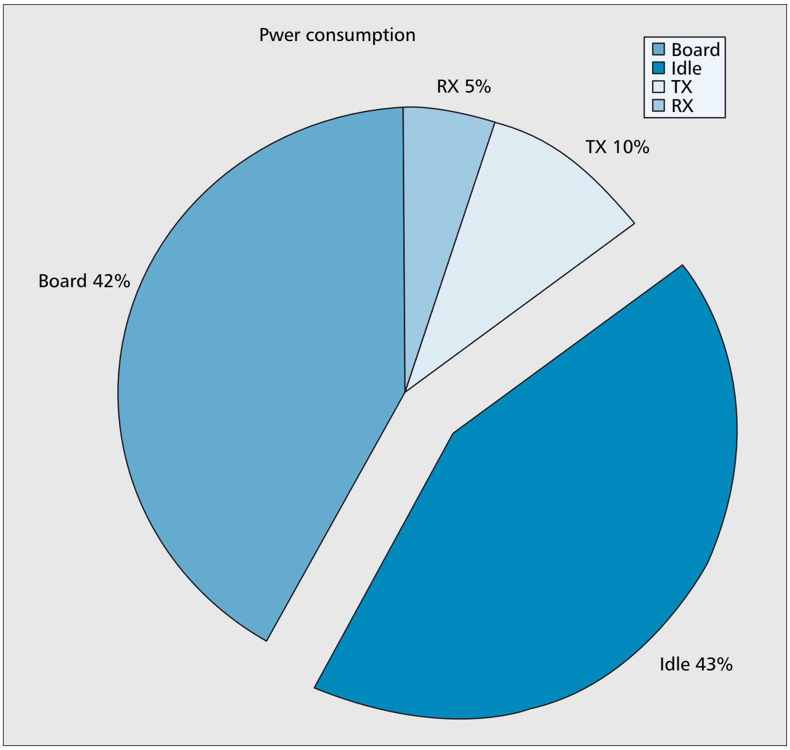

Figure 2. *Typical power consumption per day in a wireless router.*

WiFisleep — The cost and size of the solar subsystem will be proportional to its power consumption, so it is essential to design a very low-powered system. Considering that wireless cards are the most power-hungry devices in our system, our group developed a software protocol to minimize this effect. Calculating the consumption per day of the different elements involved in the router (router board and wireless cards transmitting, receiving, and idle), we can obtain a chart like the one shown in Fig. 2. The values of time spent by wireless interfaces on transmitting — 1.55 hours/day; receiving — 1.39 hours/day; or staying idle — 21.06 hours/day were obtained experimentally from the nodes operating at the Cusco network. It can be seen that the energy is mainly consumed in powering the board and maintaining the interfaces in an idle state. Therefore, a good way to save energy is to put the interfaces to sleep in some way during these idle periods.

To put that idea into operation, we developed a protocol called WiFisleep, and we implemented it in software using Python language. It does not require any communications among nodes; it just requires a homogeneous configuration and a common time reference using net-

The introduction of a PBX in every node permits the reduction of traffic in the network and ensures the availability of local telephony in case of network partition.

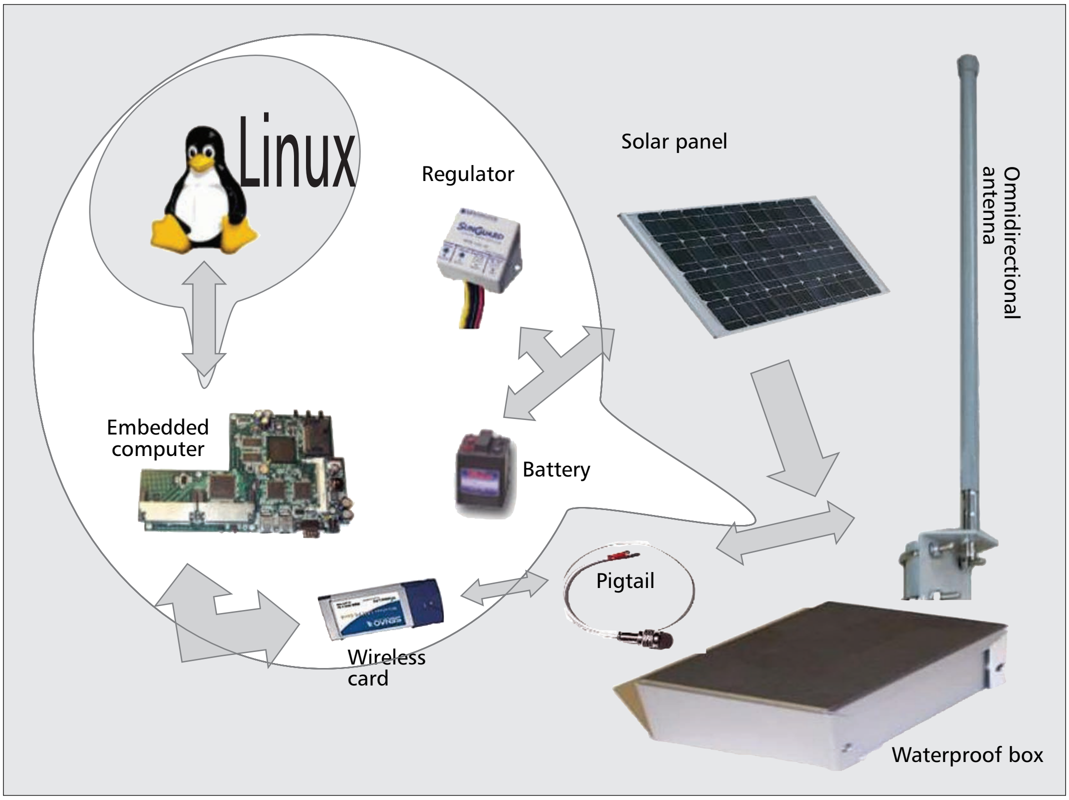

Figure 3. *Scheme of the wireless solar-powered router.*

work time protocol (NTP). It divides the time in slots so that all nodes sleep in pair slots and wake up in odd slots while the network is idle. Every time an interface wakes up, it senses the traffic activity. If data is detected, the interface will not go to sleep and will stay awake until the traffic activity ceases.

The amount of power that is saved using WiFisleep will depend on how long sleep periods are compared to awake ones, and how many hours per day this protocol works. Assuming WiFisleep works 24 hours per day, and sleep periods are nine times longer than awake ones, we can save more than 30 percent of the power.

Software Distribution — We developed an operating system, Voyage-EHAS, based in the Voyage minidistro. The total size of this version is around 150 MB. It has, among other things, the software tools required for network routing (olsrd, quagga, route), the Madwifi driver for Atheros wireless cards, the software package iproute2 to perform QoS, and the EHAS management packages, ehas-router and ehas-netman. It also has watchdog software, responsible for rebooting the unit in case of uncontrolled failure.

Because voice is a priority service in EHAS networks, we added a software private branch eXchange (PBX) named Asterisk that supports voice over IP (VoIP)-to-public switch telephone network (PSTN) switching. The introduction of a PBX in every node permits the reduction of traffic in the network and assures the availability of local telephony in case of network partition. All VoIP components in our networks use Session Initiation Protocol (SIP), although the Asterisk PBX communicates with peers using the proprietary Inter-Asterisk eXchange (IAX) protocol.

With the main purpose of making the configuration of the router as easy as possible, we are currently developing a light Web server, built from thttpd and PHP.

In Fig. 3 we show a general scheme of the solar wireless router.

Results

As a consequence of our research in IEEE802.11 technology, we obtained a first prototype of a solar wireless mesh node based on x86 boards, running our own Linux distribution. This first version was successfully used for deploying a static mesh network in an isolated mountainous rural area (Cusco, Peru), as well as another one with chain topology along the Napo river in the Peruvian jungle. In both networks, the towers were calculated and built for assuring the line of sight in all planned links, then nodes were placed at the desired height, and antennas were carefully oriented. More details about our methodology for deploying static mesh networks can be found in [10]. The network deployed in Cusco has 15 nodes with point-to-point links up to 42 km long and point-to-multipoint links up to 20 km long for the farthest client.

Table 3 shows some of the throughputs achieved for the 42 km link by injecting bidirectional traffic (in megabits per second), adjusting ACKTimeout and SlotTime parameters as in [5], working at different rates. To get these results, 24 dBi antennas and 400 mw wireless cards were used. Throughputs were measured at the appli-

Rate	Throughput achieved (Mb/s)
1M	0.55
2M	0.95
5.5M	1.64
6M	2.20
9M	3.52
11M	2.94
12M	4.00
18M	4.82
24M	6.07
36M	6.66

Table 3. *Throughput achieved at different rates.*

cation layer, sending packets over Transmission Control Protocol (TCP) at fixed rates and fixed packet sizes.

In tests in the field, we have verified experimentally that we can get up to 1.2 Mb/s of TCP throughput — unidirectional traffic — in an 84-km long link (working at 2 Mb/s speed in 802.11b mode) using 1W amplifiers.

Previous results were obtained with one-hop communications. The end-to-end performance decreases in multihop communications due to internal interferences in nodes having more than one wireless interface. In our longest available multihop path, 11 hops over 310 km in the Napo network, the end-to-end throughput obtained is reduced by 50 percent with respect to the performance of a one-hop link. This is the well-known price of using carrier sense multiple access with collision avoidance (CSMA/CA) as the MAC protocol. The authors of [3] and [4] propose a radical replacement of the protocol, but we consider that compatibility with legacy 802.11 systems is preferable.

It has been verified that VoIP services are possible and compatible with data traffic in the networks described if the network is not saturated. VoIP calls using SIP phones are possible from any point of the wireless network to the Internet or the PSTN, even through seven wireless hops covering a total of 130 km (Cusco network). However, as soon as the network becomes saturated even with low-priority traffic, VoIP calls suffer a negative impact from that saturation unless QoS support is implemented at the IP level, especially in point to multipoint links [9]. The results of QoS tests in the laboratory (using Diffserv architecture) have allowed us to guarantee the QoS to VoIP calls in case of saturation due to less priority traffic.

The power solar subsystem has been properly sized for the wireless router consumption and tested in real networks. To minimize the size of the solar subsystem, a double strategy was used: we selected a very low-powered hardware (Soekris/WRAP) and developed a software protocol called WiFisleep to minimize the power consumption of wireless cards (decreasing up to 70 percent of its nominal value).

The dynamic routing using OSPF or OLSR-ETX (depending on the topology of the network) also was tested in the laboratory with a few nodes (up to seven). OSPF showed a correct behavior in all cases. Olsrd performed well when each node had only one wireless interface but suffered from some instability problems when several wireless interfaces per node were used or when there was more than one Internet gateway. The next step will be its installation and further evaluation in a real network.

Finally, regarding the cost of a system including all the elements described, a whole node could cost about $1000 USD. In fact, the most significant costs for network deployments are towers, transport, and training for network maintainers that typically add more than $5000 USD per node.

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Discussion and Future Work

This work has presented a wireless mesh router design using IEEE 802.11 for providing a voice and data communication infrastructure adapted to the requirements of isolated rural areas in developing countries. A prototype of the design presented herein was successfully installed in two different scenarios in Peru. The provision of VoIP telephony and access to public health information systems in both networks had a very positive impact on the quality of health assistance. The diagnostic capacity at rural health centers was improved, as well as the patient evacuation system and the epidemiological surveillance mechanisms. Another benefit was the reduction of the widespread sense of isolation, both professional and personal, felt by rural health personnel.

Although most of the aspects related to dynamic routing were tested in the laboratory, their impact on the installation and maintenance of networks has not been evaluated yet. Other issues to be reviewed in a future prototype are an IP-adaptive QoS management system and a proposal for reducing or eliminating internal interference in multi-interface nodes.

We also are researching the QoS provision at the MAC layer with IEEE 802.11e over long distances, which will complement the QoS support at the IP layer.

Finally, the system presented does not have an IP self-configuring solution yet; nodes must receive a unique IP address before going in the field. The research and development of such a solution will be addressed in future work.

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