Very Long Distance Wi-Fi Networks

Rob Flickenger
Hacker Friendly LLC
410 Broadway Ave E
Seattle, WA 98102
U.S.A.

rob@hackerfriendly

Steve Okay
Inveneo
972 Mission Street, 5th
San Francisco, CA
U.S.A.

steve@inveneo.org

Ermanno Pietrosemoli
EsLaRed-ULA
Apartado 514
Mérida 5101
Venezuela

ermanno@ula.ve

Marco Zennaro and
Carlo Fonda
Abdus Salam ICTP
Strada Costiera 11
34014 Trieste, Italy

mzennaro@ictp.it

ABSTRACT

802.11 Wi-Fi technology is commonly used for creating wireless networks with a range of about one hundred meters. With careful planning and proper antennas, this same equipment can be used to make point-to-point links of hundreds of kilometers. This paper presents a successful 279 km link made by wireless experts in Venezuela, and a permanent 133 km test network in northern Italy for ongoing research.

Categories and Subject Descriptors

C.2.1 [**Network Architecture and Design**]: Wireless Communication - *802.11*.

C.2.5 [**Local and Wide-Area Networks**]: Internet – *TCP/IP*.

General Terms

Experimentation

Keywords

Low-cost networking, Wi-Fi, wireless, long distance

1. INTRODUCTION

For developing countries, wireless is the only viable alternative for providing affordable telecommunications services [1]. This has been proved in many countries, where the penetration of mobile phones is considerably higher than that of land lines. At the end of 2007 the number of mobile phones in Latin America reached over 70% of the population, whereas land lines barely touched 15% [2].

Mobile phone systems are very limited for data service and Internet access, both in terms of cost and transmission rate. Although third generation technologies can provide reasonable data rates, they do so by sacrificing range. This means that the number of base stations must be increased compared to 2G, which is a costly proposition for urban areas and hopeless for rural areas.

1.1 Alternatives

For long distance backbone networks, fiber optics is nearly always the best choice, and has been widely deployed in Europe, North America and some regions of Asia. However, fiber networks in Africa and South America only reach the major cities and leave most of the countryside underserved.

Satellite technologies are very efficient for broadcast (unidirectional) traffic, but are costly and severely limited in throughput for bidirectional Internet access.

Traditional microwave links can scale in throughput, and modern Synchronous Digital Hierarchy (SDH) systems offer high reliability but at considerable cost, both in terms of capital expenses and licensing fees. Such systems also require very well trained engineers for installation.

WiMAX has been proposed as a solution for broadband long range links. However the business case has yet to be proved, and equipment and licensing costs will be considerably higher than Wi-Fi for the foreseeable future.

1.2 Wi-Fi for Long Distance

Although it was developed for local area networks, Wi-Fi has proved to be cost effective for long distance applications [3] and the enormous success of Wi-Fi has allowed for economies of scale that will be hard to beat by alternative technologies like WiMax.

The two major limitations for using Wi-Fi over long distances are the requirement for line of sight between the endpoints and the vulnerability to interference in the unlicensed band [4]. The first limitation can often be addressed by taking advantage of the terrain elevations, or by using towers to overcome obstacles and provide Fresnel zone clearance. The second limitation is less pronounced in rural areas, and can be alleviated by migrating to the less crowded 5 GHz band.

Two further hurdles have to be overcome when applying Wi-Fi to long distance: Power budget limitations and timing limitations. The first is easily solved by using high gain directional antennas, while the timing issue can be addressed by modifying the media access mechanism, as done by the TIER group at the University of Berkeley [5].

Another issue of relevance is the use of low cost gear for the aiming of the antennas, making affordable and easier to use by people with limited training.

Thanks to a favorable topography, Venezuela already has some long range WLAN links. Since 2001, Fundacite Mérida has operated a 70 km link between Pico Espejo and Canagua.

To test the extreme possibilities of long distance WLAN, we have successfully used inexpensive Wi-Fi equipment to establish links at 101 km, 279 km, and 382 km. Most recently, we have established a permanent 133 km test bed in Italy to examine the real-world performance of a variety of wireless equipment, correlating performance with weather and other environmental factors.

2. EXTREME LONG DISTANCE

To test the limits of this technology, it is necessary to find a path with unobstructed line-of-sight and a clearance of at least 60% of the first Fresnel zone [4]. As the distance between sites increases, the curvature of the Earth becomes a serious obstacle, requiring higher elevation at both ends. Installation on towers or other tall structures is mandatory, and the longest distance links are only possible from high elevations.

2.1 Mérida to El Baúl: 279 km

When searching for an area of terrain in Venezuela with high elevation at the ends and low ground in between, we first focused on the Guayana region. Although plenty of high grounds are to be found, in particular the famous "tepuys" (tall mesas with steep walls), there were always obstacles in the middle ground.

Our attention shifted to the Andes, whose steep slopes (rising abruptly from the plains) proved adequate to the task. Pico del Aguila has an altitude of 4200 meters and is about a two hour drive from Mérida. It has clear line-of-sight to the town of El Baúl, in Cojedes State. Using the free software Radio Mobile [6], we found that there was no obstruction of the first Fresnel zone (spanning 280 km) between Pico del Aguila and El Baúl (Figure 1).
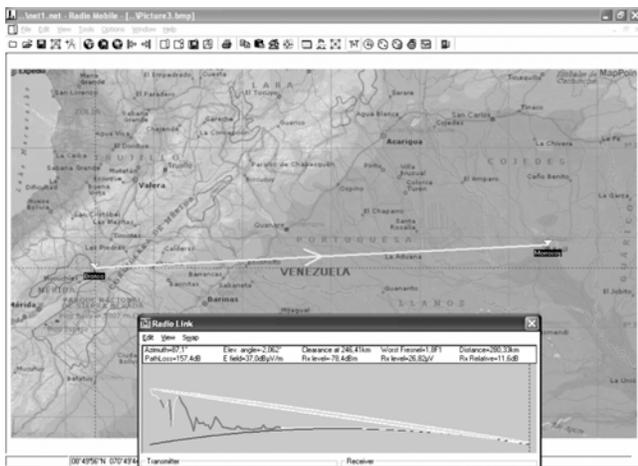

Figure 1: Radio Mobile path from Mérida to El Baúl.

2.1.1 Equipment

Once satisfied with the existence of a suitable trajectory, we looked at the equipment needed to achieve the goal. Up to this point, we had been using Orinoco cards for a number of years. Sporting an output power of 15 dBm and receive threshold of -84 dBm, they are robust and trustworthy. The free space loss at 282 km is 149 dB, so we would need 30 dBi antennas at both ends and even that would leave very little margin for other losses.

On the other hand, the popular Linksys WRT54G wireless router runs Linux. The Open Source community has written several firmware versions for it that allow for a complete customization of every transmission parameter. In particular, OpenWRT firmware [7] allows for the adjustment of the acknowledgment time of the MAC layer, as well as the output power. Another firmware called DD-WRT [8] has a GUI interface and a very convenient site survey utility. Furthermore, the Linksys can be located closer to the antenna than a laptop, so we decided to use a pair of them. One was configured as an AP (access point) and the other as a client. The WRT54G can operate at 100 mW output power with good linearity, and can even be pushed up to 200 mW. But at this value, non linearity is very severe and spurious signals are generated, which should be avoided. Although this is consumer grade equipment and quite inexpensive, after years of using it, we felt confident that it could serve our purpose. Of course, we kept a spare set handy just in case.

By setting the output power to 100 mW (20 dBm), we could obtain a 5 dB advantage compared with the Orinoco card. Therefore, we settled for a pair of WRT54Gs.

2.1.2 Site Survey

From Pico Águila, the azimuth towards El Baúl is 86°. Since the magnetic declination is 8° 16', the antenna would need to be pointed to a magnetic bearing of 94°.

Unfortunately, line of sight is obstructed by an obstacle at 94° that had not been shown by the software, due to the limited resolution of the freely available digital elevation maps. After spending several hours examining the surrounding area, we identified a more suitable location clear of obstacles in the path.

2.1.3 Proving the Path

High gain antennas for the 2.4 GHz band are not available in Venezuela. As importation costs are considerable, we decided instead to recycle a pair of parabolic reflectors (formerly used for satellite service) and replaced the feed with one designed for 2.4 GHz. We proved the concept with an 80 cm dish. The gain was far too low, so we tried a 2.4 meter reflector with an offset feed. This offered ample gain, albeit with some difficulties in the aiming of the 3.5° beam. The 22.5° offset meant that the dish appeared to be pointing downwards when it was horizontally aligned.

Several tests were performed using various cantennas [9] and a 12 dBi Yagi as a feed. We pointed the antenna at a base station of the university wireless network that was located 11 km away on a 3500 m mountain. The test site sits at 2000 m and therefore the elevation angle is 8°.

We were able to establish a link with the base station at Aguada, but our efforts to measure the gain of the setup using Netstumbler were not successful. There was too much fluctuation on the received power values of live traffic.

For a meaningful measurement of the gain, we needed a signal generator and spectrum analyzer. These instruments were also required for the field trip in order to align the antennas properly.

Once we were satisfied with the proper functioning and aim of both antennas, we decided to do a site survey at the other end of the El Baúl link. We found a hill south of the town that had two telecom towers, one of which belongs to the mayor of El Baúl.

The hill is called Morrocoy, and is some 75 m above the surrounding area, about 125 m above sea level. It provides an unobstructed view towards El Aguila. There is a dirt road to the top, which was a must for our purpose, given the weight of the antenna (Figure 2).

Figure 2: Antennas used on the Mérida to El Baúl link.

2.1.4 Performing the Experiment

After a full day of travel (with the offset antenna loaded on top of a four-wheel drive truck), one team installed the antenna. It was pointed at a compass bearing of 276°, given that the declination is 8° and therefore the true Azimuth is 268°.

At the same time, the other team rode to the previously surveyed area at Pico del Aguila in a Bronco truck that carried the 2.7 m mesh antenna.

Poor weather is common at altitudes of 4100 m above sea level. The Aguila team was able to install and point the mesh antenna before the fog and sleet began.

Power for the signal generator was supplied from the truck by means of a 12 VDC to 120 VAC inverter. At 11 A.M in El Baúl, we were able to observe a -82 dBm signal at the agreed upon 2450 MHz frequency using the spectrum analyzer. To be sure we had found the proper source, the Aguila switched off the signal. Indeed, the trace on the spectrum analyzer showed only noise. This confirmed that we were really seeing the signal that originated some 280 km away.

After turning the signal generator on again, we performed a fine tuning in elevation and azimuth at both ends. Once we were satisfied that we had attained the maximum received signal, we removed the signal generator and replaced it with a Linksys WRT54G wireless router configured as an access point. On the other end, the spectrum analyzer was substituted for another WRT54G configured as a client.

At once, we started receiving 802.11 "beacons", but TCP/IP packets did not get through. This was expected, since the propagation time of the radio wave over a 300 km link is 1 ms. It takes at least 2 ms for an acknowledgment to reach the transmitter.

The OpenWRT firmware allows for adjusting the ACK timing. After we adjusted for the increase in delay above what the standard Wi-Fi link expects, we began receiving ICMP packets with a delay of about 5 ms.

We proceeded to transfer several PDF files between our laptops, with speeds of about 65 kbps.

2.1.5 Improving Performance with TDMA

One year after performing this experiment, we found the time and resources to repeat it. We used commercial 30 dBi antennas, and also a couple of wireless routers which had been modified by the TIER group led by Dr. Eric Brewer of Berkeley University [10].

The purpose of the modification of the standard Wi-Fi MAC is to make it suitable for long distance applications by replacing the CSMA Media Access Control with TDMA. The latter is better suited for long distance point-to-point links since it does not require the reception of ACKs. This eliminates the need to wait for the 2 ms round trip propagation time on a 300 km path.

For this experiment, we installed one of the antennas at the El Aguila site. A second team installed the other antenna at El Baúl.

A solid link was quickly established using the Linksys WRT54G routers. This allowed for video transmission at a measured throughput of 65 kbps. With the TDMA routers, the measured throughput was 3 Mbps in each direction. This produced the total of 6 Mbps as predicted by simulations done at Berkeley.

2.2 El Aguila to Platillón: 382 km

Thrilled by these results, which pave the way for really inexpensive long distance broadband links, the second team moved to another location previously identified at 382 km from El Aguila, in a place called Platillón. Platillón is 1500 m above sea level and there is an unobstructed first Fresnel zone towards El Aguila (located at 4200 m above sea level). The Radio Mobile plot is shown in Figure 3.
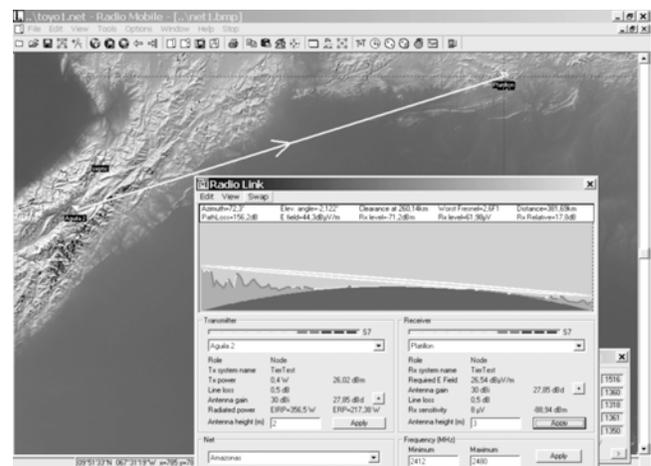

Figure 3: Radio Mobile path from El Aguila to Platillón.

Again, the link was quickly established with the Linksys and the TIER supplied routers. The Linksys link showed approximately 1% packet loss, with an average round trip time of 12 ms. The TIER equipment showed no packet loss. This allowed for video transmission, but the link was not stable. We noticed considerable signal fluctuations that often interrupted the communication.

However, when the received signal was sufficient, the measured throughput was a total of 6 Mbps bidirectional with the TIER routers implementing TDMA.

2.3 Piancavallo

In February 2007, a group of experts from the Abdus Salam International Centre for Theoretical Physics (ICTP) established a 101 km wireless link from Trieste to Piancavallo, Italy. The link path from Google Earth is shown in Figure 4.

Figure 4: Google Earth path from Trieste to Piancavallo.

For the Trieste end of the link, we used a Berkeley TIER box with a 400mW Ubiquiti SR2 radio [11] in AP mode. For the remote end, we used a matching TIER box for the first test, and a Metrix Mark II [12] using the same SR2 radio for the second test. The Piancavallo end of the link was at about 1200 meters.

Using the Metrix Mark II box and the SR2 radio card, we measured a throughput of around 85 Kpbs up/down with the bitrate of the radio fixed at 36 Mbps. When we fixed the bitrate at 11 Mbps, we measured 592 Kbps down / 616 Kbps up. The link quality varied throughout the day. The available signal fluctuated from -64 dBm to -87 dBm (a difference of 23dB!) The average of all signal samples taken was -77 dBm. We noted that the signal level definitely varied with the wind speed. We expect that the link would have been far more stable with the large dish on the Piancavallo side fixed in place more securely.

The best throughput we achieved was approximately 600 kbps, as measured by the TCP/IP performance tool iperf [13]. We used video conferencing, VoIP, chat, email, and the web on the link.

3. The Monte Cesen Testbed

Long distances are often simulated in a typical laboratory by introducing artificial obstacles or noise. Of course, this simulation does not always correspond to "real-world" performance characteristics. To address this need, we present the design and implementation of a wireless testbed network for researching the engineering issues surrounding the use of wireless long distance network links in developing countries, in both the 2.4 and 5.8 GHz frequency ranges.

In November 2007, a team from the ICTP ARPL Lab established a testbed network in these frequency ranges. The intent is to study the performance of various wireless point-to-point equipment at a range of 133 km over a span of months. The testbed is comprised of 6 links between Monte Cesen and the ICTP. Monte Cesen is a mountain in the foothills of the Dolomites, near Aviano, with an altitude of 1500 meters ASL. The ICTP ARPL lab antenna tower at the Trieste end of the link is approximately 70 meters ASL.

Specifications of the links:

- One 802.11g (2.4 GHz) control link using a Mikrotik server board and a Ubiquiti XR2 radio
- Two 802.11a (5 GHz) links using TIER firmware on a PC Engines server board and Ubiquity XR5 radios
- Four 802.11a (5 GHz) links, on Mikrotik server boards running Mikrotik Router OS with Ubiquity XR5 radios.

Figure 5: Physical installation at Monte Cesen.

The antennas are aligned using a mix of vertical and horizontal polarization, to provide the opportunity to measure the performance of various equipment at either polarization. Figure 5 shows the physical installation of the antennas (two dual-feed 5 GHz dishes, one single feed 5 GHz dish, and one 2.4 GHz dish for the control link) and the weather station.

The total cost of the wireless equipment was approximately $600 per link, including the antennas.

3.1 Network Architecture

A control link is used to provide management and access to the testbed. This ensures that system and software updates, database backups, and other maintenance traffic does not affect the performance of the links under test. An Apple Mac Mini was used as a testbed management host (TMH), providing a gateway into the testbed network. Attached to this host was a custom-made, USB-based remote power distribution unit (RPDU) to allow any one of the wireless access points to be selectively powered on or off without affecting the others.
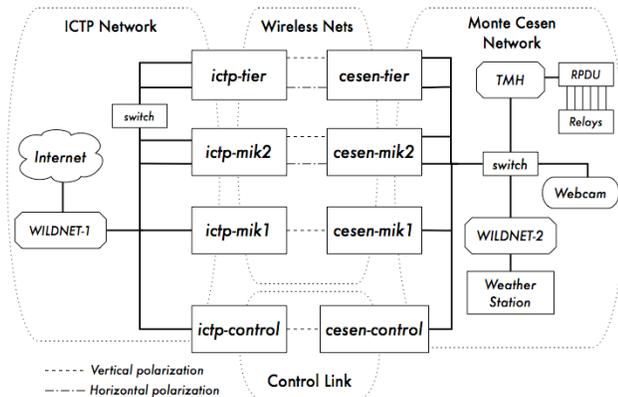
Figure 6: Monte Cesen network layout.

An embedded weather station capable of measuring wind speed, temperature, humidity, precipitation, and other data. is also installed at the remote end. A MySQL database is used to allow recording of data from the testbed links and weather station. Finally, an IP-capable webcam was mounted on the testbed antenna mounting framework to provide a visual record of the conditions at and around the installation. Ubuntu Linux servers (WILDNET-1 and WILDNET-2) on either end of the link performed link performance measurements using a variety of tools, such as fping [13] and iperf.

The network layout is shown in Figure 6.

3.2 Installation Challenges

Installation and configuration was hampered somewhat by weather factors. Some team members were from sub-equatorial Africa and not used to working in temperatures such as those experienced on Monte Cesen. Additionally, adhesives on items like electrical tape, labels and silicon sealing tape became brittle and failed in the temperatures which ranged from 0 to -10C. Backlighting and hinge supports for LCDs in some of the laptops failed due to low temperature, interrupting or delaying configuration at times. This resulted in a degree of task planning and choreography not previously required for other long distance links, even in similar locations such as Piancavallo.

Since the distance between the endpoints exceeds the 100 km achievable by adjusting ACK timings, wireless equipment on the Monte Cesen link must use some method other than 802.11 CSMA to maintain link stability. The Berkeley TIER equipment uses the TDMA scheme already mentioned. The Mikrotik equipment uses a proprietary long distance protocol called Nstreme. The approximate throughput is 3 to 4 Mbps per link.

4. Conclusions

In this paper we have shown how very long distance Wi-Fi links can be deployed using low-cost technologies. Long distance Wi-Fi links are a practical, inexpensive alternative for providing internet connectivity in developing countries.

Research is still ongoing to reduce the complexity of setting up links and to determine the optimal configuration for maximizing the performance and stability of links over long periods of time. The authors are testing new technologies to align antennas using off-the-shelf, open-source technologies that cost a fraction of commercially available equipment. The Monte Cesen network is intended to provide a "real-world" laboratory for testing low-cost wireless networking equipment at long range.

Long distances are often simulated in a typical laboratory by introducing artificial obstacles or noise. The Monte Cesen link subjects the equipment under test to much more realistic conditions, including temperature extremes and unpredictable noise sources. Members of the wireless networking community who wish to test their equipment or design experiments using the Monte Cesen network are invited to collaborate with us on future work in this field. By exploring the actual capabilities of equipment available on the market, we hope to identify low cost solutions that will most effectively bring inexpensive broadband access to the developing world.

5. ACKNOWLEDGMENTS

6. REFERENCES

[1] The coming wireless revolution, the Economist, April 26 2007

[2] Sánchez, G., Teledensity in Latin America, Research Analyst from Frost & Sullivan Communication Services

[3] Raman, B., Chebrolu, K. 2007. Experiences in using WiFi for Rural Internet in India. IEEE Communications Magazine, Special Issue on New Directions In Networking Technologies In Emerging Economies (Jan. 2007)

[4] Chebrolu, K., Raman, B., Sen, S. 2006. Long-Distance 802.11b Links: Performance Measurements and Experience. 12th Annual International Conference on Mobile Computing and Networking (MOBICOM) (Sep 2006)

[5] Patra, R., Nedevschi S., Surana, S., Sheth, A., Subramanian, L., Brewer, E. 2007. WiLDNet: Design and Implementation of High Performance WiFi Based Long Distance Networks. USENIX NSDI (April 2007)

[6] RadioMobile, http://www.cplus.org/rmw/english1.html (as seen on March 2nd 2008)

[7] OpenWrt, http://openwrt.org/ (as seen on March 2nd 2008)

[8] DD-WRT, http://www.dd-wrt.com/ (as seen on March 2nd 2008)

[9] Flickenger, R. 2008 Wireless Networking in the Developing World 2nd edition, (126-133)

[10] TIER (Technology and Infrastructure for Emerging Regions), http://tier.cs.berkeley.edu/ (as seen on March 2nd 2008)

[11] Ubiquiti SuperRange2 2.4 GHz mini-PCI radio, http://ubnt.com/products/sr2.php (as seen on March 2nd 2008)

[12] Metrix Mark II wireless networking kit, http://metrix.net/ (as seen on March 2nd 2008)

[13] Flickenger, R. 2006 How To Accelerate Your Internet, (74 and 90)