CONNECTING REMOTE SITES TO THE WIRED BACKBONE BY WIRELESS MESH ACCESS NETWORKS

Thomas Staub[⋆], *Markus Anwander*[⋆], *Kurt Baumann*[•], *Torsten Braun*[⋆], *Marc Brogle*[⋆], *Kirsten Dolfus*[⋆], *Christian Félix*[⋄] *and Paul Kim Goode*[⋆]

[⋆]Institute of Computer Science and
Applied Mathematics
University of Bern
Neubrückstrasse 10, CH-3012 Bern, Switzerland
staub|anwander|braun|brogle|dolfus|goode@iam.unibe.ch

[•]SWITCH
Werdstrasse 2, CH-8021 Zurich, Switzerland
kurt.baumann@switch.ch
[⋄]MeteoSwiss
Station aérologique, CH-1530 Payerne, Switzerland
christian.felix@meteoswiss.ch

ABSTRACT

Wireless Mesh Networks (WMNs) operating in the 5 GHz band (IEEE 802.11 a/h) offer a great opportunity to function as wireless access networks. Remote sites that lack direct access to a wired/fibre network may benefit from this technology, as it can be used to bridge possibly large distances. The high gain of directional antennas improves the reception of signals in focused directions and reduces interference from unwanted sources. Therefore, they are the preferred choice for such bridging scenarios. In this paper, we present our experiences with setting up such a Wireless Access Network using directional antennas in the area of Neuchâtel, Switzerland. We describe the necessary equipment and planning steps, highlight common pitfalls and discuss gained insights as well as experimental results. Measured data supports the feasibility of our networking approach, yet reveals the high impact of general challenges that have to be overcome in real-world deployments.

1. INTRODUCTION

Wireless mesh networks (WMNs) have been used in campus and city networks to provide high-bandwidth Internet access [1]. Experiments with real-world deployments have proven the usability of directional antennas for wireless radio networks to connect nodes over long distances [2]. Heraklion MESH [3], WildNet [4], and Quail Ridge Reserve WMN [5] are three recently deployed mesh networks. They successfully interconnect nodes by directional antennas, providing cheap, stable and robust broadband network access using low cost radio technology. Recently, wireless mesh technology has been used for establishing rural networks [6] and environmental monitoring applications [7]. Distances that have been successfully covered are in a scale of several 10 km [3] to 100 km [4]. The advantage of 5 GHz links is expected in lower interference with existing networks, which are mainly using the 2.4 GHz ISM band. Actual measurement results of far-distance 5 GHz (802.11a/h) links applying directional antennas are very rare. Literature on related experiments is however very limited and mainly covers evaluations performed in the 2.4 GHz band (802.11b/g) [3, 5, 2].

Our contribution is the deployment of a 5 GHz WMN outdoor testbed using directional antennas with links up to 14 km. We share our valuable experiences in order to facilitate similar WMN setups in the future. As with any real-world deployment, many unexpected challenges arose prior to and during network setup and operation that demand timely fixes and design decisions. In addition, we present evaluations of our deployed network which was operational for about three months.

In the following sections, we first describe the CTI-Mesh project, our motivation scenario, and the regulatory framework for our outdoor feasibility test. Afterwards, we present the equipment and software used. Then, based on the regulations and equipment, we calculate important scenario parameters like the maximum permitted output power for the wireless network interface cards, minimum antenna/mast heights, and the expected received signal strengths. Valuable experiences made during the planning and deployment as well as evaluations and discussion conclude the paper.

2. CTI-MESH NETWORK

The technology transfer project ”Wireless Mesh Networks for Interconnection of Remote Sites to Fixed Broadband Networks (Feasibility Study)” evaluated the utility and feasibility of WLAN-based WMNs in application scenarios, where remote sites need to be connected to a fixed broadband network. Examples for such scenarios are high-bandwidth sensor networks deployed in areas where fixed broadband networks have not yet been deployed or where it is considered too costly to deploy them. It has been tested whether the used hardware and software components are appropriate for the intended application scenarios. A deployment of a typical real world application as an outdoor testbed has been realized.

2.1 Project Partners

Besides the University of Bern, three industry partners, MeteoSwiss, SWITCH, and PCEngines, with different interests were involved. MeteoSwiss, the operator of the meteorological network of Switzerland, has approximately 130 weather stations (distances between them are 30 km on average) with environmental sensing equipment deployed all over Switzerland. The stations are connected to control centers either via switched telephone connections, DSL, or GPSR/UTMS. WMNs provide an alternative network access for the weather stations. Moreover, MeteoSwiss owns a number of remote weather sensors that are connected to the main weather station via wireless communication links, which could additionally profit from WMN technology. SWITCH, the provider of the Swiss national research and education network, evaluates WMNs as a possible extension of the geographic coverage to its fibre network and to offer broadband services to locations that are not close to the fibre network. In addition, WMNs provide cost-efficient network access for temporary installations. PCEngines provided the wireless mesh nodes and antennas for the project. Improvements for future products and services are targeted.

2.2 Scenario

As a test scenario, the project partners decided to connect a weather station at Payerne to the fibre backbone with an access point at Neuchâtel. A camera sensor had to be made accessible over a wireless mesh access network to the Internet by two redundant paths in order to provide robustness and reliability (see Fig. 1). The network consisted of six nodes, of which the four intermediate nodes are solar-powered (see Fig. 2 for an intermediate node). One end point of the wireless mesh access network, node01, is mounted on the rooftop of the University of Neuchâtel. It acts as gateway to the fibre backbone. The other end point, node06, operates as gateway to the sensor network with an IP capable camera.

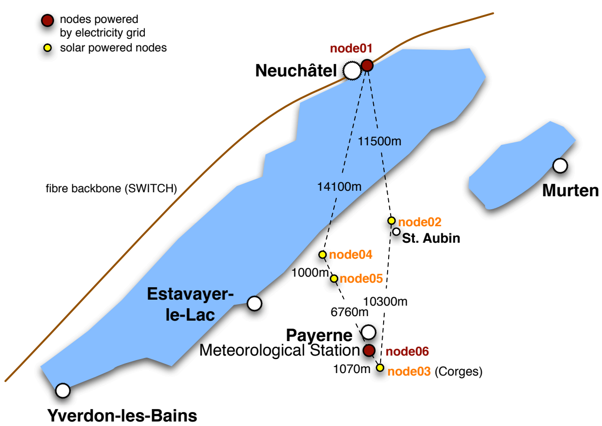

Figure 1: CTI-Mesh network deployed in the area Neuchâtel - Payerne, Switzerland

2.3 Regulations

Swiss regulations released by Federal Office of Communication (OFCOM) restrict outdoor communications following the 802.11h standard to the higher 5 GHz frequency band (5.470 – 5.725 GHz). The effective regulations concerning our outdoor testbed are listed in the technical interface specification RIR1010-04 [8], which is based on EN 301 893 [9]. They include the following restrictions:

- A maximum value of 1000mW (30dBi) equivalent isotropically radiated power (EIRP) is permitted with transmit power control (TPC). A maximum value of 500mW EIRP is permitted without TPC. With TPC, an 802.11h device shall automatically reduce its transmit power to the lowest level that guarantees a stable and reliable connection considering the expected attenuation and the variability of signal quality at the receiver. TPC results in reduced interference to other systems sharing the same frequencies. The lowest value in the TPC range of a device has to be at least 8 dB below the maximal EIRP limit.
- Dynamic frequency selection (DFS) is mandatory. It shall detect interference from radar systems, automatically switch to another channel, and therefore avoid concurrent operation with these systems on the same frequency. In addition, uniform spreading of the used spectrum is required.

Figure 2: Node05 deployed near Belmont.

2.4 Equipment

In order to facilitate future deployments we describe the used equipment. This includes the mesh nodes, electrical power supply, mast, mounting material, and tools.

2.4.1 Mesh Nodes and Antennas

A PCEngines Alix.3D2 embedded board forms the core of our mesh nodes (see Fig. 3). The board contains a 500 MHz AMD Geode LX800 CPU, 256 MB RAM, two miniPCI slots, an Ethernet interface, and a real-time clock with battery. The two miniPCI slots hold two IEEE 802.11a/b/g/h cards. The embedded operating system for the mesh node is stored on a 1 GB CompactFlash card. The Alix.3D2 board is packed in an aluminium weather sealed (IP-67) outdoor enclosure. Two directional panel antennas (23dBi gain, 9° beam width) are connected through 0.5m low loss antenna cables (1.62dB) and N-type pigtails to the wireless cards. The node's Ethernet interface is extended outside of the enclosure by a weather sealed Ethernet jack. A twisted pair cable then provides electric power and network connectivity to the node.

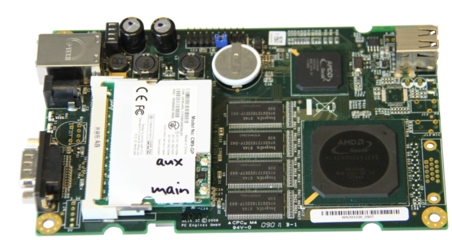

Figure 3: Mesh node: PCEngines Alix.3D board with two IEEE 802.11a/b/g/h miniPCI cards and a battery for the real-time clock.

2.4.2 Power Provisioning for the Mesh Nodes

The mesh nodes are either powered by the electricity grid or by solar panels. The two nodes, which are mounted on the buildings of the University of Neuchâtel and MeteoSwiss (node01, node06), are connected via a lightning protector and a power over Ethernet (PoE) adapter to the standard electricity supply. The four afield nodes are supplied with electricity by solar power equipment. Besides a 80W solar panel, the equipment consists of an aluminium supply box, a solar charger, an acid battery (65Ah, 12V), a lightning protector, and a passive PoE adapter. The node on top of the antenna mast is connected by a twisted pair cable to the electricity supply box. The cable also provides network connectivity over Ethernet for on-site maintenance, which has proven to be useful throughout the deployment phase. In compliance with best practise from our project partner MeteoSwiss, we mounted the solar panel vertically which on one hand reduces the efficiency of the panel, but avoids other energy harvesting problems due to leaves, dust, rain, snow, and icing. The battery is dimensioned to support self-sustaining node operation without recharging by the solar panel for about 10 days. During normal operation, the measured power consumption of the mesh node is approximately 3.3 W (271 mA, 12 V).

2.4.3 *Masts*

Telescopic masts (sideways slotted aluminium tubes, max. height 9m) with tripods are used to install the directional antennas and the mesh node in order to minimise disturbance and building activities. The mast type has been selected considering costs, transportability, project duration, and higher acceptability for the land owners providing the node sites for the installations. The telescopic mast is held by a mast tripod and a rope guying. We weighted the tripod with sand bags in order to get a basic stability of the mast. Iron stakes further fix the tripod to the ground. The mast is guyed on two levels, each with three ropes. We selected a braided polyester guy rope with low stretch and easier handling than a steel guy wire. A first rope equipped with thimbles and wire clamps on both sides is connected with S hooks to the guying clamp on the mast and to the rope tightener. Then, a second rope is attached to the other side of the tightener and thereafter fixed to the ground by a wooden pile.

2.4.4 *Wall Mounting*

The above described mounting support has been used for all nodes except the node on the platform roof of the University of Neuchâtel. There, we mounted the antennas and the mesh node on a L-tube that has been anchored to the wall (see Fig. 4). Mounting of the antennas and nodes require several small parts like U-bolts, screws, and nuts.

2.4.5 *Tools and Utilities*

In order to assemble and mount the mesh nodes, different tools are required. The most important ones are a sledge hammer, slotted and Philips screw drivers, different wrenches, Allen keys, water pump pliers, a hammer, a knife, an angle measurement plate protractor, binoculars, a clinometer, an amplitude compass, a digital Volt/Ampere meter, a RJ45 crimp tool, a tester for twisted pair cables, and two carpenter's levels. Moreover, a socket wrench with ratchet handle makes life easier. A foldable ladder is useful as well. A sack barrow helps transporting the material and relieving the back. Finally, a folding chair makes on-site configuration tasks more comfortable.

Figure 4: Assembling of node01 on the platform roof of the University of Neuchâtel.

2.5 Maximum Output Power, Minimal Antenna Heights, and Expected Received Signal Power Levels

During the planning phase of the project, we calculated relevant parameters for our setup. These include the maximum permitted output power of the wireless network interface cards to comply with regulations, the minimal required antenna heights to guarantee good connectivity, and the expected received signal power levels to cross-check during the deployment.

The OFCOM limits the maximum transmission power to a value of 1000mW EIRP when using TPC (see Section 2.3). EIRP [10] is defined as the emitted transmission power of theoretical isotropic antenna to produce the same peak power density as in the direction of the maximum antenna gain. It is calculated by subtracting cable losses and adding the antenna gain to the output power (see Equation 1). The received power level at the receiver input (S_i) is shown in Equation 2. For our calculations we used the Free Space Loss propagation model as defined in Equation 3.

$$EIRP = P_{out} - C_t + G_t \quad (1)$$

$$S_i = P_{out} - C_t + G_t - FSL + G_r - C_r \quad (2)$$

whereas
$EIRP$:= Equivalent Isotropically Radiated Power in dBi
S_i := Received power level at receiver input in dBm
P_{out} := Transmitted output power in dB
C_t := Transmitter cable loss/attenuation in dB
G_t := Transmitting antenna gain in dBi
G_r := Receiving antenna gain in dBi
FSL := Free Space Path Loss in dB
C_r := Receiver cable loss/attenuation in dB

$$FSL = 10\ log((\frac{4\pi}{c}df)^2) \quad (3)$$

whereas
FSL := Free Space Path Loss in dB
f := Frequency in Hz
c := Speed of light in a vacuum 300'000'000 m/s
d := Distance between transmitter and receiver in m

It is required that at least 60% of the first Fresnel zone are free of any obstacles in order to use the FSL model for calculation of the attenuation. Otherwise, additional attenuation has to be added. Equation 4 calculates the radius of the zone that has to be free around the line of sight. The earth curvature is a further obstruction of the Fresnel zone. Hence, the minimum antenna height has to consider it as well. Equation 5 defines the additional antenna height EC_m due to the earth curvature [11]. It also considers the effect of atmospheric refraction, which causes ray bending at microwave frequencies. In practice, the reception of the microwave signal is possible a little beyond the optical horizon. The minimum antenna height H_{min} is then defined in Equation 6. For our calculations in Table 1 we used the values $EIRP = 30dBm$, $f = 5.5GHz$, $C_r = 1.62dB$, and $C_t = 1.62dB$.

$$FZ_{r(m)} = 0.6 \times \frac{1}{2}\sqrt{\frac{d \times c}{f}} \quad (4)$$

$$EC_m = \frac{d_1 \times d_2}{12.8 \times k} \quad (5)$$

$$H_{min} = EC_m + FZ_{r(m)} \quad (6)$$

whereas
$FZ_{r(m)}$:= Radius for 60% of the first Fresnel zone
EC_m := Additional antenna height due to earth curvature
d_1, d_2 := Distances point ↔sender/receiver in km.
$k := \frac{4}{3} \times$ earth radius (6'371 km)

Table 1: Links using 1000mW EIRP

$Node_{xx}$	d_m	$FZ_{r(m)}$	$H_{min(m)}$	FSL_{dB}	$S_{i(dBm)}$	$P_{out(mW)}$
01 ⇔ 02	11500	7.513	9.463	128.47	-77.09	7.277
02 ⇔ 03	10300	7.110	8.668	127.51	-76.13	7.277
03 ⇔ 06	1070	2.291	2.308	107.85	-56.46	7.277
06 ⇔ 05	6760	5.760	6.431	123.86	-72.47	7.277
05 ⇔ 04	1000	2.215	2.223	105.26	-53.87	7.277
04 ⇔ 01	14100	8.319	11.239	130.24	-78.86	7.277

As all our node sites are located on top of hills, our telescopic masts with a height of 9m are sufficient. Keeping the antenna heights below 10m further avoids the necessity to request a building application from the local authorities.

2.6 Software

The mesh nodes run an embedded Linux distribution with a Linux 2.6 kernel as operating system. The Linux distribution is an own development and called ADAM (Administration and Deployment of Ad-hoc Mesh networks) [12, 13]. It provides a build system for an embedded Linux distribution and mechanisms for fail-safe configuration and software updates. The ADAM build system generates software images with a small footprint for several embedded mesh node platforms (e.g., PCEngines, Meraki Mini, and OpenMesh Mini).

ADAM has been inspired by OpenWrt [14], but completely separates binaries and configuration data in order to enable distributed network-wide updates. Configuration and software updates are performed in a completely distributed manner incorporating a pull-based distribution scheme based on the existing management agent cfengine [15]. Several fallback mechanisms guarantee safe operation and node availability, even in presence of configuration errors and faulty software update images.

The communication software consists of the wireless driver, the Linux IPv4/IPv6 dual stack, and a routing daemon. A patched version of MadWifi 0.9.4 [16] is used for the wireless driver. The Linux network stack as well as all the network tools on the ADAM image supports IPv4 and IPv6. The routes inside the wireless mesh network are automatically established by the olsrd routing daemon [17], an open source implementation of the Optimized Link State Routing (OLSR) [18] protocol.

A concurrent IPv4 and IPv6 configuration has been selected for the CTI-Mesh network. Public IPv4 and IPv6 addresses have been assigned to every wireless interface in the network. In addition, the gateway node (node01) in Neuchâtel and the mesh node (node06) in Payerne have public IP addresses assigned to their Ethernet interface enabling access to either the fibre backbone or the IP webcam. The network could also have been setup with network address translation for the IPv4 addresses at the gateway node. However, due to easier accessibility, all nodes use public IP addresses. Every intermediate mesh node sets up a DHCP server providing private addresses on its Ethernet interface for on-site maintenance.

3. NETWORK DEPLOYMENT

3.1 Planning, Predeployment, and Deployment Process

A field test requires several steps in planning and predeployment. We recommend the following actions as our best practise: time planning, selection of testing area, finding appropriate locations for intermediate nodes, reconnaissance of node sites, agreements with land owners, determining and ordering appropriate equipment and tools, preparation of equipment, setup of software and configuration, predeployment tests, and final deployment.

A complex project with several external dependencies requires extensive time planning and scheduling. One has to consider the availability of means of transportation, equipment, and external parties, such as public administration and land owners. Further restrictions may be caused by site accessibility and weather conditions.

Besides a time schedule, a testing area and the elevated node sites providing line-of-sight connection are required. Accurate electronic maps help to determine candidate locations for the deployment. As there are always differences between maps and reality, a next step is to go on-site (reconnaissance) and verify whether the sites are actually useable. Then, the land owners have to be contacted in order to get a permission for using their property for the tests. For getting the agreements, we had the best experiences when talking face-to-face.

Another activity is checking and preparing the equipment. Once the ordered equipment has been delivered, completeness and functionality should be checked. It is then advisable to prepare the material before going in the field, e.g. assembly of nodes and antenna, preparing guying ropes by cutting them and adding thimbles and wire clamps.

The next step should be a predeployment test. All equipment is assembled completely and set up outdoors. This helps in identifying defective and missing parts. Moreover, first stability tests of hardware and software can be performed.

After the predeployment tests, one can proceed to the final deployment. Certainly, there are always some problems that arise after the planning and predeployment phase. The next section gives an overview of different challenges that occurred during our whole deployment.

3.2 Deployment Experiences

During the deployment we had to find practical solutions to several problems and challenges. We classify the challenges into the following six categories.

3.2.1 Software Problems

Some software problems arose during the project. First, the outdoor use of 802.11h (TPC and DFS) in combination with ad-hoc mode is not commonly used and therefore not the highest priority for the MadWifi developers. Thus the wireless driver provides poor support for these configuration settings. By applying several patches from the OpenWrt project [14], we significantly improved the system's stability and operation. Second, the routing daemon stopped working occasionally. Monitoring the routing daemon and restarting if necessary solved this problem.

3.2.2 Mechanical Challenges

The mechanical challenges included correct antenna alignment at setup, sinking in of tripods, torsion of mast elements by fixed guying clamps, and defective material. The correct alignment of the antennas is crucial as directional antennas are used. After having calculated the angles and elevations by using maps, there are four mechanical problems for correct alignment.

First, the two antennas have to be fixed to the top mast element with the correct intermediate angle. We adjusted the pre-calculated angle using a precision mechanic universal Bevel protractor.

The second problem is keeping the exact direction of one antenna aligned to a reference system on the bottom element of the telescopic mast. Any attempt to lift the mast elements in vertical position results in torsion of the top element compared to the bottom element. We therefore assembled the mast completely in horizontal position and then erected it in one piece (see Fig. 5). In order to transcribe the antenna direction to the reference plate, we used two carpenter's levels when the mast was in horizontal position. One level was positioned on one of the antenna and balanced. The reference plate was then aligned and balanced with the other one. Using an amplitude compass on the reference plate, the antenna could then be aligned correctly. Since preliminary tests [19] revealed that visual alignments of the antenna failed, an amplitude compass and an inclinometer have been used for correct alignment. Afterwards, we fine-tuned the alignment with the help of the received signal strength. Although the alignment with the amplitude compass generally worked well when being in the field, there were magnetic interferences from generators on the platform roof of the University of Neuchâtel which we required several attempts for the alignment of the antennas of node01.

The third mechanical challenge was the sinking in of the tripod into the soft and rain-sodden soil after heavy rain falls. The results were lopsided masts. Thus, we stabilized the ground with concrete paving slabs as shown in Fig. 6).

The fourth mechanical challenge was an unexpected torsion of some mast elements, which occurred after some time and resulted in connection losses of the directional antennas.

Figure 5: Complete assembly of telescopic mast in horizontal position before final setup.

Figure 6: Concrete paving slab to prevent sinking in of the tripod, sand bag and iron stake to stabilize mast.

The reason was the fixed mounted guying clamps used. On all node sites, the guying ropes could not be fixed with intermediate angles of 120°. Therefore, the ropes' tensions produce a torsion force, which then turns the mast element. New movable guying clamps (fibre-enforced plastic) as shown in Fig. 7(a) solved the problem by decoupling the mast elements and the guying.

3.2.3 Missing or Defective Material

Another problem is missing or defective material. The complete setup of the material during the predeployment tests helped us to minimise the consequences such as unnecessary on-site operations and delays. Furthermore, the predeployment tests showed the necessity of two guying levels to avoid oscillations of the mast top with the antennas.

3.2.4 Technical Communication Problems

During the network setup two communication problems appeared. First, we discovered unexpected packet loss on the wired link between the border router and the gateway node node01. The dedicated twisted pair cable (100m) in combination with the data link lightning protector produced high attenuation and collisions. Reducing the cable length to 50m by taking advantage of the existing building wiring eliminated the problem and resulted in the expected 0% packet loss on the wired link. Second, the different wireless links interfered with each other as they communicated on the same channel. The interference was reduced by alternating use of

(a) Movable guying clamp to prevent torsion of mast (b) Broken antenna due to strong winds and loose guying (node02)

Figure 7: Exemplary challenges

three channel sets and exploiting the two antenna polarisations (horizontal and vertical).

3.2.5 *Natural Environment*

The natural environment had several influences on our feasibility study. Besides rain-sodden ground as described above fog, storms, and animals had an impact on the network. The solar panels used should have normally produced enough energy to charge the batteries and power the mesh nodes 24/7 throughout the year and independent of weather conditions. Nevertheless, we observed two nodes that completely drained their batteries and thus stopped working for approximately one week in November 2009. The other two solar-powered nodes had completely charged batteries in the same period during daytime. In fact, bad weather conditions, including locally dense fog over several weeks, prevented the solar panels from producing enough energy for charging the batteries. Once the solar panel delivered again enough electric power, following the bad weather period, the nodes restarted normal operation without any operator intervention.

Furthermore, parts of our equipment were severely damaged during storms. First, lightning destroyed the web cam on the roof of the MeteoSwiss building during a thunderstorm. The mesh node was not affected due to the data line lightning protector. Second, a windstorm broke one of the masts as one guying rope had become loose (see Fig. 7(b)). As no further mast was buckled, even during heavier windstorms, we are convinced that the selected mast material is sufficient as long as the guying is correctly applied. Birds of prey used our masts and antennas as raised hides. Since they also sat on the antenna cables, they loosened the connector on the antenna. Tightening and gluing the connector reduced the effect. We did not succeed in keeping the birds away from the masts. Other animals taking profit of our installations such as spiders, ants, beetles and mice did not influence the network.

3.2.6 *Administrative Challenges*

The last category are administrative challenges. First, we required the agreements for hosting a node. After the time-consuming determination of appropriate node sites and their landlords, convincing the landlord to give an agreement is demanding. Face-to-face communication and showing the equipment were the key elements for success. Second, determination of the suppliers for all the required equipment and tools was difficult and keeping track of all the parts and pieces is a necessity.

4. EVALUATION

The aim of the project was to connect sensing equipment over a WMN to the wired/fibre backbone. As a show case application, an IP camera was connected and accessible from the Internet during the deployment.

In [19], we presented some preliminary measurements. During these measurements, strong winds caused periodic movements of the antenna top which resulted in high packet losses. In the final deployment, this effect has been eliminated by guying the antenna to the ground with ropes.

For all measurements, the CTI-Mesh network used a fixed data rate of 6 Mbps for the IEEE 802.11h interfaces. Setting higher data rates is possible, but the longest links stretching over 10 km may then become unavailable.

In order to give an impression of the achievable bandwidth over the deployed network, we performed TCP bandwidth measurements using the tool iperf [20]. The results are shown in Fig. 8 and 9. The measurements were started in sequence and lasted for 10 min. Data values were produced for periods of 10s. In the graphs, the data is represented by its median value, the 25% percentile and the 75% percentile (box), and the minimum and maximum value (whiskers).

First measurements were run from the nodes towards the gateway (node01) (see Fig. 8). The results are similar for all nodes with a median value of 439 kbps. Due to the orthogonal use of polarisation and channels, there is almost no intraflow interference along the multi-hop path.The bottleneck for the TCP transmissions is the link with the lowest bandwidth.

Fig. 9 presents the second measurements, performed between direct neighbours. It shows that the overall bandwidth is mainly limited by the long distance links above 6 km. The capacity of the 1 km link between node04 and node05 reaches about 55% of the set data rate (6 Mbps) which lies slightly below the commonly reported throughput values. In fact, this link could not be positioned ideally. A bordering forest located in the middle of the link covered more than the 50% of the first Fresnel zone. The low value for the 1 km link between node06 and node03 may be explained by the fact that setting the correct elevation angle (3° due to the difference in altitude) for the antennas was very difficult with our equipment. Moreover, the link is aligned directly with the city centre of Payerne and we identified several neighbouring concurrent networks that produced interference.

In order to monitor the network's availability and the link/route quality, we logged the routes to node06 with the corresponding routing metric ETX (Expected Transmission Count) cost values at node01 every 10min.ETX defines the number of transmissions that are required to successfully transmit a packet. In Fig. 10, the weekly ETX values are depicted and show that most values are near to the optimum of 3.0 for the three hop path (node01$\leftrightarrow$node06). ETX values above 9.0 usually occurred when the connection was lost or after the connection became available again. Fig. 11 provides an overview of the general route availability towards node06 and the IP camera for 81 days.

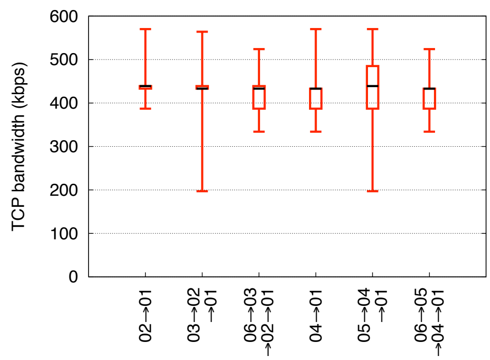

Figure 8: TCP bandwidth for the connections to node01

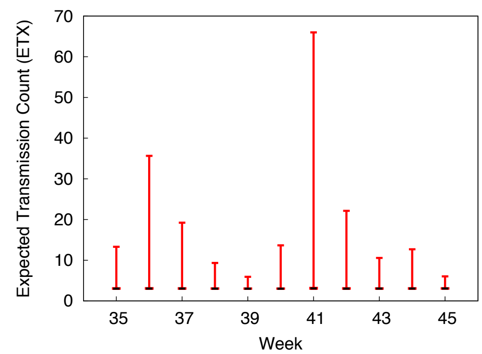

Figure 10: ETX values for best route from node01 to node06.

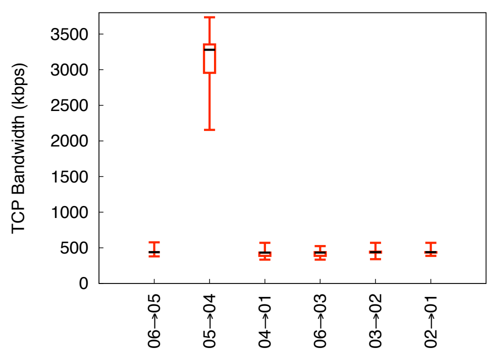

Figure 9: TCP bandwidth for each link

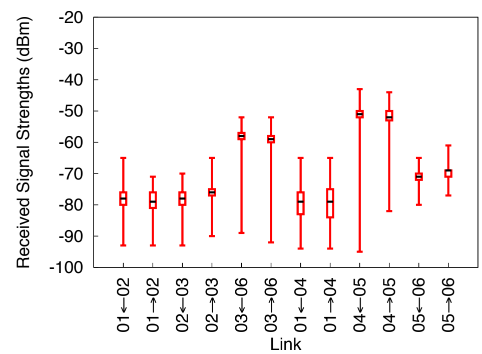

Figure 12: Received signal strengths for all six links

Several events had an impact on the route availability, e.g., wind breaking the mast of node02 on day 45 which was replaced nine days later. Moreover, stability problems of the wireless driver led to non-functioning wireless devices. The effect could be minimised by automatic service restarts and reboots after day 44. The drawback of some unnecessary restarts is that the maximal achievable route availability was reduced to about 99%. In many situations, this may be sufficient as most sensor data can be aggregated and then transmitted with some delay. Moreover, redundant paths can be used to cope with short link outages.

By periodic ICMP ECHO measurements, we further measured the average delay and the corresponding packet loss on the path between node01 and node06. After fixing the software issue and replacing the mast of node02 (day 54), the measured average round trip time (RTT) is 11.6ms and the average packet loss is 7.18%.

In order to verify our deployment, we logged the signal strength values at each node (see Fig. 12). The resulting median values are symmetric for both directions of the same link and correspond to the calculated signal strengths in Table 1. The difference is partly due to TPC adjusting the transmission power. Further reasons have to be investigated.

Despite using alternating antenna polarizations, high quality cabling, orthogonal channels and channel separation, the network performance may still suffer from adjacent channel interference and, if using multi-radio systems, board crosstalk and radiation leakage [21, 22, 23]. Although not observed in our setup, increased separation of the antennas and additional shielding is recommended.

5. CONCLUSION AND FUTURE WORK

We presented our deployment experiences for a solar powered wireless access mesh network for meteorological data acquisition. They provide a valuable starting point for any future WMN outdoor deployments, where we strongly advise to perform extensive predeployment tests. Besides testing the communication software, it is advisable to set up the complete nodes including masts and solar equipment before on-site deployment. This enables identification of missing or defective equipment and tools before going into the field. Moreover, replacement parts should always be kept available. Otherwise, setup and repairs may be delayed by additional on-site operations or even by long delivery times for spare parts.

Our evaluations showed that our setup can provide a network service for transmitting weather data (430 kbps over 20 km). The network stability can be further improved, e.g. by replacing or extending the OLSR routing daemon to avoid route fluctuations and migration of the used MadWifi wireless driver to its successor driver. Moreover, self-healing mechanisms could be enhanced by integrating a hardware watchdog that could recover a node from undefined states.

In order to use a similar outdoor network for testing various new protocols and architectures, we propose to add self-healing and remote access mechanisms to each mesh node, e.g. by introducing an additional management node per mesh node. The second node could provide remote access via an UMTS/GPRS link. Moreover, it would enable reloading isolated mesh nodes with new software and collecting additional monitoring data, e.g. log data from the solar charger. In addition, an authentication, authorization and accounting (AAA) infrastructure could be integrated in the WMN.

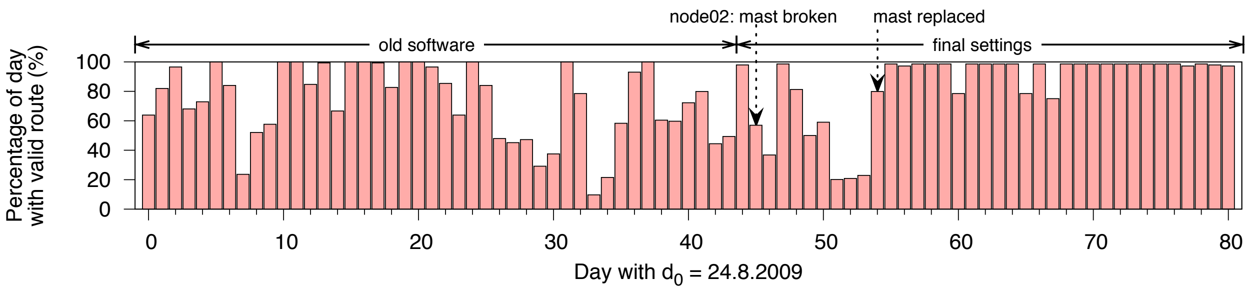

Figure 11: Route availablity to node06 / IP camera at node01

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