Design and Deployment of a Wireless Sensor Network Testbed for Forest Monitoring

Entwurf und Entwicklung eines drahtlosen Sensornetz-Testbeds für Wald-Monitoring

Masterarbeit von Iliya Gurov

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Vorgelegte Masterarbeit von Iliya Gurov

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Darmstadt, den 15.01.2013

(Iliya Gurov)

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Contents

1 Introduction

1.1 Motivation

Wireless sensor networks (WSNs) are composed of resource-constrained tiny devices that are often embedded in harsh and large environments. These type of distributed systems are an ideal tool for large-scale monitoring of real-world phenomena [1, 13, 20, 21, 24]. However, the wirelessly communicating sensor nodes are often prone to errors and malfunctions due to radio and sensor irregularities in the complex, real-world environment. They can often exhibit a limited accessibility in the field because nodes are often deployed across large areas. Furthermore, inspecting sensor nodes' internal states can be a tedious task to do. All these aspects make software development for sensor networks hard. Despite the existence of sensor networks simulators like TOSSIM [12] and COOJA [15] that can scale up to thousand of nodes, allow various parameters' tunning and ease the software development of sensor network systems, their principal limitation resides in introducing real-world phenomena such as the one caused by unpredictable and constantly changing weather conditions into the simulation. This can result in differences between the behavior of the system in simulation and the behavior of the actual system in the real-world. On the other extreme, using real-world deployments for experimentation is costly and often these deployments are shortly-lived.

To overcome the drawbacks of simulation-based evaluation of WSN protocols and algorithms, it becomes necessary for researchers to move a step further from simulators and develop, deploy, and debug applications on realistic large-scale sensor networks. As shown in Fig. **??**, WSN testbeds have been proposed as a solution that combines the best of simulators and real-world deployments. They provide software developers with the possibility of deploying and debugging their firmware in a realistic physical environment by means of additional infrastructure and real radio hardware. They simplify the experimentation, enabling theoretical exploration and a high level of experiment reproducibility.

1.2 Problem Statement

The physical properties of the site where a testbed is deployed has a major impact on the obtained results, in particular with respect to the wireless environment. To date, most testbeds have been deployed on indoor premises, which simplies the required infrastructure. These indoor, lab-based facilities do not exhibit important outdoor physical phenomena such that caused by the harsh and changing weather conditions. As a result, they may not approximate well outdoor deployments such as large-scale monitoring of outdoor environments, civil

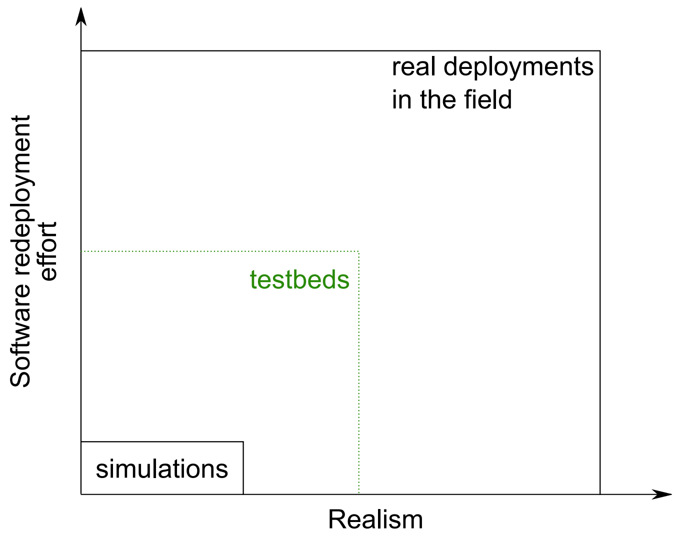

Figure 1.1: Testbeds as a solution to close the gap between simulators and real deployments.

structures, animal habitats and agricultural scenarios. Indoor testbed facilities do not yield the targeted level of realism needed for outdoor scenarios. As a result of not testing an outdoor application in the context of an appropriate experimentation facility that approximates well the targeted environment, unexpected problems can occur when the network is deployed outside in the field. These problems, often caused by environmental triggers such as temperature, humidity, lightning or interference, can affect various hardware components like sensors, connectors, oscillators, radio and batteries. In Fig. **??** - it is shown how the temperature influences the oscillator frequency variantion. As the temperature increases, the oscillator drift also increases, which in turn leads to desynchronized node schedules. In Fig. **??**, as the temperature increases, the oscillator startup latency also increases, leading to unnecessary watchdog resets.

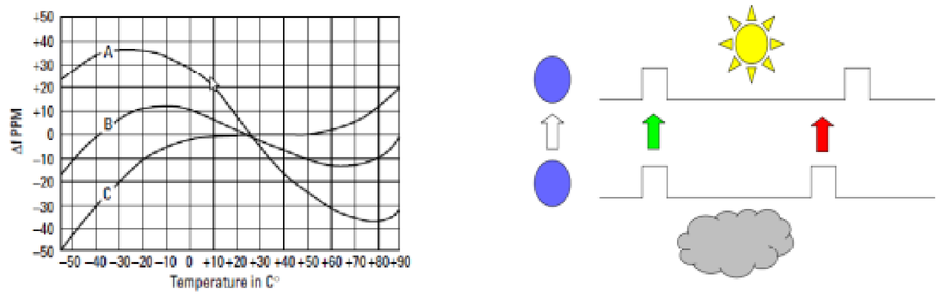

Figure 1.2: High temperature creates oscillator drift which in turn desynchronizes node schedules.

Discovering such problems and unexpected behaviors later in the deployment phase is often a difficult and tedious process. Furthermore, especially in the case of large-scale WSNs, fixing and handling these problems could be even more difficult.

On the other side, the construction of outdoor testbeds present a number of unique challenges that make their construction non-trivial. To begin, in outdoor setups, two main infrastructural elements are either not available or as easily accessible as in indoor facilities: the power network and the control and data backchannel (e.g., Ethernet, USB). This either requires their

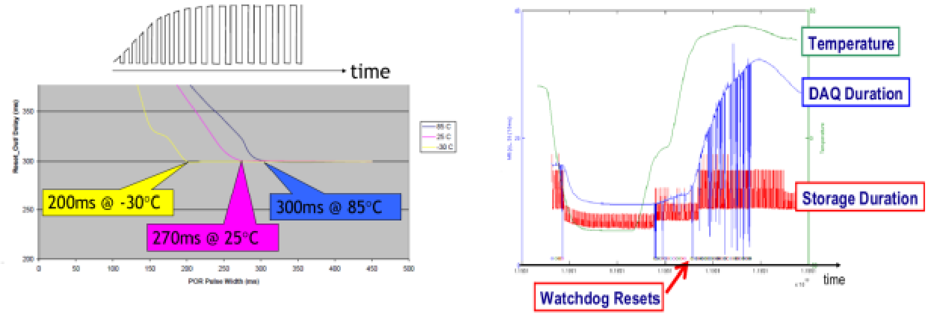

Figure 1.3: High temperature creates oscillator startup latency which in turn leads to watchdog resets.

deployment and reasonable, safe integration into the environment (an intuitively laborious task, which leads to an efficient and robust infrastructure) or the construction of a wireless backchannel (lower deployment effort, but less robust). Second, the variable weather conditions, as well as vandalism (common in public spaces) call for a careful design of a station enclosure for the sensor node (and any required, additional testbed hardware). Last, an adequate wireless node platform must be identified, together with a set of sensors that enable environment-dependent applications.

1.3 Contribution

To address the issues described above, in this work we describe the design and deployment of an outdoor forest WSN testbed, safely integrated into the environment. To the best of our knowledge, this the first outdoor, permanent and unattended sensor network testbed to be made publicly available. This testbed is to be integrated into TUDμNet [16], the metropolitan-scale federation of WSN testbeds deployed in the city of Darmstadt, Germany. The venue of this outdoor site is the botanical garden (BG) of the Technische Universität Darmstadt. Its unique characteristics such as 9.25 rainy days per month and temperature varying in average between -2 °C and 24 °C, enable researchers to test their software in an outdoor experimentation environment with changing weather conditions, which is crucial for outdoor sensor network systems. The software developers can benefit from the higher level of realism that an outdoor experimentation facility offers as shown in Fig. **??**, by detecting bugs and problems or discovering new properties early in the testing phase.

Another interesting aspect which emerges in the context of this work is the evaluation of the properties of wireless communication in outdoor scenarios, as compared to indoor ones. So far, networks deployed outdoors have not been made available to allow other researchers to validate their result on these deployments. Therefore, at the end of this work, we present an initial evaluation of link quality which was performed on the targeted site.

Due to the time-consuming deployment processes, the three objectives that this work have are the following:

Objective 1 The analysis and design of a first outdoor testbed's infrastructure to be deployed in the botanical garden of the Technische Universität Darmstadt.

Objective 2 The actual deployment of the testbed, which implies carrying out some of the steps mentioned in objective 1, as time allows.

Objective 3 Performing an initial evaluation of link quality on the targeted site.

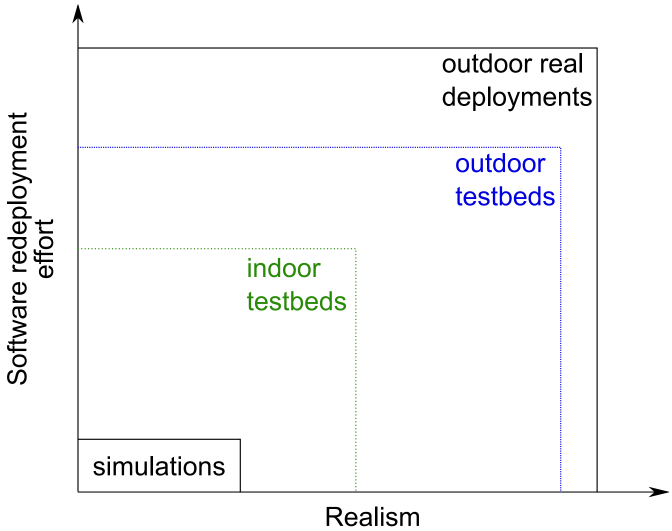

Figure 1.4: Outdoor testbeds targeted to bring more realism in the evaluation of outdoor WSN deployments.

1.4 Thesis Organization

The rest of this thesis is organized as follows. Chapter 2 gives insight into the state-of-the-art related to the most well-known experimentation facilities and their suitability for testing outdoor applications. Chapter 3 introduces the main design decisions regarding the testbed's venue, architecture, enclosures and enclosures' hardware. In the of this chapter we describe the integration of this outdoor site into TUDμNet as well as the TUDμNet's architecture and its control infrastructure as solution for managing experiments at metropolitan scale. Chapter 4 discusses our deployment endeavor in the botanical garden as well as the conducted link quality evaluation and the obtained result. In the last chapter, Chapter 5, we summarize our work and point out the future directions that we will be consider as short-term and long-term projects.

2 Related Work

Sensor network testbeds have been introduced with the goal to close the gap between real deployments in the field and simulators. Testbeds are frequently used for experimenting with new systems' design and validating expected behavior of various applications, algorithms and protocols as last experimentation step before the launch of the system. Generally speaking, testbeds share two main functions: centralized node reprogramming (i.e., flashing) and data collection for a posteriori evaluation. The distinguishing factors are:

- target application domain;
- underlying architecture;
- services offered.

Understanding these three testbeds' aspects in detail will give an overview of what decisions and challenges researchers need to face when designing and building WSN tesbteds and point out the current lack of permanent outdoor experimentation facilities that are open to use from the sensor network's community.

2.1 Target Application Domain

Testbeds can be realized through indoor or outdoor facilities, depending on the application domain they are designed to investigate. Based on the target application domain, decisions about the underlying architecture and software mechanisms are taken. For example, outdoor installations, targeted at the evaluation of outdoor WSN systems, lack the two main infrastructural elements that are typical for indoor testbeds: a power network and a control and data backchannel. The difficulty to lay such an infrastructure typically leads to relying on wireless communication between the different entities in the architecture, which makes them more portable (i.e., easier to deploy), but also more difficult to operate. In contrast, indoor testbeds often use a wired infrastructure, which is on one hand a more expensive solution, but on the other hand more reliable.

2.2 Underlying Architecture

Not only the target application domain influences architecture's design, but also the architecture itself determines testbed's properties. We distinguish between two main architectural designs: two-tier architecture with a central server and directly attached sensor nodes, as shown in Fig. 2.1, left, and a three-tier architecture featuring an intermediate gateway devices' layer. The backbone could be either wired, using Ethernet and USB connections, or wireless. An example of a two-tier testbed with a wired backbone is Vinelab [22], an indoor testbed featuring 48 TelosB nodes covering a one-floor laboratory. Vinelab uses USB interconnections to a central server. CiteSense [14] is an example of a two-tier testbed that has connections to a server via wireless links. We discuss CitySense in more detail in Section 2.4.3. In general, two-tier testbed facilities provide a good experimentation environment for evaluating network connectivity, radio propagation and resource management systems.

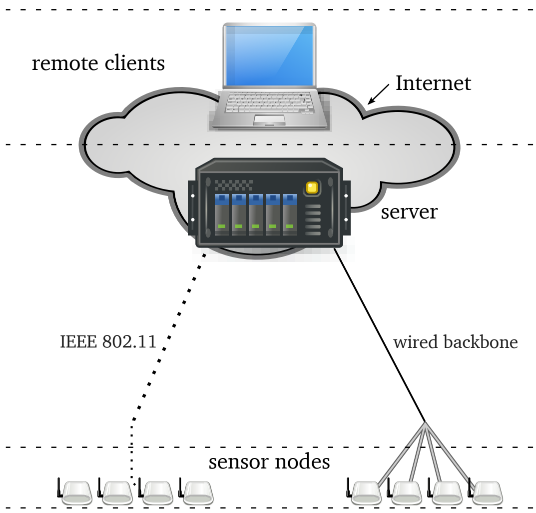

Figure 2.1: A two-tier testbed architecture.

The other approach is a three-tier achitecture (cf. Fig. 2.2) which adds a level of complexity to the system by introducing an additional layer between the central server and the nodes. This intermediate layer of gateways (GW) between sensor nodes and the server increases system reliability and allows finer control over attached nodes. In addition, it also opens further possibilities such as experimentation on the integration of IPv6 networks with WSNs.

In a three-tier-based system, sensor nodes are attached via inexpensive USB cables to USB-to-Ethernet devices that act as intermediate gateways. Laptop computers, embedded Linux servers or custom-built hardware can play the role of GW stations, often static nodes that provide passive experimentation support, but also can act as a part of the experiment. Examples of testbeds - built using a three-tier architecture - are MoteLab [23] and TWIST [9], which we discuss in detail later in Section 2.4.1.

Single-site testbeds usually do not grow beyond a size of 100-200 nodes because of cost and space constraints. An approach to reach an ever larger scale is the federation of individual WSN experimentation facilities interconnected over the Internet. In this way, distributed testbeds appear as one unified laboratory at the application layer that enables testing and benchmarking in a controlled way in different real-world scenarios. Such a federation is WISEBED [2], which consists of 9 geographically distributed networks in Europe, connected using virtual links. A to-

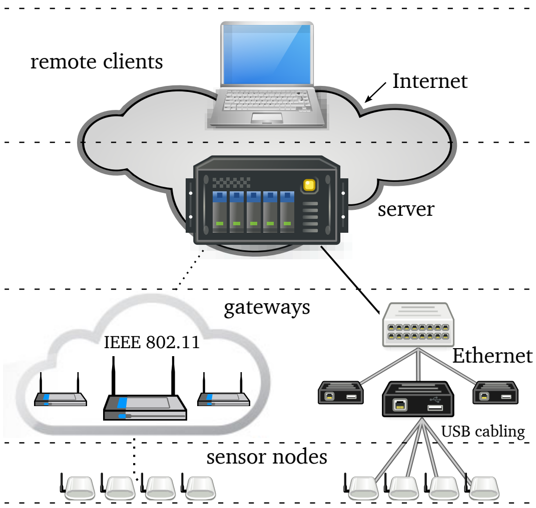

Figure 2.2: A three-tier testbed architecture, introducing an intermediate gateway device layer.

tal of 750 heterogeneous nodes, indoors and outdoors, are available for researchers to evaluate their sensor network-related work.

Another approach that enables the evaluation of sensor network systems in multiple environments is the relocatable testbeds approach. Also called nomadic testbeds, these can be easily moved between sites, which allows the evaluation of systems in different environments. In order to allow easy relocation and high flexibility, nomadic testbeds use 802.11 b/g networking as data and control backchannel. This facilitates further the inclusion of mobile nodes into the experiments, which enables new testing possibilities by introducing different experimentation scenarios. Sensor nodes are attached to mobile objects with controllable trajectory, allowing repeatable mobility patterns, which is an important feature for achieving high experimentation reproducibility. A typical example is Sensei [18], a nomadic sensor network testbed supporting mobile nodes, which is discussed in more detail in Section 2.4.2.

2.3 Services offered

The majority of testbeds follow the experiment life cycle shown in Fig. 2.3. In the first phase, the experiment is defined by specifying the number and type of resources needed, the programs to upload used for flashing the nodes and the metrics to be collected. This information is provided by the user either via a web interface or by script-based tools. In the second phase, called scheduling, an experiment is scheduled for execution and the required resources are reserved. The scheduling usually offers a web interface-based calendar, in which a user can specify a start and end time of an experiment. Users' quotas are employed to avoid a long-term blocking of resources.

The execution phase is the one that mostly differentiates one testbed from another in terms of services offered. Many testbeds just provide basic nodes' reprogramming and data logging features at this level and do not support any mechanisms to control the experimentation's flow,

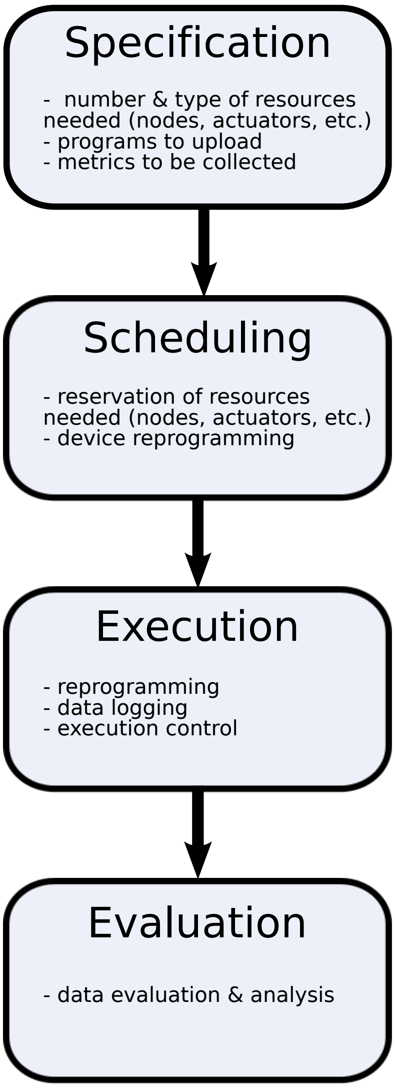

Figure 2.3: Experiment Life cycle using a WSN Testbed Facility.

i.e. after the scheduling is done, the resources are reserved and the nodes are reprogrammed and instrumented for data logging, the user cannot influence the experimentation environment or the current setup by any means and must wait until the end of the experiment to get the data to be evaluated. Some testbeds, however, offer an access to ongoing experiments where the user is able to adjust different experimentation's aspects such as emulating node deaths or turning on actuators that can influence sensor readings (turning on lighting to influence light sensors). Such control mechanisms introduce more realism into the experiments, making testbeds more scientifically attractive for the evaluation of sensor network systems. Real-time monitoring of experiments is another powerful feature that allows users to debug the experiments and follow the execution more easily. This is, however, usually missing in testbeds that use a wireless backchannel to control experiments because it is harder to operate. In the last, evaluation phase, data is made available to the user for its posterior evaluation.

2.4 Testbed's Suitability for Outdoor Applications

First, we define the term testbed's suitability for outdoor applications. We say that a testbed is suitable for evaluating outdoor applications if it yields a good approximation of the outdoor environment. In order to give an insight about how suitable current WSN experimentation facilities for evaluating WSN outdoor applications are, well-known experimentation facilities are described in the next three subsections and summarized in Table 2.1. We start by discussing static indoor testbeds as considered to be the least suitable, going through relocatable testbeds that exhibit higher suitability compared to the one offered by the static indoor locations and then at the end of the chapter current outdoor testbeds are presented as the ones that yield the most adequate level of realism of the outdoor environment as depicted in Fig. 2.4.

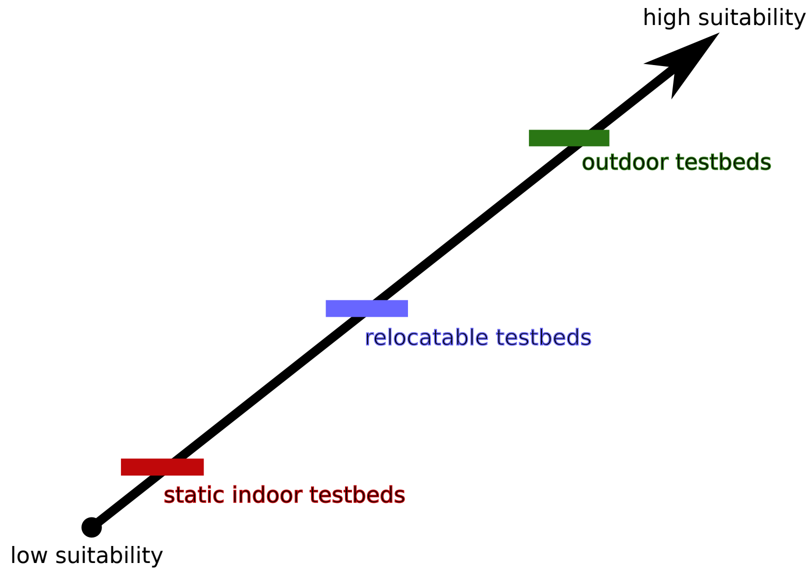

Figure 2.4: Testbeds' suitability for outdoor WSN experimentaton.

2.4.1 Static Indoor Testbeds

Due to sensor nodes' limited resources such as power, memory, CPU and radio range, static testbeds normally do not use the radio for reprogramming the nodes. In order to ensure a reliable reprogramming of nodes, they provide a backbone infrastructure for communication. Often, a central server is in charge of flashing the nodes and instrumenting them for logging data to a central database. The USB interfaces of the nodes are used for attaching the nodes to central gateways, because USB can power the nodes, be used for flashing the nodes and logging the data output from the nodes. Such testbeds are Harvard's MoteLab [23] and Berlin's TWIST [9].

MoteLab is an indoor testbed, whose main goal is to offer a facility that is open and easy to use from researchers worldwide. 190 Tmote Sky sensor nodes are deployed over three floors in the EECS university building in Harvard. It offers a web-based interface for programming, debugging and accessing data for evaluation. Since its creation in August 2003, they have been around 10,000 executed jobs on MoteLab.

TWIST is another indoor static testbed spanning three floors of the TKN office buildings in Berlin measuring more than 1500 m^2 of instrumented space. It supports heterogeneity by having 100 Tmote Sky and 100 eyesIFXv2 sensor nodes. In addition to the typical testbed features, such as node configuration, network-wide programming, and gathering of application data, the concept of emulating node deaths by using port power switching of USB 2.0 hubs was first presented in TWIST.

Another indoor testbed environment is the Kansei Testbed [8] at the Ohio State University targeted towards large indoor sensor network deployments. It features 210 sensor nodes placed on a 15 x 14 rectangular grid, where each node is attached to a powerful gateway station. It uses an Open-Source Linux-Apache-MySQL-PHP Perl implementation technology and web-based scheduling interface, similar to MotaLab's. It allows visualization of sensor readings, debugging and health monitoring.

The wired, fixed, lab-type infrastructure of these testbeds makes them very useful for experiments on algorithms for network connectivity, radio propagation and resource management. But because of their indoor nature, they do not approximate well the outdoor environment which makes them less suitable for experimentation of WSN outdoor systems.

2.4.2 Relocatable Testbeds

The only well-known and publicly available WSN testbed that falls into this category is Sensei [18] - a relocatable, wireless sensor network testbed with support for mobile nodes. It uses devices called sensor hosts at the intermediate tier of the 3-tier architecture model. These sensor hosts act as gateways stations. Any Linux machine could serve as a sensor host as long as it is equipped with USB interfaces for attaching the sensor nodes. In Sensei, the gateways are implement using Asus WL-500G wireless access points which run a minimalistic distribution of Linux called OpenWRT [3]. The sensor hosts communicate with a site manager that keeps track of the sensor nodes, provides direct access to the hosts via the control channel and monitors and log events. An experimental user connects to the control interface used to visualize testbed's events and control experiments. Sensei supports also mobile nodes carried by autonomous robots that reveal new scenarios and challenges into the experimentation. Such a challenge is to create repeatable movements needed for repeatable experiments, in which the core problem is the real time localization of the movable nodes.

Because of their nomadic nature, relocatable testbeds make possible the evaluation of WSN applications in different environments ranging from lab environments to *in situ* installations. Due to their wireless 802.11 b/g control channel network testbeds' relocations are easy. Thus, this makes them more suitable for the evaluation of WSN outdoor applications in comparison to static indoor locations. On the other hand, the wireless backbone communication is more difficult to operate and more prone to interferences. Often, in order to ensure the coexistence of IEEE 802.15.4 radio and WLAN often precautions such as the use of non-overlapping channels and careful choosing of the sensor nodes' positions have to be taken. Furthermore, it is recommended that experiments should be preceeded by additional interference measurements in order to ensure their feasibility and correctness that can be tedious and time-consuming.

2.4.3 Outdoor Testbeds

There have been several attempts to build outdoor facilities for experimenting with WSNs. The most representative among these are probably but probably among them the ones that have contributed at most to the research in this area are the Trio [7] and the CitySense [14] testbeds.

Trio featured 557 solar-powered sensor nodes, seven gateway nodes and a root server, covering an outside area of $50,000m^2$. With its 557 sensor nodes, Trio was one of the largest testbeds built yet. The testbed featured a new sensor network platform that provides sustainable operation, enable efficient *in situ* interaction and supports fail-safe programming. During its continuous operation in the last four months of 2005, it raised new challenges with the network management, power management and networking software not discovered in the context of small-scale or indoor settings until then.

CitySense is an open, city-wide sensor network testbed that features more than 100 stations deployed on buildings and streetlights throughout the city of Cambridge, MA. Stations are equipped with embedded PCs with WiFi and sensors for monitoring air quality, weather, road traffic, contaminants, etc. One of its goals is to leverage experience with Harvard's MoteLab to provide a shared experimental facility with a larger coverage area. It presents an opportunity for software developers to develop, deploy, and experiment with sensor networks at scale in complex real-world outdoor urban environment.

Considered as the most suitable for the evaluation of outdoor WSN applications, these outdoor experimentation facilities dealt with challenges such as over-the-air programming of the nodes and efficient energy usage. Their main limitation, though, is that that they are usually shortly-lived as in the case of Trio. At the time this work was conducted, CitySense seems to have been discontinued. Furthermore, because of these testbeds' wireless nature and the dynamics of the renewable energy, used in the form of solar power supply, additional management software, not seen in permanent, wired experimentation facilities, had to be constructed to operate the testbed services. Consisting of environmentally-responsive energy management, collection and dissemination protocols, among others, this software stack often exhibits weaknesses in the protocols and managements strategies.

All these issues, occurring in the context of wireless outdoor WSN testbeds, justify the importance of an outdoor, permanent and publicly accessible experimentation facility that can offer software developers a robust and reliable environment for the evaluation of their sensor network-related work. With TUDμNet's outdoor site we aim to achieve this goal.

	Mobility		Location		Backbone		Publ. avail.
	static	nomadic	indoor	outdoor	wired backbone	wireless backbone	
Motelab	✓	✗	✓	✗	✓	✗	✓
TWIST	✓	✗	✓	✗	✓	✗	✓
KANSEI	✓	✗	✓	✗	✓	✗	✓
Sensei	✗	✓	✓	✓	✗	✓	✓
Trio	✓	✗	✗	✓	✗	✓	✗
CitySense	✓	✗	✓	✓	✗	✓	✓
TUDμNet	✓	✗	✓	✓	✓	✗	✓

Table 2.1: Summary of the most well-known WSN testbeds.

3 Testbed Design

WSN testbeds are a valuable research tool as they facilitate the software development for sensor network systems. However, installing such an experimentation facility is an expensive and time-consuming endeavor. The costs for the initial hardware acquisition and installation might be even negligible compared to maintenance and operation costs. Since we target a long term, permanent operation, our goal is to keep operation and maintenance costs as marginal as possible, but to achieve this, a careful design and deployment is mandatory.

First, the choice of the testbed's venue is often considered as one of the first design steps. Given its outdoor nature, several outdoor locations were considered and their main characteristics are discussed in Section 3.1. In addition, due to its outdoor nature, an outdoor tesbed's construction reveals challenges not seen in the construction of indoor experimentation facilities. The lack of the two main infrastructural elements, the power network and the control and data backchannel (e.g., Ethernet, USB), makes the deployment of outdoor setups non-trivial. There are two approaches that we considered: a wired 3-tier gateway network which uses power and Ethernet cabling infrastructure or a solar-powered, wireless mesh-gateway network. Both of them are discussed in Section 3.2 and the reasons that made us choose one of them are presented. Due to variable weather conditions as well as possible vandalism, station enclosures were carefully designed. They are discussed in Section 3.3. Then, we describe the hardware within these enclosures - a network router which acts as a gateway, a network switch used to distribute Ethernet to the stations, a cable junction box which plays the role of a power splitter and an adequate sensor node platform. Furthermore, an external, analog soil moisture sensor that enables environment-dependent applications was identified and is respectively reviewed in Section 3.5.

3.1 Venue Selection

A medium-sized city, like Darmstadt, offers many possibilities for deploying such an outdoor WSN infrastructure. We considered three outdoor locations which were possible targets to host a WSN testbed: the Herrngarten, the largest and oldest park in the city, spanning an area of 250.000 m^2, the backyard of the Computer Science Department and the Botanical Garden maintained by the Technische Universität Darmstadt.

The backyard of the Computer Science Department has the advantage of being close to our offices. However, its size is only 400 m^2, which does not allow a deployment of a network other than that of a small-size WSN. In addition, it lacks the variety of trees and plants in comparison to the one that exists in the other two locations, which in turn doesn't make it attractive for monitoring.

Although both, the BG and Herrngarten are open to public, the main advantage the BG has over Herrngarten is that it is maintained by the University, hence possible cooperation with the Biology Department is much more feasible to achieve. We considered this cooperation as an important decision point because of the possible cooperation projects that emerged in the context of this testbed. A number of various environment-dependent applications that were outlined in our conversations with the biologists were considered, one of which has been implemented as part of this work. Secondly, the level of vandalism is lower compared to the one observed in the Herrngarten, which is often used as a venue of different social events. Last but not least, the unique characteristics of the BG, described below, made us choose the BG as a venue of our outdoor testbed.

The botanical garden of the Technische Universität Darmstadt is situated in the east part of the city, spanning an area of 55,000 m^2 (cf. Fig. 3.1, left, circled in pink). It consists of an indoor and an outdoor part. As a target of our first trial deployment, we considered the outdoor coniferous area, shown in Fig. 3.1 (right, circled in pink). This coniferous area spans approximately 200 m^2 and consists of 30 evergreen conifers. It is divided into two parts by a narrow sandy path which crosses it roughly in the middle. We call these two parts the coniferous north and the coniferous south areas as labeled in the map.

The inner part of the BG is a large greenhouse complex with an area of 1700 m^2, located to the right of the coniferous area. A variety of exotic plants makes this indoor environment quite unique and interesting for monitoring. In addition, a rain forest hall, part of this greenhouse complex, emulates outdoor environment conditions quite well, though situated indoors, which makes it an interesting sub-site that will be targeted in future work.

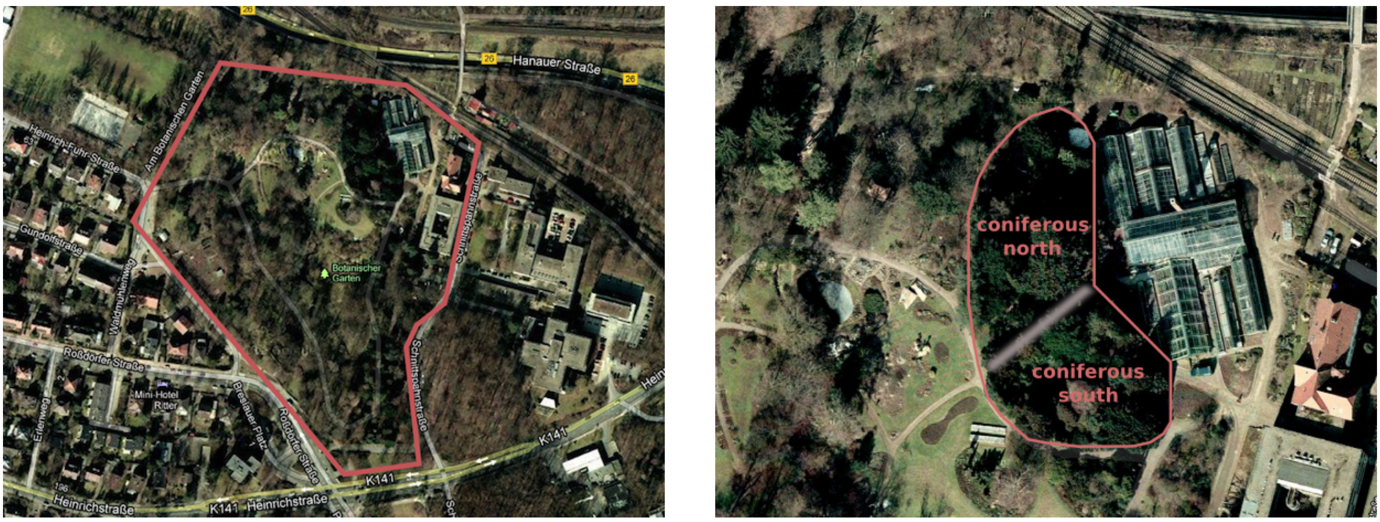

Figure 3.1: Left: The entire botanical garden. Right: The coniferous region as a part of the outdoor area in the BG.

A very interesting aspect of the coniferous area is the variety of evergreen conifers that live there. These trees, brought to Darmstadt from different forests all-over the world, have different properties. Interestingly, although most of them (such as the Metasequoia known also as the dawn redwood) live in wet sites in their native habitat, they also tolerate dry soils and seem to subsist in quite dry regions [11]. Up to a depth of around 50 cm, the soil is mostly sandy. Below that limit, it is rocky and rich in air gaps. These various trees' properties makes the monitoring of the moisture absorption during different periods (e.g. during heavy rainfalls) quite interesting. We decided to explore and integrate an environment-dependent application in the context of the outdoor testbed. In addition to the basic WSN infrastructure accessible to testbed users, the testbed will generate location-specific data sets, which are of interest to the biologists. In our conversations with them, it learnt that for them it is important to know the amount of water that goes into the soil and respectively how much is actually absorbed from the trees. In order to do that, on one hand, we need to monitor the soil moisture levels. Thus, we equipped our stations with soil moisture sensors. This process is described in detail in 4.3. On the other hand, we also need to analyze the total amount of water that goes into the soil which is the sum of the water that originates from the water sprinklers and the one caused by rainfalls. In order to do so, however, weather stations need to be deployed. The integration of these weather stations is left as future work.

3.2 Architecture

There are two architectural approaches that we considered: a wired 3-tier gateway network which uses power, and Ethernet cabling infrastructure and a solar-powered, wireless mesh-gateway network. In order to be able to evaluate these two variants, in this chapter we list the main differences between a wired and a wireless testbed and between a wired and a wireless backchannel. Then, we present our design choice and the reasons that make us take it.

3.2.1 Control and Data Backchannel

The control and data backchannel is primarily used by the server to distribute the software under test (SUT) to the respective sensor nodes. SUTs are the program images to evaluate which users create and upload to the server. The backchannel is the communication line used also typically by the testbed to send the captured debug messages to the server for any posterior SUT debugging and analysis. In general, the backchannel can be either wired or wireless. Depending on what kind of backchannel we have, we classify two types of testbeds: wired or wireless testbeds.

Wireless testbeds use the wireless backchannel to distribute SUTs to the sensor nodes and to transmit control and debug messages. The 802.11 b/g control and data channel network allow testbeds' relocations to be performed with less effort. In addition, they do not require expensive cabling infrastructure for the deployment phase. On the other hand, the radio backbone communication is more difficult to operate and more prone to interference issues. For example, in Deluge [10], a mechanism to distribute TinyOS[1] programs over the air, it might happen that backchannel's control and data messages themselves interfere with the SUT's network traffic, making it tough to debug networking issues. In addition, the reported image dissemination performance (250 seconds to disseminate 25kB image when operating with 88.4 bytes/second on average) places a considerable overhead on a testbed, which is a critical point in a testbed that must be shared by many users.

Wired testbeds rely on a wired backchannel. At the cost of running cables through the environment, this provides a faster and more robust experimentation facility.

With respect to the power network, two alternatives were considered: solar-powered stations and a wired infrastructure that consists of underground power cables. While a wired testbed cat operate at 100% duty cycle all the time, a wireless outdoor testbed that relies on a solar energy harvesting might not offer this ability in different intervals depending on the time of the year and current weather conditions. A wired backchannel also yields great visibility for the developers providing a reliable real-time monitoring and data collection services.

To conclude, while a solution based on the wireless backbone and solar-powered stations in a mesh-gateway network might be a more economic alternative, it is often not robust enough, and very hard to operate. Therefore, in this work we adopt the first approach. Each station, consisting of a gateway and a sensor node (and any required, additional testbed hardware), is provided with power and Ethernet with the help of underground power and fiber-optic cables.

3.2.2 Cabling

For the implementation of the Ethernet network, we considered two alternatives: CAT5 copper cables installed with a series of active hubs or other repeater devices, or building the Ethernet network using fiber-optic cables.

Ordinary CAT5 copper cables are not designed for outdoor uses. Extreme temperatures and humidity usually shorten their useful lifetime. Furthermore, a single Ethernet CAT5 cable, whether indoor or outdoor, is only designed to function over a distance of about 100m. If the range of an Ethernet outdoor network based on CAT5 cables need to be extended, active hubs or other repeater devices would need to be installed with a series of CAT5 cables. This leads to a higher complexity that we wanted to avoid in such a public, outdoor place, where the integration of each device requires permission from the respective authorities. Furthermore, fiber-optic cables are often recommended as an alternative to copper cables in open-air systems. Therefore, we chose fiber-optic cables which provide Ethernet with high performance, electrical isolation and distance (tens of kilometers with some versions). There exist two types of opti-

[1] An open-source operating system designed for wireless embedded sensor networks. `http://www.tinyos.net/`. Last accessed on January 26, 2013.

cal fiber cables: a multi-mode optical fiber (MMF) and a single-mode optical fiber (SMF). The equipment used for establishing communication over single-mode optical fiber is usually more expensive than that over MMF, but SMF itself is usually cheaper in bulk. Typically, single mode fiber-optic cables are used in long distances and higher bandwidth applications run by telecommunication companies, colleges and universities. Thus, for our application the SMF suits very well and we chose it over the MMF. An SMF cable is shown on Fig. 3.2, left.

As for the power network, our deployment requires a power cable suitable for underground, outdoor deployments. The three-phase, NYY-J underground power cable with a diameter of 2.5mm (cf. Fig. 3.2, right) fulfills these requirements. According to the specification, the cable can be deployed in environments, where the temperature ranges from -40 °C and 70 °C. This power cable can be safely installed in open air, in underground, in water, indoors, in cable ducts, power stations, for industry and distribution boards as well as in subscriber networks, where mechanical damages are not to be expected. The described properties of the underground NYY-J power cable make it a suitable solution for our outdoor deployment. Deploying it underground together with the fiber-optic cable is described in detail in Section 4.1.

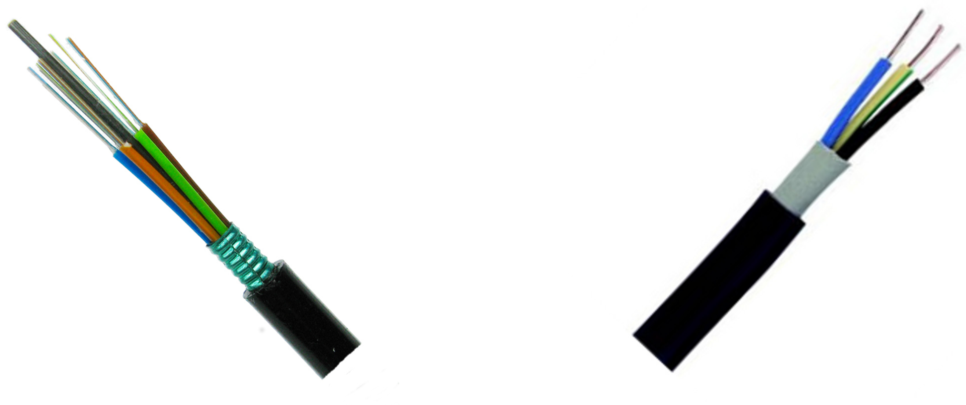

Figure 3.2: Left: A SMF fiber-optic cable. Right: The three-phase NYY-J underground power cable.

3.3 Station Enclosures

The design of an enclosure presents a variety of choices. To begin with, the outdoor nature of our testbed requires that the enclosures are waterproof and protected against contact and against penetration of dust. Furthermore, due to the fact that the BG is a public facility, the enclosures have to be designed so that only authorized persons can open them. At the end of this section, we discuss the ventilation of the enclosure as an important design decision.

Enclosures have to be chosen according to the international protection (IP) rating[2] standard (cf. Table 3.2). The IP code classifies the degree of protection provided against an intrusion

[2] http://www.iso.org/iso/iso_catalogue/catalogue_tc/catalogue_detail.htm?csnumber=39578. Last accessed on January 26, 2013.

of foreign objects and water. Due to the variable weather conditions and the water sprinklers used for irrigation purposes in the BG, our goal was to choose enclosures with at least an IP 66 that corresponds to total protection against contact, protection against penetration of dust and protection against high pressure water jets from any direction and temporary flooding. In order to prevent access from unauthorized people to the content of the boxes, the design of the enclosure had to allow the integration of some kind of locking mechanism.

An enclosure able to house the entire set of hardware devices required in a station was the Hugro Economic Box, which is made of ABS plastic featuring IP 66. The temperature range for which it was designed for is between -40 °C and +85 °C, making it very much suitable for outdoor applications. The enclosure is shown on Fig. 3.3. It has an integrated plastic mounting panel which allows devices to be attached easily inside the box using screws. Locks were used for locking the box in order to prevent possible theft. The cost of one enclosure is approximately 45 US $, making it an attractive low-cost solution.

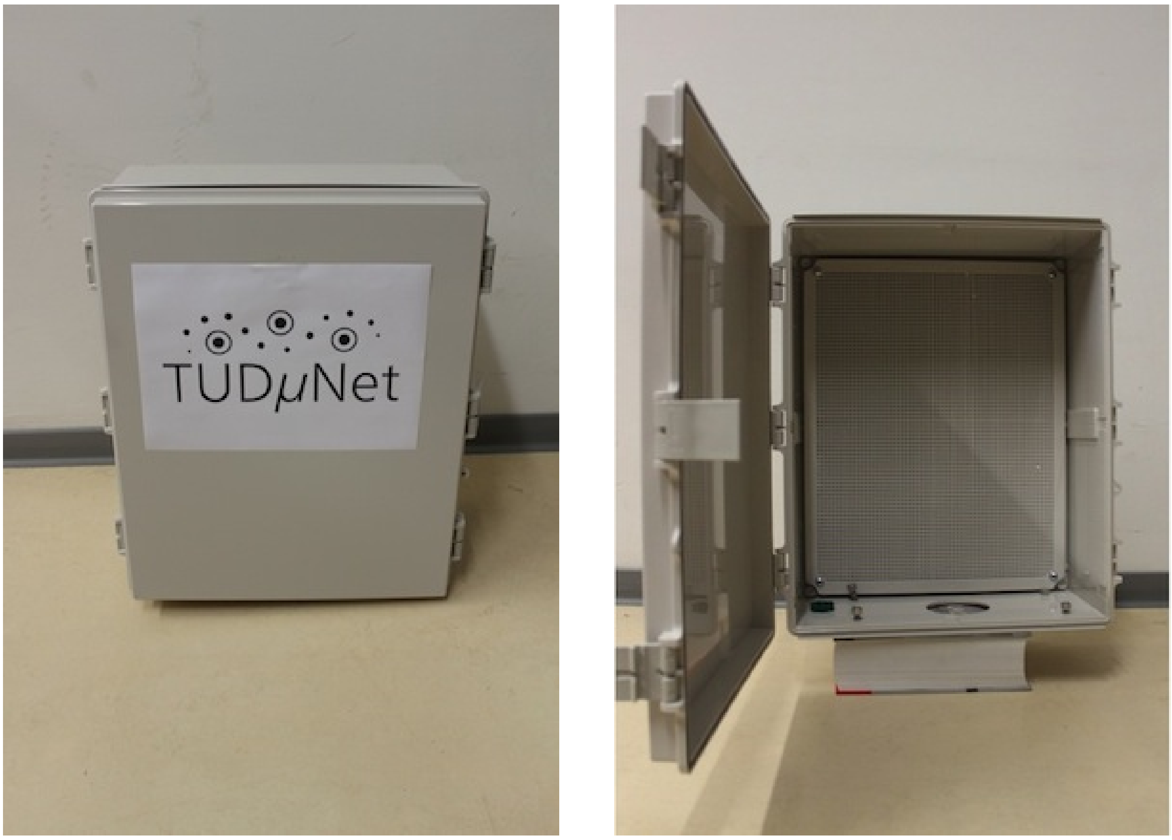

Figure 3.3: The HUGRO IP 66 enclosure.

Another important design aspect that had to be considered is the enclosure's ventilation. The enclosures contain electrical devices that constantly produce heat. Therefore, to control the inside temperature and prevent the condensation of water, proper ventilation elements had to be chosen. Since an active, powered ventilation would have required additional maintenance efforts and would have decreased the IP rate of the enclosure itself, we chose the drainage and vent plugs shown in Fig. 3.4, left, to orchestrate the enclosure's ventilation. Featuring an IP 64, these plugs combine the function of a vent plug with the functions of a drain plug into one single device. By means of the continuous pressure equalization between the interior of the enclosure (P1 in Fig. 3.4, middle) and the ambient atmosphere (P2 in Fig. 3.4, right), heat accumulation is prevented and condensation of water is minimized. In addition, if water should happen to enter the enclosure from outside or water condensates inside the box, it is drained off automatically via the plug as shown in Fig. 3.4, right. The price tag for this valve is about 15 US $.

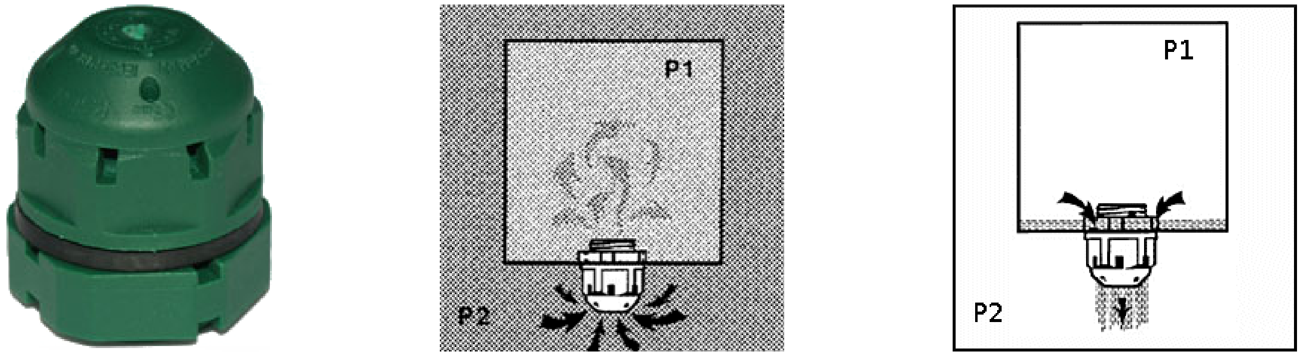

Figure 3.4: Left: The drainage and vent plug. Middle: Functional principle of the EWLS: The breathing gland reliably equalizes any temperature-related pressure differences between the interior of the enclosure (P1) and the ambient atmosphere (P2). Right: Condensed water or water that has entered the equipment from outside is drained off via the drain plug. The pictures have been reported unchanged from [19].

Before the actual deployment of the enclosures, we designed a construction to be used for holding the enclosure itself. In our discussions with the main gardener of the BG, we agreed on having them on 1m above the ground. In this way we avoid exposing them on direct high pressure water jets such as the one coming from the water sprinklers. For this purpose, we used 1.5m metal pipe as a vertical pillar. On one of its ends, the metal pipe has a metal plate with four holes in each corner. In order to have a stable construction, we attached the enclosure on the top of this metal plate using four screws. The first prototype of the construction is shown on Fig. 3.5.

Fig. 3.6 shows how the vent plug was mounted in the enclosure. To this end, a hole was drilled in the enclosure using a holesaw.

3.4 Station's Hardware

In this subsection, we discuss the enclosure's components in more detail. All stations have the same hardware except for two stations (one in the coniferous north and one in the coniferous south area) which we call the **main stations** and which have an additional hardware as described later in the chapter. These two **main stations**, as explained in more detail in the implementation chapter 4, have more responsibility than that of the others, called **peripheral stations**, and act as power and Ethernet splitters.

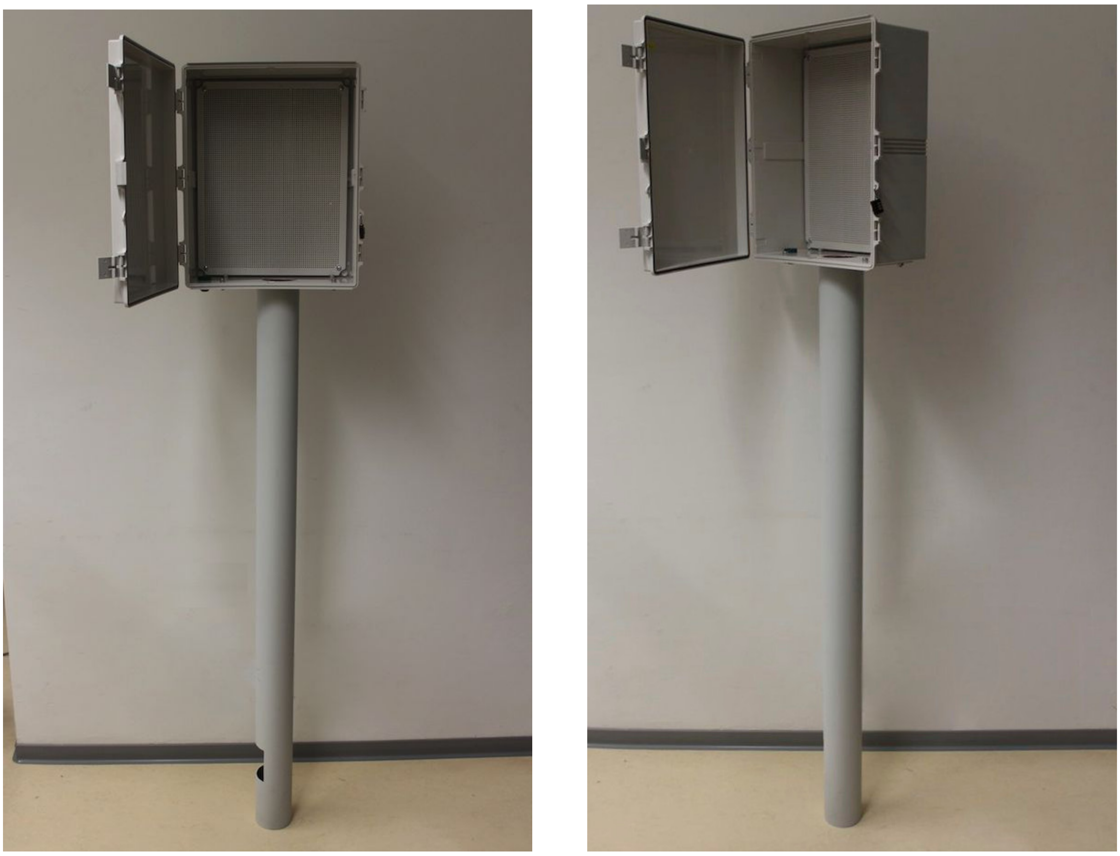

Figure 3.5: First prototype of the stations: The enclosure mounted on a pipe.

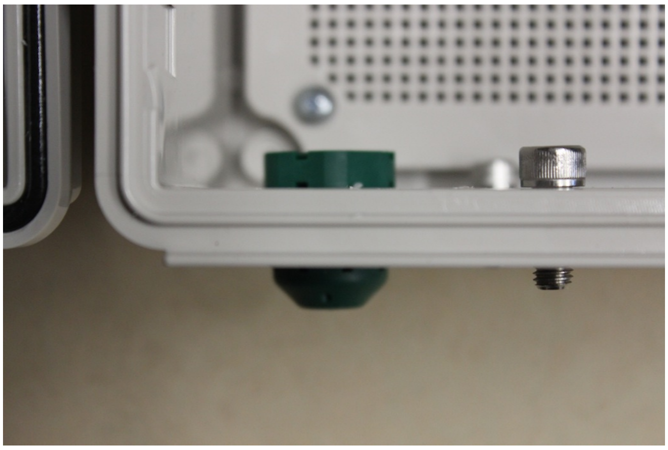

Figure 3.6: The vent plug mounted in the enclosure.

- **main stations** - contain all the devices described below, have higher priority and act as power and data splitters;
- **peripheral stations** - contain a sensor node and a gateway.

A Network Devices

Each enclosure contains a Buffalo Router shown in Fig. 3.7, left, that acts as an intermediate gateway in the 3-tier testbed's architecture. On the Buffalo WZR-HP-AG300H[3] we run a customized Linux version called OpenWRT with sensor node management tools. The gateway's USB port is permanently connected to the sensor node via USB cabling. In this way, power is provided from the gateway i.e, no battery pack is needed. In addition to the sensor node and the gateway, the two **main stations** contain a HP2520G-8 Layer 2 network switch, shown in Fig. 3.7, right. These switches are in charge of the Ethernet network and act as Ethernet splitters providing network for the rest of the stations. In order to implement the fiber-optic connection, a small form-factor pluggable (SFP) Mini-GBIC transceiver is used in the **main stations**. This GBIC transceiver interfaces the switch motherboard to the fiber-optic cable. In addition, a fiber-optic passive distributor, shown on Fig. 3.8, is also used so that it allows easy reconnections in the future and does not require an expensive cable termination of the fiber-optic cable every time a device needs to be replaced.

Figure 3.7: Left: The HP2520G-8(J9298A) Switch and the SFP Mini-GBIC transceiver. Right: The Buffalo WZR-HP-AG300H Router.

B Cable Junction Box

As a power splitter in each of the **main stations**, we used the Hensel cable junction box K 9105 shown in Fig. 3.9. According to the specification, it is designed for normal indoor environment and protected outdoor environment. This cable junction box features IP 55 and is placed inside the enclosure, which itself has a degree of protection corresponding to IP 66. For this particular component we wanted to have an additional protection because of its 220 voltage operation, therefore a box with a higher IP rate was chosen. The junction box allows the connection of maximum 6 three-phase or five-phase power cables with diameter of 2.5 mm, which is just enough for our deployment (one incoming power cable coming from the basement + four outgoing power cables to the rest of the stations in each part of the coniferous region). It is made of a thermoplastic material and its size is 125.00 x 167.00 x 82.00 mm making it compact so that it fits well into the enclosure.

[3] `http://www.buffalo-technology.de/`. Last accessed on January 26, 2013.

Figure 3.8: A fiber-optic passive distributor manufactured by the R&M company.

Figure 3.9: The Hensel cable junction box used as a power splitter in the two **main stations**.

C Sensor Node Platform

As a node platform, we chose the TelosB Wireless Sensor Module [17], shown in Fig. 4.3, because it is one of the most well-known platform used in the WSN community. The TelosB node platform was designed and developed by UC Berkeley to enable WSN research. In order to facilitate experimentation it was constructed such that it should be easy to use, exhibit minimal power consumption and hardware robustness. Featuring 8MHz Texas Instruments MSP430 micro-controller, 250kbps 2.4GHz IEEE 802.15.4 Chipcon Wireless Transceiver and USB support, it enables experimentation in WSNs in both lab, testbeds and deployment settings.

Figure 3.10: TelosB ultra-low power wireless module.

3.5 Soil Moisture Sensors

In order to enable environment-dependent application for soil moisture monitoring, soil moisture sensor are required. They are used for measuring the amount of water content in the soil. Depending on the technology used, we can classify them in three types:

- Resistance measuring sensors - often for home use, consist of two electrodes measuring the resistance of the soil.
- Neutron moisture meters - use high-energy (fast) neutrons to detect indirectly the water content of the soil.
- Frequency domain sensors - have an oscillating circuit, which operating frequency depends on the value of the soil's dielectric constant. We can differentiate between two types of frequency domain sensors:
  - Fringe capacitance sensors - use capacitance probes to measure the water content of the soil. Since the dielectric permittivity of the water(80) is much higher than that of the other constituents of the soil (mineral soil: 4, organic matter: 4, air: 1), the dielectric permittivity of the soil is a sensitive measure of water content. Thus, when the amount of water in the soil changes, the dielectric permittivity of the soil also changes, which results in the capacitance probe measuring higher capacitance according to Eq. 3.1 that can be directly correlated with a change in the water content.

$$C = \epsilon_r \epsilon_0 \frac{A}{d} \tag{3.1}$$

where
C is the measured capacitance;
A is the area of overlap of the capacitor plates;
ϵ_r is the relative static permittivity (sometimes called the dielectric constant) of the soil
ϵ_0 is the electric constant ($\epsilon_0 \approx 8.854x10^{-12}Fm^{-1}$); and
d is the separation between the capacitor plates.

– Electrical impedance sensors - consist of soil probes which measure the electrical impedance of the soil.

For our testbed, we chose fringe capacitance sensors because they are fast, safe and relatively inexpensive means for measuring the soil water content. The characteristics of the two most well-known models from this category, the Decagon EC-5 and Vegetronix VH400, are summarized in Table 3.1. The VH400 soil moisture sensor probes from the US company Vegetronix are a low-cost solution that uses transmission line techniques to measure the dielectric constant of the soil, is insensitive to water salinity and it does not corrode over time as the conductivity based probes do. Although the Decagon EC-5 soil moisture sensor has been used more in research projects till now and has proven to be a very good tool for measuring the water content in the soil, the Vegetronix VH400 has some important advantages over its competitor:

- The VH400 soil moisture sensor probe uses less than 1/16 of the power of the EC-5, which makes it consume less battery that in turn leads to sensor network systems with longer life.
- The VH400 soil moisture sensor probe has an internal voltage regulator and can be operated from a very wide range of input power supply voltages from $3.3V$ to $24V$. The EC-5 only has a range of 2.5 to $3.6V$. Because the EC-5 does not have an internal voltage regulator, volumetric water content (VWC) readings can be inconsistent as the input voltage varies. The VH400's internal voltage regulator guarantees that despite the input supply voltage the output will be consistent.
- The biggest advantage of the VH400 soil moisture sensor probe over the EC-5 is the cost. The average price for which a VH400 can be bought is 37 US $, while the Decagon EC-5 price is about 100 US $.

Sensor model	Price	Technology	Description
Vegetronix VH400	$37	fringe capacity sensor	analog, measures VWC, range 0 - 100% VWC, insensitive to water salinity, will not corrode over time, supply voltage 3.3VDC - 20VDC @ 7mA, Accuracy 2%
Decagon EC-5	€100	fringe capacity sensor	analog, measures VWC, Range 0 - 100% VWC, supply voltage 2.5VDC - 3.6VDC @ 10mA, Accuracy 2%

Table 3.1: Detailed description of the VH400 and the Decagon EC-5 soil moisture sensors.

For our application, we chose the VH400 primarily because it of its lower cost, as compared to the Decagon EC-5 and in addition it has an internal voltage regulator which allows any input voltage in the range of 3.3 V up to 24 V.

The VH400 was tested in our office environment before the actual deployment in the BG. To this end, we used the plant, shown on Fig. 3.12. The plant has been monitored using a VH400

Figure 3.11: VH400 soil moisture sensor.

for a period of two weeks starting from November 23, 2012 and until December 5, 2012. The output of the VH400 can be seen on Fig. 3.13. The time is displayed on the x-axis, whereas its output is shown on the y-axis. The monitoring application and the driver for interfacing the sensor are written for Contiki [6] and explained in detail in Section 4.3. The plant was watered just once on November 26, 2012 at about 1 p.m. At that time, there is a rapid increase of the water content in the soil measured by the VH400 which can be seen from the plot. After that, the soil in the plant dried continuously, as expected.

Figure 3.12: Plant monitoring using a VH400 soil moisture sensor mounted on a TelosB node.

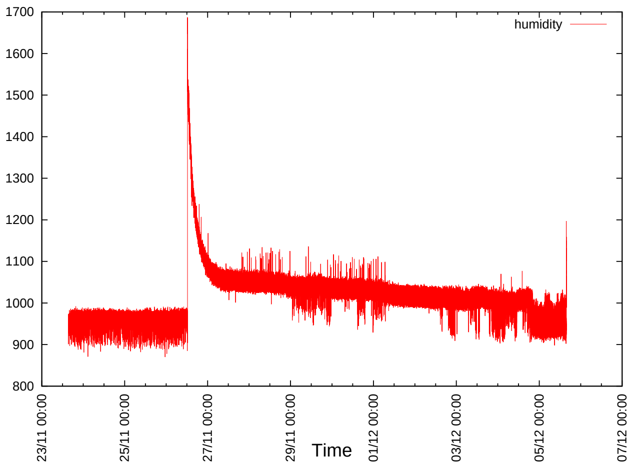

Figure 3.13: Plant monitoring using the VH400.

3.6 TUDμNet

The outdoor testbed described in this chapter is to be integrated with the already existing TUDμNet testbed federation. Next, we describe this integration as well as TUDμNet's architecture and the control infrastructure as solution for managing experiments at metropolitan scale.

3.6.1 TUDμNet's Architecture

To begin, TUDμNet features a 3-tier structured architecture (cf Fig. 3.14). The first tier is composed of the sensor nodes to be flashed with the users' experimentation programs at the beginning of an experiment. These experimentation programs are `.ihex` files generated by Contiki's or TinyOS's build systems. The tier is also heterogeneos containing currently three types of nodes: TelosBs, Z1s[4], JCreates[5]. All three types are based on the MSP430 microcontroller and have a variety of built-in sensors (light, humidity, temp) and external ones (CO, C02, soil moisture sensors). The second tier is composed of the Buffalo WZR-300NH routers, described in the previous section, which act as gateways. Their USB interfaces are exploited in such a way that between 1 and 5 sensor nodes are connected permanently to them via USB hubs and cables. On these routers we run a minimalistic linux-based operating system, which is used primarily to route network traffic. The OS is called OpenWRT and the top of it we also operate sensor node management tools (e.g., serial forwarder, BSL) which are important system elements. Finally, the third tier consists of a central server that is in charge of coordinating all testbed's activities: specifying and scheduling an experiment, executing it and logging the data to a database. The traffic between the central server and the gateways of each testbed's site is routed through MANDA, Metropolitan Area Network (of DArmstadt) operated at speed of the order of Gbit/s.

3.6.2 The BG Testbed as Part of the TUDμNet Testbed Federation

The BG outdoor testbed is to be integrated as a fourth site of TUDμNet testbed federation which goal is to bring certain well-defined scenarios into experimentation. With this new testbed, TUDμNet will include a total of four sites located at metropolitan-scale (cf Fig. 3.15). The first one is hosted at the Databases and Distributed System's group offices at the Computer Science Department, and it is a typical office environment. It has a total of 62 TelosB and 20 Z1 nodes and targets WSN experimentation in the areas of network connectivity, radio propagation and resource management, sensing and actuation. The second one is located at the GKmM[6] Lab at the Technology and Innovation Center (TIZ building), where a disaster sce-

[4] http://www.zolertia.com/ti. Last accessed on January 26, 2013.
[5] http://www.sentilla.com/. Last accessed on January 26, 2013.
[6] `http://www.gkmm.tu-darmstadt.de/`. Last accessed on January 26, 2013.

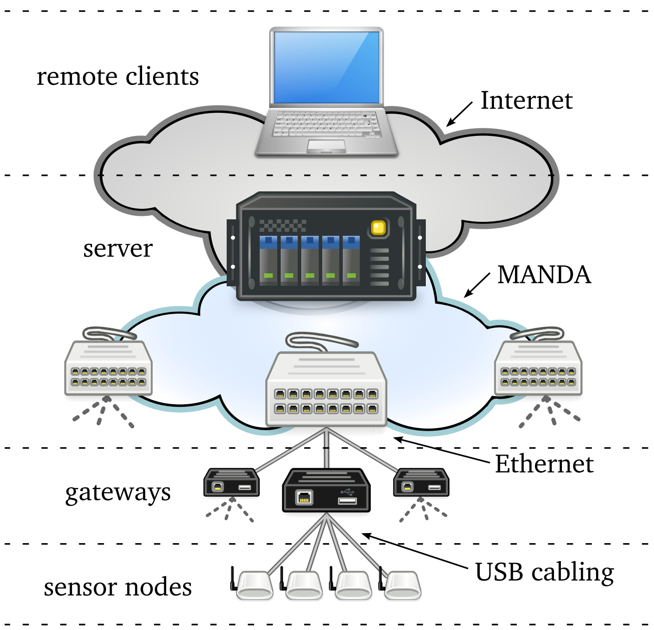

Figure 3.14: TUDμNet's architecture.

nario arena is monitored with a grid of 50 TelosB nodes located at the ceiling. Each node is equipped with external CO, CO2 sensors and targets gas plume detection scenarios. The third site is the surPLUShome, an award-winning solar house, that features 20 Z1 nodes and enables experimentation with indoor environmental monitoring applications.

Due to its outdoor nature, the BG testbed opens doors to a new unique application domain not found in any of the other TUDμNet's sites: outdoor environmental monitoring. Software developers who work on WSN applications such as outdoor environmental or habitat monitoring could benefit from the realistic experimentation environment that this outdoor facility yields. They can be aware and possibly handle problems triggered by outdoor physical phenomena such that caused by the harsh and changing weather conditions in the testing phase which is not possible in indoor experimentation environments.

3.6.3 Control infrastructure

TUDμNet's core relies on the set of software tools originally developed for MoteLab. Users access the testbed by a web browser to set up an experiment, schedule an experiment using a calendar-based interface or download experiment's data for evaluation. The web server runs on the central server which is in charge of schedulling, flashing and instrumenting the nodes for data logging.

The control infrastructure is composed of four main software components:

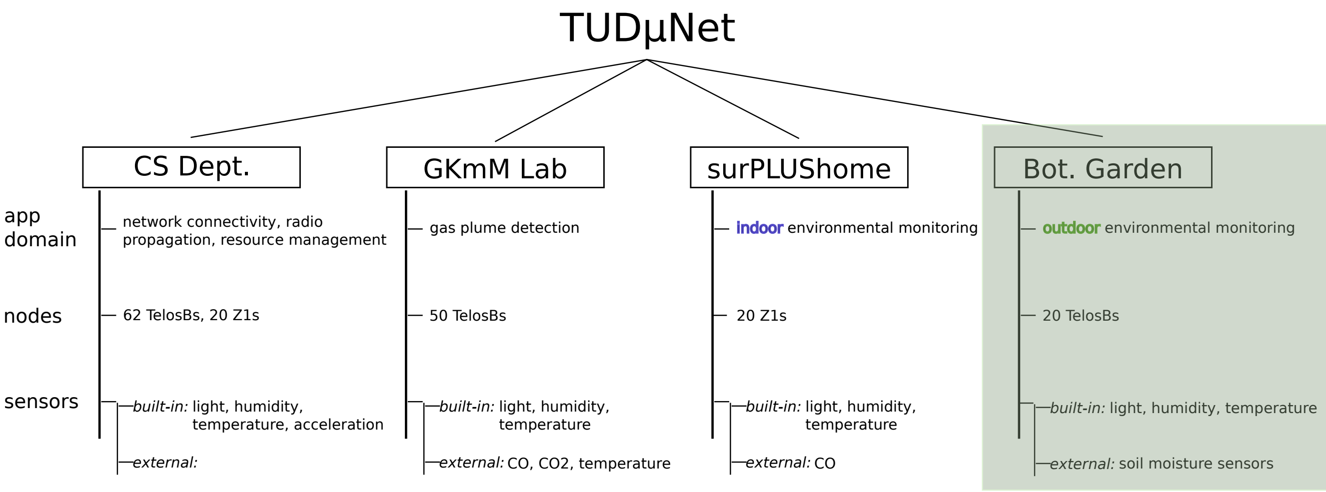

Figure 3.15: TUDμNet testbed federation.

- Web interface - users use the web interface for describing and scheduling experiments and download data for posterior evaluation. The web pages are PHP-generated and the scheduling interface is calendar-based.

- MySQL Database Backend - the data from the experiments is stored in a MySQL database as well as nodes' and gateways' metadata.

- Data Logger - C-based module that is started in the beginning of each experiment and ends at its end. It collects data from the nodes which participate in the experiment, parses it and inserts it the MySQL database.

- Experiment Daemon - Perl script which run as a cron job and continuosly checks whether there are pending jobs or such that need to be teared down.

1st. index Figure	Foreign Bodies Protection	2nd Index Figure	Water Protecion
0	No protection against accidental contact, no protection against solid foreign bodies	0	No protection against water
1	Protection against contact with any large area by hand and against solid foreign bodies with diameter greater than 50 mm	1	Protection against vertically falling drops of water.
2	Protection against contact with the fingers, protection against solid foreign bodies with diameter larger than 12 mm	2	Protection against direct drops of water up to 15 °C from vertical.
3	Protection against tools, wires or similar objects with diameter $>$ 2,5 mm, protection against solid foreign bodies with diameter greater than 2,5 mm	3	Protection against direct sprays of water up to 60 °C from vertical.
4	Protection against tools, wires or similar objects with diameter greater than 1 mm, protection against solid foreign bodies with diameter greater than 1 mm	2	Protection against water sprayed from any direction.
5	Full protection against contact, protection against interior injurious dust deposits	5	Protection against low pressure water jets from any direction.
6	Total protection against contact, protection against penetration of dust	6	Protection against high pressure water jets from any direction and temporary flooding
		7	Protection against temporary immersion
		8	Protected against long periods of immersion under pressure.

Table 3.2: International Protection Rating.

4 Testbed Deployment

In this chapter we describe the actual deployment of our testbed. In Section 4.1, we discuss the deployment of the power and Ethernet network. Then, in Section 4.2, we explain how the stations were deployed outside in the garden. At the end of the chapter, in Section 4.3, we describe the soil moisture monitoring application which was developed in the context of this work.

4.1 Power and Ethernet Deployment

Although power and Ethernet are not available outside in the BG, there were two indoor locations that we considered as power and Ethernet sources: the main gardener's house next to the small lake which can be seen on Fig. 4.1, right, and the greenhouse complex. We chose the second alternative, because the path from the guardian's house to the coniferous area was extremely rich in trees' roots and digging there could have been dangerous for the trees themselves. Therefore, using fiber-optic and underground power cables we extended the Ethernet and power networks from the greenhouse complex to the so called **main coniferous north** and **main coniferous south** stations shown as blue points in Fig. 4.1. As mentioned in the previous chapter, these two **main stations** have a higher priority than the others and act as power and data splitters. The **main coniferous north** station provides power and Ethernet for the four **peripheral stations** (marked in green) in the north coniferous region by using the network switch and the power cable junction box (described in Chapter 3 in Section 3.4). The **main coniferous south** station plays the same role in the south coniferous region.

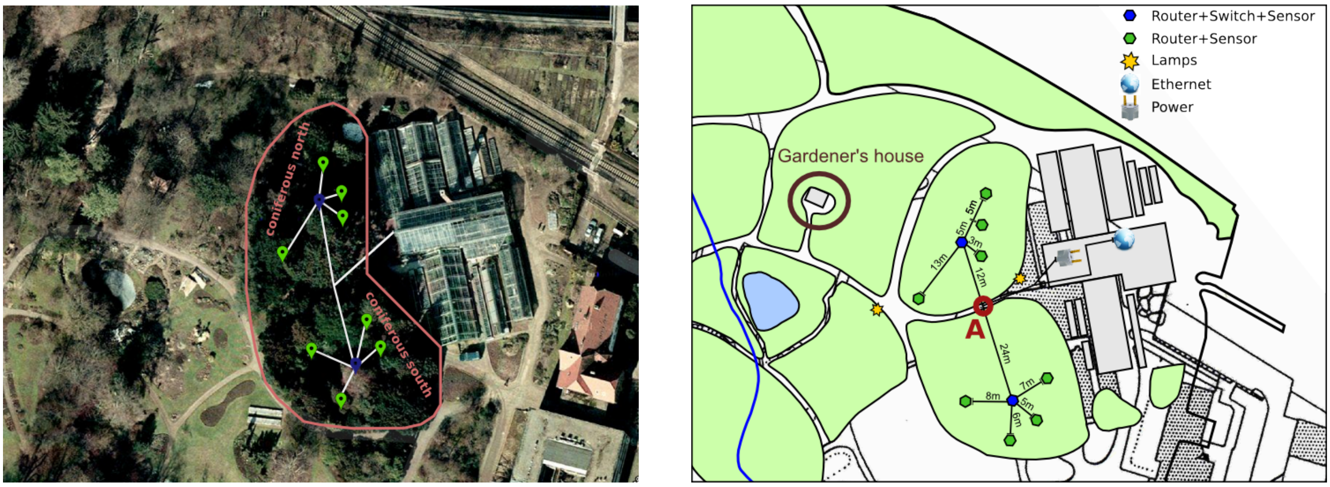

Figure 4.1: Left: The coniferous area with the approximate positions of the ten stations. Right: A rough infrastructure map of the testbed.

The deployment of the fiber-optic and the underground power cables was a laborious task because of the safety regulations which such an outdoor infrastructure in a public place should comply with. One of these regulations states that power cables have to be installed at least at 60 cm soil depth to avoid frost. A channel of approximately 70 m in length and 60 cm in depth that starts from the entrance of the greenhouse complex and goes to the two **main stations** was digged. Then, the cables were safely placed into it and then the channel was respectively covered. Steps from this process are shown in Fig. 4.2: the very beginning of our digging endeavor is shown in the left picture while the right one illustrates the process of closing the channel.

Figure 4.2: Left: The digging of the channel in which the underground power and the fiber-optic cable were placed. Right: Covering the channel.

For the deployment of the Ethernet network, we placed two separate fiber-optic cables from the basement to each **main coniferous north** and **main coniferous south** station. To each of the **main stations** we used a separate fiber-optic cable. Each cable segment was about 150m and threaded through the existing cable channel infrastructure through the greenhouse complex, again for safety reasons, which required spanning heights from the cellar to 10m high. Furthermore, cutting these segments was also a laborious task to do because it required unrolling the heavy cable drum.

Regarding the infrastructure of the power network, a new power facility was installed by electricians from the Technische Universität Darmstadt's Infrastructural Group, which protects the main power network against lightning bolts on the field, as well as the testbed devices from power peaks. From this power facility, located in the greenhouse, we deployed one underground NYY-J power cable from the basement up to the branch-joint point(cf. Fig. 4.1, right, labeled as a red A). There we deployed the so called branch-joint, which functions as a power splitter. It has an IP of 65 and was deployed at 60 cm soil depth. Steps from the construction process of this branch-joint, also carried out by the electricians, are shown on Fig. 4.4. On the left figure, the process of connecting the three phases of the three underground power cables (the input power coming from the basement, the coniferous north and the coniferous south underground power cables) is depicted. On the right one, the filling of the branch-joint with synthetic resin

Figure 4.3: Fiber-optic cable drum.

liquid is shown. After the liquid hardens, it prevents any water from getting in touch with the cables' wiring and causing damage to the power infrastructure.

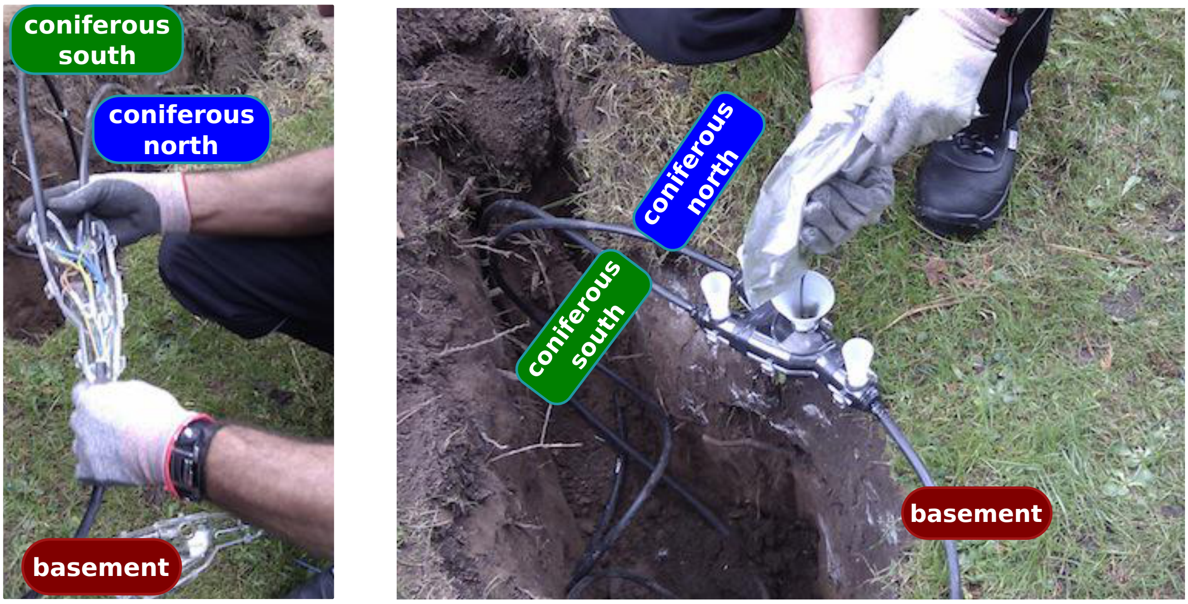

Figure 4.4: Left: Wiring the phases of the three cables. Right: Filling the branch-joint with synthetic resin.

4.2 Stations Deployment

After the power and the Ethernet networks were extended, the two **main stations** were deployed in the coniferous area. Using a soil driller, holes at a depth of 50 cm were made and then the pipes were placed into them. The fiber-optic cable and the underpower cable were passed through the pipes together with the soil moisture sensors as shown on Fig. 4.5, left.

Once we ensured that the pipes were installed properly and steady, the enclosures were mounted on the top of them and fixed to the metal plates using screws (cf. Fig. 4.5, center and right).

Figure 4.5: Steps from the deployment of the stations in the coniferous area.

As lessons learned, it should be considered that designing enclosures for such an outdoor infrastructure is not a trivial task. We wanted to have stations that are as small as possible so that they attract less attention in a public place such as the botanical garden of Darmstadt. Therefore, the first prototype of our stations was very compact leading to the need of careful planning of how the different elements inside them have to be positioned. We thus were forced to design and construct several holding elements so that every device is positioned precisely in its predefined place which was a time-consuming endeavor. Thus, for the future stations, we plan to have slightly bigger enclosures which could potentially save us time and give us more freedom operating with the inside of the box.

4.3 Environment-dependent Application for Soil Moisture Monitoring

In this section, we present the setup in which three VH400 soil moisture sensors are mounted on a TelosB node. Then, a Contiki OS [6] driver for interfacing the soil moisture sensors and a Contiki application which samples continuously data from these sensors are discussed. Contiki is a small open source operating system for sensor nodes designed according to the limitations of these resource constrained devices such as code memory on the order of 100 kilobytes and less than 20 kilobytes of RAM. It is based on an event-driver kernel in order to reduce the size of the system.

For our environment-dependent application, we decided to connect three external VH400 soil moisture sensors to one TelosB module. The VH400 consists of 2m cable that on one end has one prong and on the other end has three wires. As mentioned, each TelosB module was equipped with three VH400 sensors, where probes are buried in the soil respectively at 1, 1.5 and 2m depth (cf Fig. 4.6). The three wires of the other end of each sensor are connected to the 10-pin expansion connector of TelosB nodes. The 10-pin connector is situated on the far side of the board from the USB connector. It provides digital and analog inputs and is the primary connector. Additional devices may be connected to it using an IDC header, an IDC ribbon cable, or by designing a printed circuit board that solders directly on to the IDC header providing a robust connection to the module. Its schematic is given in Fig. 4.7. The bare wires of each node are connected to pin9, Analog Ground (GnD), red wires are connected to pin1, Analog VCC (AVcc), and the black wires of the sensors, connected respectively to pin3(ADC0), pin5 (ADC1) and pin7(ADC2), are programmed as input of the sensors.

The Contiki OS provides sensor drivers for the built-in TelosB sensors such as temperature, humidity and light which are in charge of operating and controlling them. For successful communication between the TelosB and the VH400 sensors for collecting soil humidity data, we developed a Contiki OS VH400 driver. Using this driver our application was able to sample ADC data from the soil moisture sensors.

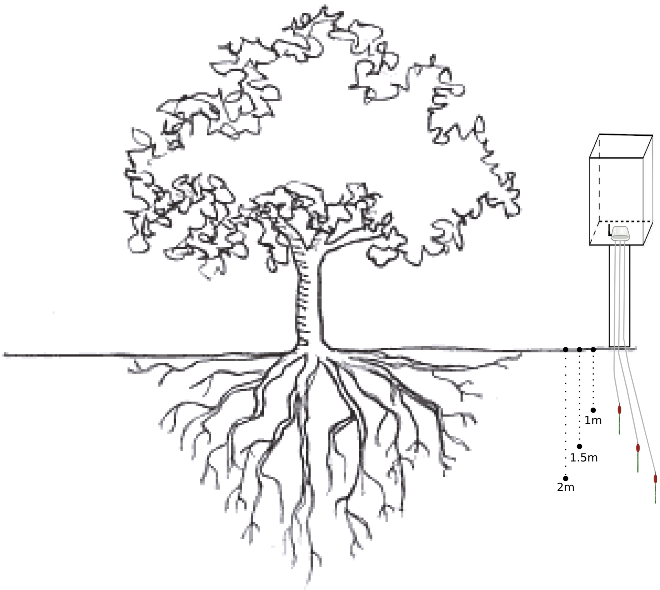

Figure 4.6: VH400 sensors mounted on a TelosB module located at 1, 1.5 and 2m depth in the soil.

Soil moisture data can be collected while nodes are idle and no activity is present (i.e., no experiments are being run). Another strategy would be to have nodes dedicated to the data collection which do not participate in the experiments. Finally, the data collection can be implemented so that it takes place at reserved time slots for this exclusive use. Considering that in this very first stage, our network is rather small, the first approach will be adopted.

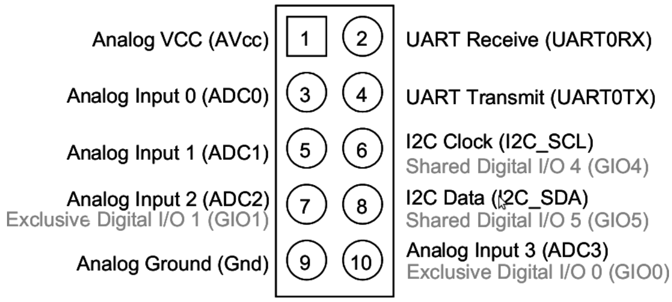

Figure 4.7: The 10-pin expansion connector.

4.4 Empirical Link Quality Evaluation

Although the final deployment of permanent **peripheral stations** could not be carried out timely, an initial evaluation of link quality was performed on the targeted site using battery-powered nodes, and coincidentally to a snowfall in the city of Darmstadt, which can be later used to evaluate network properties under extreme weather conditions. To this end, we deployed additional 18 nodes (9 in the north and 9 in the south coniferous area) as shown on Fig. 4.8. The temporary nodes were battery-powered and placed in small plastic enclosures which protect them from the outdoor environment (cf. Fig. 4.9). Then, the resulting 380 low-power links between these 20 nodes were quantified.

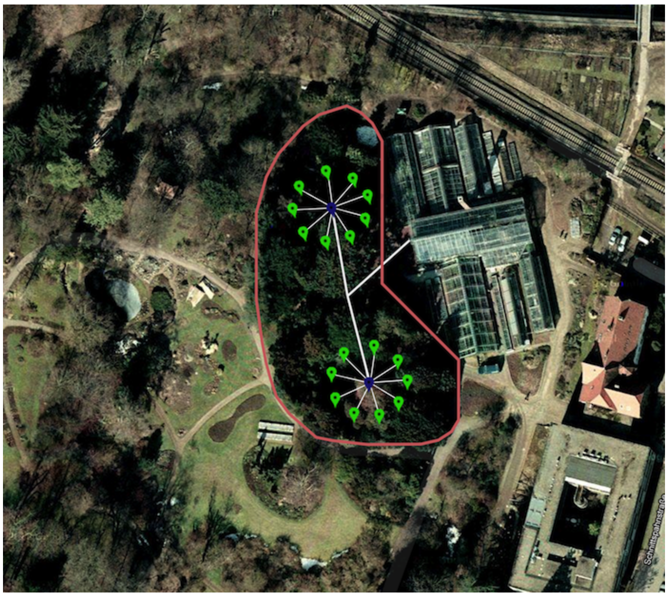

Figure 4.8: The BG testbed. Blue markers are the deployed **main stations**, green markers are the temporarily TelosB nodes.

The TelosB nodes use the CC2420 radio chip from Texas Instruments, which complies with the 802.15.4 standard. The CC2420 together with an internal antenna operate at 2.4 GHz. For our experiments, we choose channel 26 from the 802.15.4 standard which precludes interference with the existing WiFi 802.11 networks. The evaluation program instructs the nodes to send 200 packet probes to each of the other nodes in the network in a round-robin fashion. Receiver

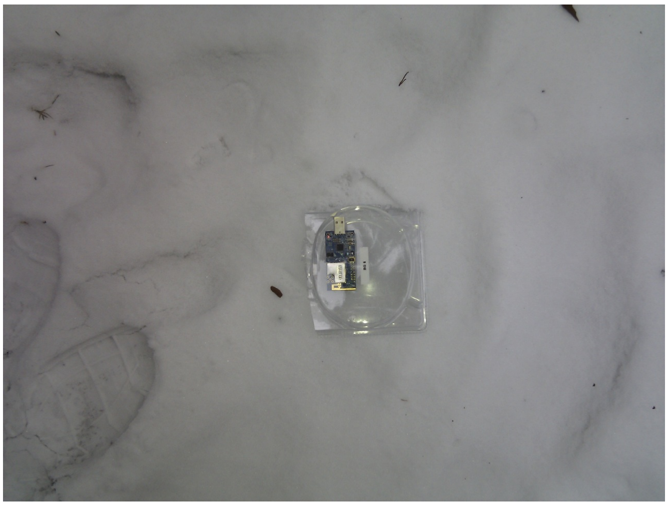

Figure 4.9: A temporary enclosure (the green marker in the above picture) used as a container for each additional node.

nodes maintain statistics about the received packets. A message is considered lost if it fails the CRC checking executed by the CC2420 chip. Using sequence identifiers of the messages links are evaluated and statistics is stored. The evaluation program was written using Contiki and its Rime protocol stack [5].

4.4.1 Packet Delivery Ratio Behavior

The Packet Delivery Ratio (PDR) represents the ratio of the number of successfully received packets from the receiver over the number of transmitted packets sent by the sender. Fig. 4.10 depicts the packet delivery ratio for different transmission powers. Each curve undergoes three regions: disconnected region, links with no connectivity at all, transitional region, links with intermediate quality (unstable, not correlated with distance links, which are commonly defined as links having an average PRR between 10% and 90%) and connected region, containing only perfect links. Clearly, the higher the transmission power applied, the more links were observed in the connected region. However, the transition region also grows as can be seen by the width of the rectangles, tagged with the percentage of links that belong to it.

Observation 1: As the transmission power increases not only the connected region increases but also there are more links located in the transitional region.

Next, using Fig. 4.11, we investigated how the PDR is related to the distance between the sender and the receiver and in particular we observe closely this relationship in the transitional region.

While the majority of the links in the connected region are links at short distances, there are also perfect links at higher distances. Similar is the situation in the disconnected region, where although most of the links are links where the receiver is farther from the sender, there were some short distance links with a pure PDR. In the transitional region, we observe links which

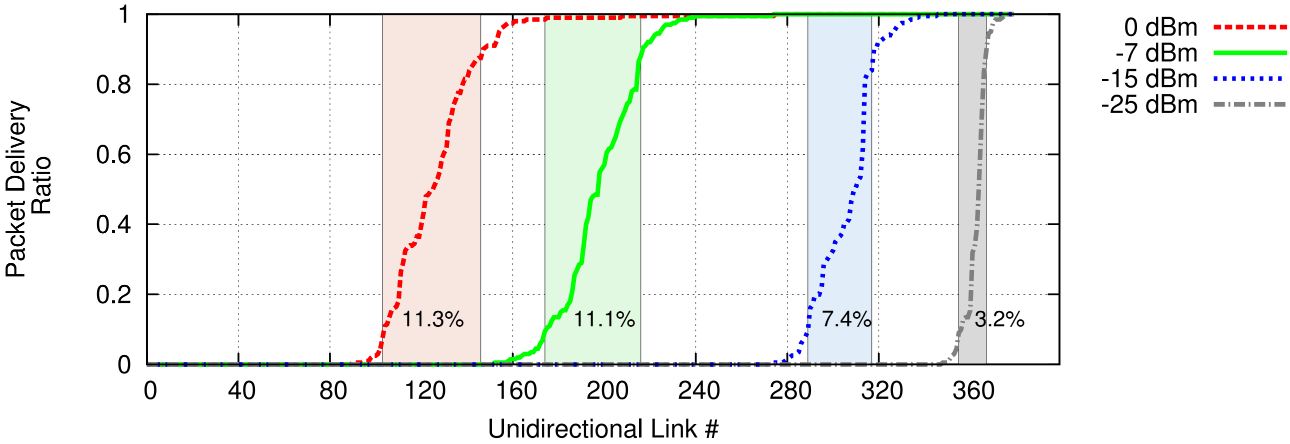

Figure 4.10: Measured PDRs for different TX power levels. The color rectangles denote the transitional regions.

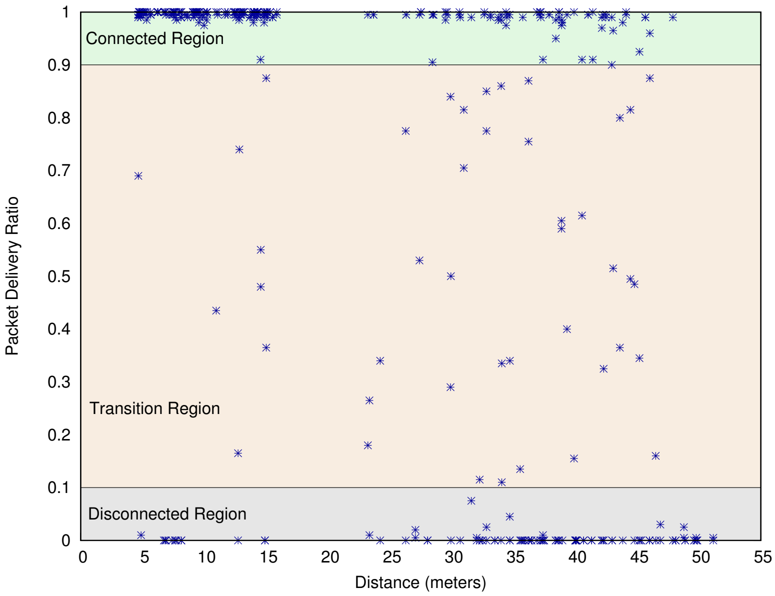

Figure 4.11: The three reception regions: connected region, transitional region and disconneted region for output power equal to 0 dBm. Link quality is not correlated with distance, especially in the transitional region.

are quite unstable and not correlated with distance. Indeed, two receivers placed at the same distance from a sender can exhibit different PDRs. For example, links in the range between 10m and 15m in the transitional region were observed with PDRs of approximately 0.15%, 0.36%, 0.44%, 0.48%, 0.55%, 0.75% and 0.88 %. Therefore, we can conclude that the link quality is not correlated with the distance, especially in the transitional region.

Observation 2: PDR is not correlated with the distance between the sender and the receiver and this is particularly true for the transitional region, where the distribution is completely random.

Pure hardware-based estimators do not consider link asymmetry. A link asymmetry between two parties is exhibited when a node can transmit to another node, but not vice versa. As De Couto et al. showed in [4], link asymmetry leads to the existence of multiple minimum hop-count paths with poor throughput. As a result, routes with significantly less capacity are often preferred from minimum-hop-count routing protocols instead of choosing the best paths in the network. Fig. 4.12 shows the measured PDR for both link directions in which bars start at the minimum between $PDR_{a \to b}$ and $PDR_{b \to a}$ and end at the maximum. All links a $\Longleftrightarrow$ b that exhibit link asymmetry are enclosed by the highlighted rectangle which spans 72.1% of the links. Out of them, 43 links, 22% out of all 190 bidirectional links, are considered as significant, i.e. having $PDR_{a \to b} - PDR_{b \to a} > 20\%$. Furthermore, all 20 nodes were affected by the link asymmetry as shown on Fig. 4.13.

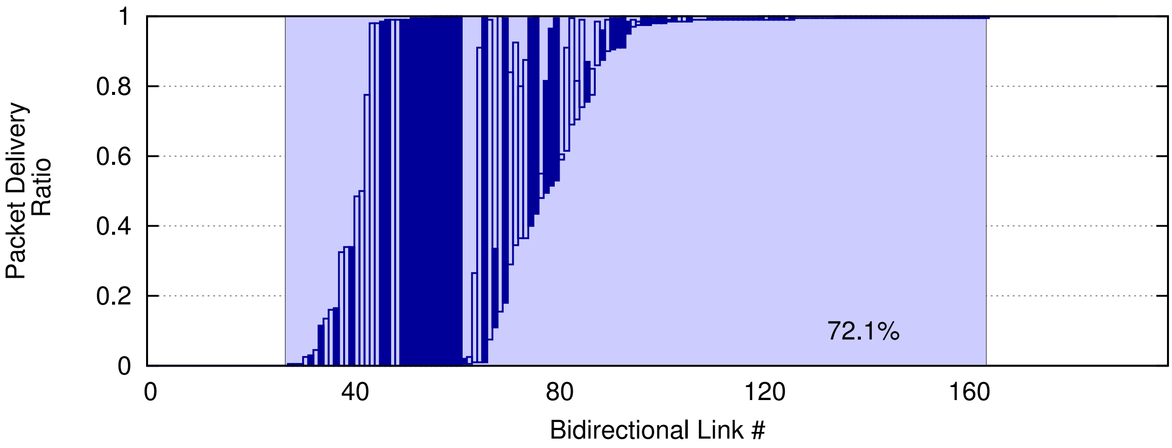

Figure 4.12: Measured PDR for each bidirectional link using transmission power of 0 dBm. Each bar represents one bidirectional link a $\Longleftrightarrow$ b with the maximum and minimum chosen between the $PDR_{a \to b}$ and $PDR_{b \to a}$.

Observation 5: Link asymmetry is important and has to be considered when designing higher-layer network applications. Network protocols and algorithms that rely entirely on minimum hop-count to discover their neighbors can run into situation when nodes select an unfavorable next-hop neighbor

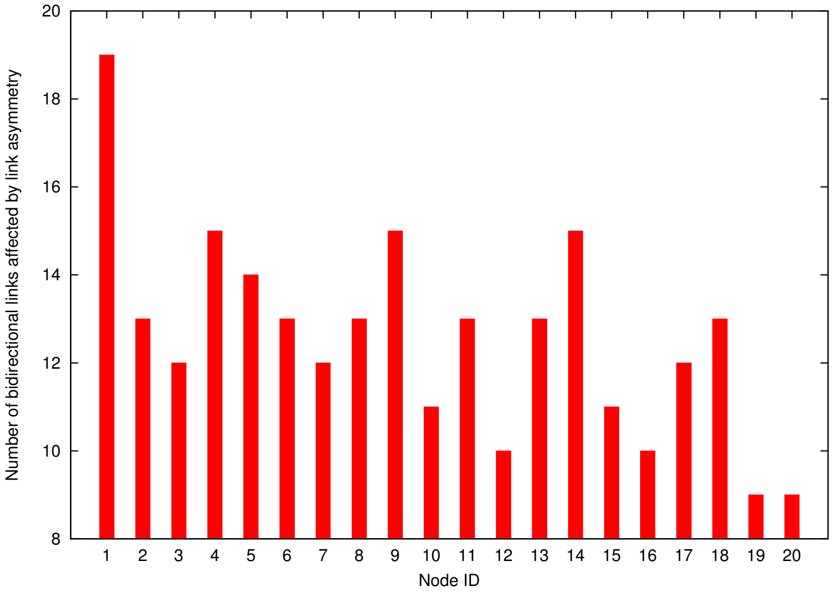

Figure 4.13: Number of link asymmetry-affected bidirectional links per node.

5 Conclusions and Future Work

5.1 Conclusions

In this work, we discussed the challenges of moving a testbed from the friendly confines of the indoors to the unpredictable world outside. We presented the design and deployment of an outdoor, permanent and unattended sensor network testbed to be made publicly available. Deployed in the BG of the Technische Universität Darmstadt, the testbed was safely integrated in the environment. Two **main stations** were deployed and integrated as a fourth site of TUDμNet. This outdoor experimentation site targets the evaluation of outdoor WSN applications. It enables researchers to test their software in an outdoor experimentation environment with changing weather conditions.

As a cooperation project with the biologists, we explored different soil moisture sensors. Each of the stations was equipped with the chosen VH400 sensor. Daily data collection is planned to take place when nodes in the testbed are idle and no activity is present i.e., no experiments are being run.

At the end, we conducted an evaluation study of the low-power links of the testbed. For this purpose, additional 18 nodes were connected and the resulting 20 nodes, middle-sized network was characterized.

5.2 Future Work

As a short-term goal, we will target the deployment of the 8 peripheral nodes attached to the **main stations**. We also plan to camouflage them to better integrate into the environment and label them with stickers warning about the electrical voltage danger.

As long-term future work, we plan to expand the testbed to a middle-size WSN. Testing at realistic scale is important, because each order of magnitude increase in network size brings a new set of unforeseen challenges which in turn closes further the realism gap between outdoor experimentation testbeds and real outdoor deployments. As a goal, we target to increase the size of the outdoor site up to 100 nodes, spanning the entire area ($55,000m^2$) of the BG.

The inner part of the BG will be also targeted. The rain forest hall, a sub-site, which could initially be categorized as an indoor deployment, is challenging as a real outdoor site due to its induced environmental properties. The exotic plants in this rain forest room make this location even more attractive for future monitoring.

While extending the network, we also intend to explore the possibility of using renewable energy, in the form of a solar power supply. Our plan is to power part of the outdoor network using a solar panel set for outdoor wireless cells.

As another future direction, we intend to extend the scope of the environment-dependent application that was developed in the context of this testbed. As described in Chapter 3 and 4, the testbed currently offers a fine-grained monitoring of the soil moisture levels. But in order to be able to do the more complex analysis (measuring the amount of water that goes into the soil and respectively how much is actually absorbed from the trees), weather stations, delivering the daily rainfall data, must be deployed. Such a system was determined as a very valuable tool from the biologists' perspective.

Finally, we plan to exploit and systematically evaluate technologies such as power over ethernet (PoE), or USB over Ethernet in the context of the testbed. Their integration could potentially lead to reductions in deployment costs.

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