Repeatable Experiments with Mobile Nodes in a Relocatable WSN Testbed

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***Abstract*—We present Sensei-UU, a testbed that supports mobile sensor nodes. The design objectives are to provide wireless sensor network (WSN) experiments with repeatable mobility and to be able to use the same testbed at different locations, including the target location. The testbed is inexpensive, expandable, relocatable and it is possible to reproduce it by other researchers.**

Mobile sensor nodes are carried by robots that use floor markings for navigation and localization. The testbed is typically used to evaluate WSN applications when sensor nodes move in meters rather than millimeters, eg. when human carries a mobile data sink (mobile phone) collecting data while passing fixed sensor nodes. To investigate the repeatability of robot movements, we have measured the achieved precision and timing of the robots. This precision is of importance to ensure the same radio link characteristics from one protocol experiment to another.

We find that our robot localization is accurate to ±1 cm and variations in link characteristics are acceptably low to capture fading phenomena in IEEE 802.15.4. In the paper we show repeatable experiment results from three environments, two university corridors and from an anechoic chamber. We conclude that the testbed is relocatable between different environments and that the precision is good enough to capture fading effects in a repeatable way.

I. INTRODUCTION

Many Wireless Sensor Network(WSN) application scenarios include one or more mobile sensors or a mobile sink. Participatory sensing is one example scenario where a mobile phone is used to capture sensing data, both while on the move as well as for tapping data from static sensors.

A testbed is a necessary complement to simulation and emulation. While simulation is excellent for creating repeatable experiments and to study scalability of WSN protocols and applications, it is notably difficult to simulate real movements, actual radio characteristics and what happens when real code runs on real hardware. On the other hand, it is a challenging problem in testbeds with mobile nodes to create repeatable movements with enough precision for evaluating protocols and applications. It is even difficult in a controlled lab environment to create repeatable movements but it is even harder in the "wild", the real target environment.

To tackle these problems, we present Sensei-UU - a WSN testbed that supports repeatable and reproducible movement scenarios of mobile sensor nodes. Sensei-UU allows us to perform experiments with mobile sinks, experiments where smart phones interact with WSNs, and experiments where WSN nodes can control their position depending on sensor readings, etc. These types of experiments can be performed at different locations to capture effects caused by the environment, which is hard to do if the testbed is too coupled to a physical location.

We can also evaluate participatory sensing applications with Sensei-UU. Such experiments make use of sensors and communication functionality of smart phones which are part of testbed. The smart phones have internal sensors but can also have external sensor hardware attached over USB.

Our contribution in this paper are experimental results that demonstrates the precision in the movement repeatability and the ability to achieve the same radio characteristics from one run to another. There is a natural variance in movement and radio environment and we measure our repeatability in terms of variance. A high variance will mask differences in protocol behaviors and our ability to understand the effect of different protocols constructs.

The primary properties of Sensei-UU are: (1) an inexpensive, yet precise approach to repeatable and reproducible of WSN applications that include mobility in a testbed setting, and (2) a relocatable testbed which enable experiments with the same testbed set-up in different radio conditions and with different sensory inputs.

Sensei-UU uses robots that carry sensor nodes to create movement repeatability. The robots are based on Lego NXT and they use a simplistic localization and navigation method based on waypoints on a floor. The testbed is therefore typically used in applications when sensors move meters rather than millimeters. The reason why we use Lego robots are that they are inexpensive and that they can be reproduced at other places by other research groups. The waypoints consist of regular tape taped on the floor, which defines the path the robot will follow. It is straightforward to both define a path and to lay out the waypoints.

In this paper we show that even this simplistic robot can move in a repeatable pattern with high accuracy. We find that our robot localization is accurate to ±1 cm and variations in link characteristics are acceptably low to capture fading phenomena in IEEE 802.15.4. We have previously used much more expensive robots with higher precision but the cost and the general availability of them is a hindrance for other groups to recreate the testbed.

In the following section we will relate our testbed to other testbeds and how they create repeatability. In the following section, the design of Sensei is presented and thereafter we present repeatable experiment results from three environments, two university corridors and from an anechoic room. Repeatability is evaluated by studying precision in location and timing over consecutive runs in an indoor setting. Reproducibility is evaluated by setting up the same experiment in three different locations. We have confidence that variance in results obtained in the experiments are caused by variations the surrounding environment rather than by the testbed itself. We conclude that the testbed is relocatable between different environments and that the precision is good enough to capture fading effects in a repeatable way.

II. RELATED WORK

Most WSN testbeds are based on an indoor fixed setup and do not provide sensor node mobility. In general, testbeds consist of two parts, the actual sensor nodes which communicate over the WSN radio channel, and an observation and control infrastructure. The infrastructure typically consists of one or several sensor hosts (small computers) that observe and control sensors. The sensor hosts communicate with a management unit over a network, typically USB, Ethernet or WLAN. See Figure 1. The infrastructure is used for programming sensor nodes, logging, and injecting data into the sensor nodes. It is an important design issue that the infrastructure do not have any influence on the regular operation of the sensor nodes. Testbeds with this general approach include Motelab [9], Tutornet [8], and TWIST [4]. To our knowledge, these testbeds currently do not support mobile nodes.

Mobile Emulab [5] is an indoor WSN testbed with six robots carrying sensor nodes. Localization of the robots is performed by combining inertial measurements from the robots with measurements from ceiling-mounted cameras which can detect fiducials on the robots. Robots in Mobile Emulab can be positioned freely in the designated area, whereas robots in Sensei-UU follow pre-defined paths. While our approach constrains the robot's mobility, it also lowers the complexity of the testbed and makes it largely independent of a positioning infrastructure, such as ceiling-mounted cameras. Sensei-UU is easily relocatable to other places which is not the case with Emulab.

The Kansei WSN testbed [3] includes five robotic mobile nodes that each carry an Extreme Scale Mote and a Tmote Sky [6]. The robots can move within an array of stationary nodes and act as mobile sensor nodes or trigger sensor events in the stationary nodes. Methods for robot navigation and localization are not explicitly described in the Kansei papers.

MiNT[1] is an IEEE 802.11b testbed including mobile nodes. Similar to our approach, MiNT incorporates mobile nodes based on Lego NXT robots. However, in MiNT, a robot only carries an antenna that is cabled to a stationary node. This cabling severely limits the mobility of the robots.

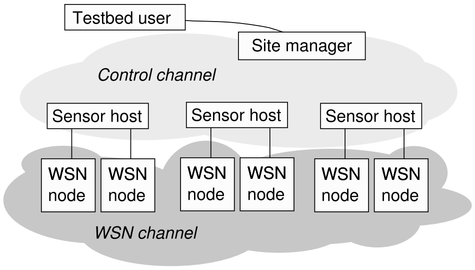


Fig. 1: The high level design of Sensei-UU.

III. TESTBED DESIGN

Sensei-UU follow the general architecture of testbeds as depicted in Figure 1. The sensor nodes are attached to *Sensor hosts*. The Sensor hosts communicates with the *Site manager* which is also the gateway to the testbed and the sensor nodes. The sensor nodes are normally attached to Sensor hosts via their USB interfaces, which are used to observe and control the operation of the sensor nodes. All sensor nodes and their Sensor hosts are designed as being mobile, even though most of them do not move during an experiment.

In addition, Sensei-UU is designed for heterogeneous sensor nodes, expandability and for relocation to diverse environments. Other important designs objectives are low cost and reproducibility of the testbed at other institutions. To achieve the relocation and expandability features, the interconnecting network is based on IEEE 802.11b/g. It gives flexibility to deploy nodes anywhere and an unlimited number of sensors as long as there is WLAN coverage and capacity. Avoiding a wired network simplifies relocation of the testbed – setting up the testbed in a new location mainly involves ensuring that all nodes know their current position. Sensei-UU lets every sensor host keep track of its own position and report its coordinates to the site manager. Hence Sensei-UU is not tied to one specific external position system which make it easy to use different positioning techniques, including GPS.

A. *Control channel*

All sensor nodes are attached to a control channel via their Sensor hosts, and can be addressed and controlled individually. Currently IEEE 802.11b/g is used as the control channel, but the design is not limited to IEEE 802.11b/g; IEEE 802.11a can also be used as well as a wired Ethernet. The range of IEEE 802.11b/g is often large enough to cover a small deployment. For longer distances, Sensor hosts can be used as relays or WAN technologies can be used to connect to the Site manager.

Using a wireless control channel operating in the 2.4 GHz ISM band raises concerns when sensor nodes also communicate in this frequency band. In particular, we are concerned with interference between IEEE 802.11b/g and IEEE 802.15.4, a popular choice for radio communication in sensor networks. We have previously analyzed interference between the two radio standards[7] and concluded that both can coexist if non-overlapping channels are chosen and care is taken how and where nodes are placed.

B. Mobile nodes

Mobile nodes in Sensei-UU are built with off-the-shelf hardware to make them reproducible and affordable for other researchers. A mobile node in our testbed consists of a Lego NXT robot, a sensor node, and a smartphone. The robot supplies mobility and carries the sensor node and the smartphone, In Figure 3a, the Lego robot carries a smart phone and a TelosB sensor node. Although a custom hardware solution to mobility might offer higher precision control, we argue that the Lego robots offer a better price/performance trade-off with sufficient precision.

Since Sensei-UU is a relocatable testbed, mobile nodes need to be able to easily move and navigate in a new environment. To this end, the robot navigates on a track system that is defined by tape on the floor. The robot follows the track defined by the tape and can be started and stopped arbitrarily by the testbed user. The track system also contains specially marked positions on the track called waypoints, which aid the robot in navigation. The robot is built with two downward facing color sensors that are positioned so that they can detect the edges of the track. In that way it can follow the tape. The use of tape on the floor to define tracks makes it affordable to construct large track systems in which multiple nodes can travel. The size of the mobility patterns are limited by the WLAN coverage of the Control channel and available open space.

The automatic line follower software running on the Lego NXT controls the movement of the robot. Its main task is to follow a tape line, either straight or with curves, and to detect waypoints where it also can turn. The robot continuously estimates the traveled distance on the basis of wheel revolutions, and periodically reports this estimate to the smartphone. These estimates are used to determine the robot's position and report it to the site manager. The Lego NXT also reports if it detects waypoints on the track. As the true positions of waypoints are available in the smartphone, potential errors in position estimate can be corrected whenever a waypoint is passed. Hence, localization errors only accumulate between adjacent waypoints.

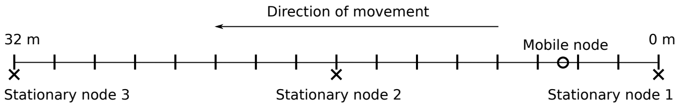


Fig. 2: Experimental setup for evaluation of link characteristics in a corridor environment

IV. EVALUATION

It is important to understand the source and magnitude of variance between experiments in the testbed. Some variance is due to properties of and imperfections in the testbed itself, while some variance can be explained by different conditions in the surrounding environment.

When mobile nodes are included in an experiment, it is important to know how similar they move between runs to ensure repeatability. A mobile node adds variance due to error in positioning and error in timing. A node needs to be at the same place at the same time in different runs of an experiment.

A. Mobility precision

The mobile nodes can travel along any path that can be realized with tape, not only straight lines. Although, if such a path has sharp turns the speed of the robots might have to be decreased. We have previously evaluated the robots' localization and positioning precision [7]. In short, the mean localization error is below 5 mm over 2 m straight lines and less than 17 mm over 2 m curved lines. In both cases the standard deviation is below 5 mm. The higher mean error on curved lines is due to the problem of making perfect arcs with tape. It is of interest that the variance does not increase although the mean error increases, this shows that robots' movement are repeatable. The timing is also highly accurate. The standard deviation between the arrival times on a 3 m path is approximately 0.2 s.

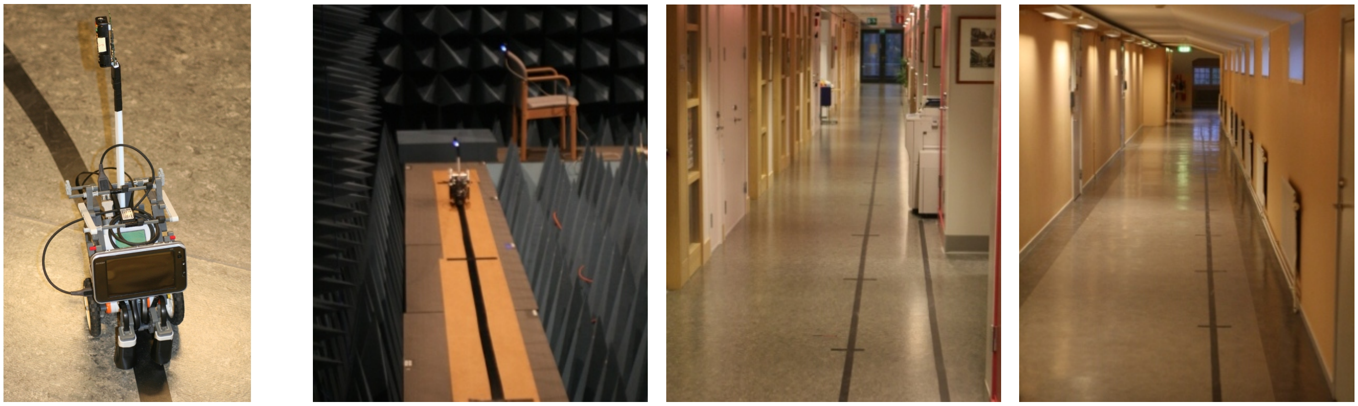
B. RSSI measurements

MAC level, routing and higher level protocols as well as applications react on the quality of the underlying wireless links to the neighbors it can hear. The Received Signal Strength Indicator (RSSI) is an important quality parameter for these protocols. For example, RSSI is frequently used for deciding on an handoff to another node. In order to do repeatable experiments with alternative protocols the RSSI from all neighbors should be identical in time and space, from one experiment to another. If there is significant variance in RSSI it will be hard to compare the efficiency of alternative protocols or different application designs.

We evaluate the received signal strength indication (RSSI) and its variance in three different environments (Figure 3b-3d). First, we did measurements in an anechoic chamber to understand the variance added by our testbed. The purpose of an anechoic chamber is to reduce reflections of RF signals as such reflections cause fading effects. It also shields the experiment from external radio interference. Second, we performed measurements to study the effects of the environment. Third, we repeated those measurements in another location to investigate the impact of different environments.

1) Experimental Setup: The overall setup for the two latter experiments is shown in Figure 2. The robot's path is a 32 m long, straight track. We use 17 waypoints on the track with a distance of 2 m between two consecutive waypoints. Three stationary sensor nodes are placed 0.5 m next to the track at 0 m, 16 m, and 32 m. TelosB sensor nodes are used for both the stationary sensor nodes and the mobile sensor node.

We set up a similar experiment in an anechoic chamber(Figure 3b). The experiment setup that could fit in the anechoic chamber is a only 8 m path with limitations as to where stationary nodes are positioned. The mobile node travels the track that corresponds to the first 8 m of the full scale set-up described earlier. We have the sensor hosts and other testbed hardware, including the IEEE 802.11 control channel,



(a) A mobile node consisting of a Lego robot, a sensor node, and a Nokia N810.

(b) The anechoic chamber.

(c) The Angstrom building.

(d) The Polacksbacken building.

Fig. 3: Pictures of a robot and the different experiment sites.

inside the chamber because we want to include their effects in the results.

To compare results between the anechoic chamber and from the other two experiments, the stationary node 1 has the same relative position in all setups, while node 2 and 3 had to have different positions. Thus, the measurements from node 1 are compared over the experiments.

We use a Contiki [2] program to measure the RSSI of packets received by the mobile node. In this program, a stationary node sends a PING packet to the mobile node and the mobile node responds with a PONG packet that contains the RSSI value with which the PING packet was received. The three stationary nodes send PING packets in a strict round-robin fashion to avoid packet collisions. Each node sends 3 packets per second, which results in 3 RSSI samples per second per link. We use IEEE 802.15.4 channel 26 for communication between sensor nodes, and transmission power is set to 1 mW.

2) Anechoic chamber measurements: The measurements in the anechoic chamber aim to study the impact of our testbed on our experiments. In theory, if the anechoic chamber was perfect and there were no other sources of interference, the RSSI would be logarithmically decreasing as a function of the distance between the sender and the receiver. Our hypothesis is therefore that any variance between runs or deviations from the theoretical model would be caused by our testbed. However, in reality, we can only determine the upper limit of the impact of our testbed as the chamber and the radio transceivers are not perfect. Figure 4a shows the RSSI and standard deviation (SD) of node 1. As expected, there is still some variance and the RSSI level does not fall perfectly with distance. The measurements in the anechoic chamber are a good estimation of the variance introduced by Sensei-UU and therefore serve as our base case to estimate Sensei-UU repeatability.

The first measurements are from a corridor in the Angstrom building on our campus. Here we expect to see fading effects due to reflections from walls, etc. We want to evaluate application behavior when mobile nodes travel in and out of range of other nodes, i.e., how an application would perceive the links while moving a longer distance.

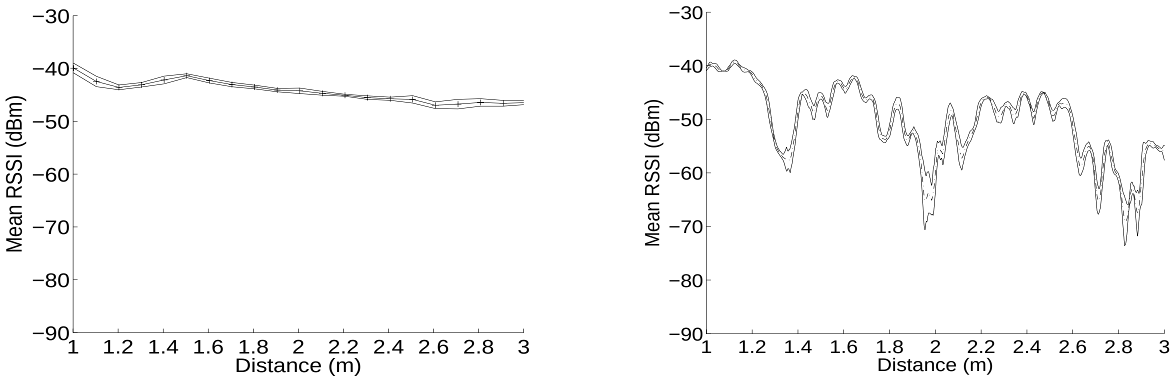
To make an overall comparison between the RSSI measurements, we filter the raw RSSI data from the 32 m measurements in order to remove the small oscillations. We filter the data using a moving average with a window size of 10 samples (corresponds to 1 meter) and an even sample weight. This filter is a low pass filter used to emphasize the long distance trends.

Figure 5a shows the filtered mean RSSI of the three nodes. From the figure, we find that node 1, which is located close to the starting point, achieves the highest RSSI at the beginning of the experiment, as expected. Then the RSSI of node 1 drops as the robot is moving closer to node 2. The robot is closest to node 2 in the middle of its path and accordingly the peak in the graph of node 2 is in the middle of the figure. The RSSI of node 3 becomes the highest among the three nodes when the mobile node is close to the end of its path as expected.

3) Measurements in the Polacksbacken building: We repeated the Angstrom experiments in another building, called Polacksbacken, to study the reproducibility and repeatability of our testbed.

Figure 5b shows the filtered RSSI from the Polacksbacken building. Comparing Figure 5a with Figure 5b, the three nodes have the highest RSSI readings at similar positions. However, the three curves have different local peaks at the two different sites. We believe that the differences are due to the particular corridor structures in the two different buildings such as different materials in the walls, etc.

If a WSN application would be deployed in these two different environments, the performance could differ. For example, if a node picks its routing neighbors by the highest RSSI, the mobile node would change from node 1 to node 2 at 5 m in the Angstrom building while the corresponding change would at earliest take place at 10 m in the Polacksbacken building. This type of differences between environments is what Sensei-UU



(a) Mean RSSI and standard deviation for node 1 in the anechoic chamber. The mean is calculated over 10 runs.

(b) Mean RSSI and standard deviation for node 1 in the Angstrom building. The mean is calculated over 10 runs.

Fig. 4: RSSI measurements for node 1 from the anechoic chamber and the Angstrom building.

is designed to evaluate.

The ability to set up Sensei-UU in different environments allows performance experiments not only in the lab, but also in potential target environments. Figure 5 shows that the environment might have a significant impact on a WSN application, depending how sensitive the application and its underlying protocols are to RSSI changes.

V. CONCLUSIONS

Our Sensei-UU WSN testbed supports mobile sensors. Lego robots are used to carry sensors and to create repeatable movements. It is also relocatable which makes it possible to easily evaluate applications and protocols in different environments.

From our evaluation, we conclude that the mobility precision of Sensei-UU is high enough to capture short term link effects such as local fading points caused by reflections. The accuracy of the robots' movement is good enough to recreate the varying signal strengths at the moving node, both temporally as well as spatially. The reported experiment in the anechoic chamber increases our confidence that the robot approach does not introduce significant variance in measurements. The spatial variance, the testbed itself, and the normal background radio noise in our buildings cause a signal strength variance that do not mask fading and other radio phenomena of importance for WSN communication protocols.

Regarding our goal to repeat experiments at different locations, we find that Sensei-UU suits our needs. When comparing the signal strength variations of the same experiments but in two different corridors we see that the overall RSSI shapes are similar in general but are different in details due to fading. In both corridors, as well a in the anechoic chamber, we have different fading patterns but the important result is that the variances are in the same order. These three measurements increase our confidence that the testbed itself adds little and controlled variance to an experiment.

Also, by relocating the testbed to different environments we have reasons to believe that there is no obvious systematic errors in the relocation principle since the behavior and variance are similar. This increases our confidence that the testbed can be recreated at other sites.

VI. FUTURE WORK

We are currently designing an experiment to evaluate how well different data collection protocols works with a mobile sink.

So far, we have only used one robot during our experiments. When extending experiments to use multiple robots simultaneously, it becomes necessary to deal with path planning to avoid collisions, scheduling of movements, etc.

While a Lego NXT-based mobility solution works well in indoor environments with flat surfaces, it may not be the best choice for outdoor experiments or in larger indoor areas. For such scenarios, it may be desirable to use other types of robots.

Sensei-UU is licensed under the GNU Public License (GPL) and will be publicly released together with configuration instructions for sensor hosts.

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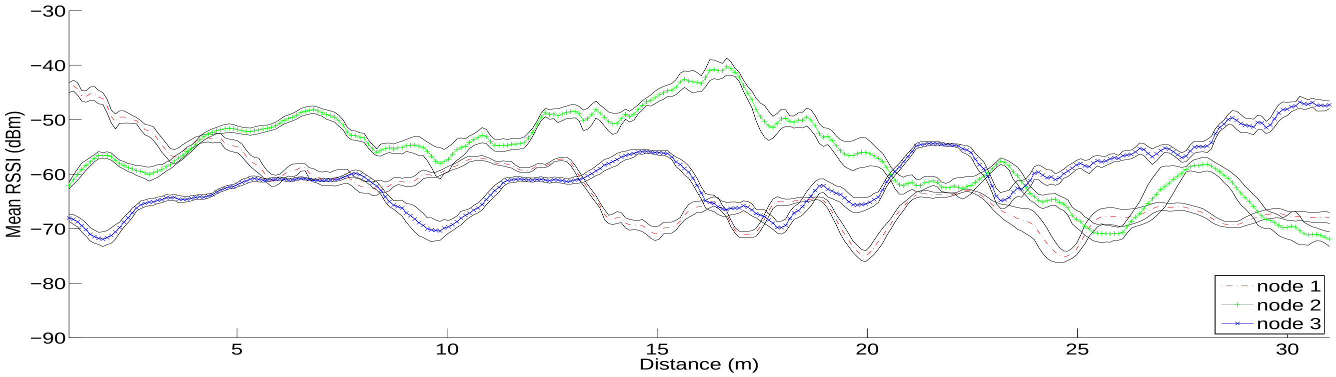
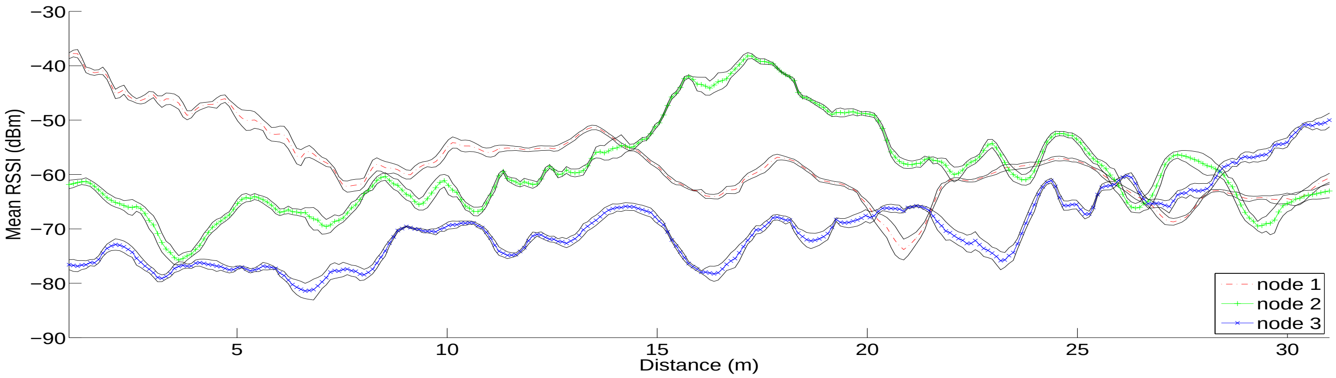


(a) Mean RSSI and standard deviation in Angstrom building from 10 runs smoothed over a 1 m window.



(b) Mean RSSI and standard deviation from the Polacksbacken building from 10 runs smoothed over a 1 m window.

Fig. 5: RSSI measurements from two experiments in different locations.

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