Repeatable Experiments with Mobile Nodes in a Relocatable WSN Testbed

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Many sensor network application scenarios include mobile nodes, such as a moving sink. Evaluating such applications in a testbed is challenging since the testbed has to support mobile nodes. We present Sensei-UU, a sensor network testbed that supports mobile sensor nodes. The testbed is inexpensive, relocatable and possible to reproduce by other researchers. Its primary design objectives are to support experiments with repeatable mobility and to support relocating the testbed deployment to different locations. Mobile sensor nodes are carried by robots that use floor markings for navigation and localization. The testbed can be used to evaluate applications in which sensor nodes move in the order of meters rather than millimeters, e.g., when a human carries a mobile phone that collects data while passing stationary sensor nodes. To investigate the repeatability of robot movements, we measure the achieved precision and timing of the robots, and find that our robot localization is accurate to \(\pm 1\) cm. Furthermore, we investigate variations in radio signal strengths between mobile and stationary nodes. We study the impact of imprecise movements, external sources of interference, and environmental influences. We conclude that Sensei-UU supports experiments in which these variations are acceptably low to capture small-scale fading phenomena in IEEE 802.15.4.

1. INTRODUCTION

Many Wireless Sensor Network (WSN) application scenarios include one or more mobile sensor nodes or a mobile sink. In a participatory sensing scenario, people on-the-move often use their smartphones to sense the environment and to communicate sensor data to a server or to other people’s smartphones. In a more static scenario, a moving smartphone may act as mobile sink to static sensors previously distributed in the environment. Both scenarios represent a complex system with many interacting sensors, real time sensing, a time varying radio environment and mobility that are hard to systematically evaluate.

Simulation is by far the most dominating method to evaluate protocols and applications since it can create repeatable environments, including repeatable mobility. With a repeatable environment we mean that different test objects can be compared in the exact same situation from one simulation to another. Furthermore, parameters can be easily and systematically evaluated including the number of nodes, their speed and direction. However, simulations must be complemented by real experiments in order to get full trust in simulation predictions. Real experiments may expose interactions that are not predicted by simulation models or foreseen by a protocol designer. Results from real experiments can also be used to verify and refine simulation models.

Various testbeds are used to experimentally and systematically evaluate WSNs. Testbeds provide observation tools, methods, and other ways to compare and evaluate alternative real hardware and software. Since real experiments can not take place in a completely controlled and repeatable world as in simulations, it is a challenge to design a testbed, particularly with moving nodes. In fact, in some experiments it is even desirable to have variations in the environment in order to expose the system under evaluation for unpredictable events.

For smartphone scenarios it can be expected that the movement speed is walking speed or slower, especially if we restrict ourselves to an indoor situation. For example, a smartphone acting as a sink could be carried in a corridor while reading stationary sensors.

A straightforward evaluation approach is to simply let humans carry mobile nodes which collect sensor data. They then walk or stop according to movement instructions [1, 2]. An experiment is then easily repeated by asking the humans to follow the instructions again. There are several problems associated with this approach, one of the most important problem is the human inability to repeat experiments with sufficient mobility precision to capture effects caused by the environment rather than by variations in their movement patterns. A solution to this problem is to replace humans with robots that can repeat the same movement from one experiment run to another with better precision [3, 4]. A key question is: “What precision is sufficient?”

A major design issue for all testbeds is to ensure that the impact of the testbed on the evaluation is not significant or at least controllable. For robots carrying nodes it is therefore important that the robots are at the same place.
at the same time with the same speed, or with sufficiently small differences, for all runs - the acceptable tolerance depends on the application under test. If that is the case we can assume that a sensor node experience the same radio connectivity pattern with other nodes at all times for all runs, modulo natural variation in background radio noise. With radio connectivity we do not only mean the ability to receive a signal but also the data quality in terms of correctly transferred symbols, frames and packets. The Received Signal Strength Indicator, RSSI, is perhaps the most fundamental quality indicator of a good connection. It depends not only on the distance between nodes but also on the structure of the environment. When a node is moving it may experience a regular fading phenomena in RSSI, due to reflections in the environment. The fading RSSI dips are very profound and are very sensitive to position (and indirectly to speed). For the 2.4 GHz band we need a precision better than 1 cm to capture the phenomena.

We have developed Sensei-UU – a testbed that supports a robot-based solution for mobility at walking speeds and indoor usage [5]. In this paper, we evaluate the movement precision of Sensei-UU in terms of variations in RSSI from one run to another.

Our contribution can be summarized as follow. We demonstrate that the testbed:

- repeatably can capture fast fading effects in the 2.4 GHz band at walking speed.
- has enough precision and small enough variance to accurately capture external interferences.

The high precision of Sensei-UU allows for experiments in different environments with confidence that differences in the results are caused by the environment factors rather than the method to do measurements and the testbed itself.

The Sensei-UU has two significant novel features compared to other testbeds: it is relocatable and easily reproducible.

The testbed does not depend on any fixed infrastructure which makes it relocatable to new locations. It is not only possible, but also quite easy to bring the entire testbed to a target environment to evaluate an application in the real setting. The control infrastructure, a wireless control channel, is part of the testbed. Therefore, there is need for an existing wireless network at the new location. The testbed architecture and relocation feature is described in more detail in Section 4.

A key problem that exists for many robot-based testbeds is the difficulty to reproduce the same experiments at other locations. Existing robot solutions are either expensive or dependent on a local infrastructure for positioning. The Sensei-UU testbed, on the other hand, is based on inexpensive WLAN routers, USB hubs, and Lego NXT robots. Positioning is based on regular tape on the floor. All parts are inexpensive and can be easily assembled at other sites. Our software is freely available.

2. RELATED WORK

Testbeds have successfully been used to evaluate many aspects of wireless sensor networks. Most WSN testbeds follow an indoor set-up approach, in which all sensor nodes are attached to a fixed control infrastructure, as well as communicating through their regular radio channels. This infrastructure is used for management and observation of nodes including programming, logging data, and injecting sensory data into nodes. The motivation for a separate infrastructure, instead of using the regular sensor node radios, is to keep the testbed’s influence on the WSN low, i.e. there should be no significant impact on the sensor nodes and their communication. Typical infrastructures consist of low-power control computers, such as laptops or WLAN access points, to which one or more sensor nodes are connected, usually over USB. The control computers in turn communicates with a user server.

Testbeds that follow this approach include MoteLab [6], NetEye [7], Re-Mote [8], Tutornet [9], TWIST [10], and w-Lab.t [11]. They differ in their hardware components, software architecture and user management. Existing deployments are as large as a couple of hundreds of nodes. The TelosB sensor node stands out as being the most widely used node in these testbeds. The software of most of them are freely available.

To our knowledge, these testbeds currently do not support mobile nodes, even though some authors mention incorporation of mobile nodes as future work. In Sensei-UU, it is straightforward to add mobile nodes, as we will describe in this paper.

2.1. Testbeds with mobile nodes

Three testbeds are reported to support mobile nodes: Mobile Emulab [3], Kansei WSN testbed [4] and MiNT-m [12].

Mobile Emulab uses six mobile robots from Acroname, each of which carry one MicaZ node. They are complemented with 25 stationary MicaZ nodes. The nodes are confined to a 60 m² area. A WLAN infrastructure is used for management of the nodes. To position a robot, an experimenter sends a request to a central path planner, which constructs a plan, comprising a series of movements which are transferred to the robot. To ensure repeatability of experiments, Mobile Emulab assess positioning error. To do this it uses ceiling-mounted cameras for localization in combination with inertial movement measurements. This combination allows the robots to be freely positioned within the designated area. For a traveled distance of two meters, the error is reported to be below 2 cm. In Sensei-UU, robots instead follow predefined paths marked on the floor. Our approach, compared to Emulab, lowers the complexity of the movement control and it is not dependent on a ceiling-based infrastructure with cameras. The Mobile Emulab also uses off-the-shelf components but the robots are about twice as expensive as our Lego NXT-based robots.

In the Kansei WSN testbed [4], three different arrays of sensor nodes are used: (1) a stationary array, which consists of 210 Extreme Scale Motes [13]. (2) A portable array
of 50 Trio motes [14] for gathering data in-field. (3) A mobile array of five robot based mobile nodes, each carrying one Extreme Scale Mote and one Tmote Sky node [15]. The robots are intended to move within the stationary array and to act as mobile sensor nodes or to trigger events in stationary nodes. The methods for robot navigation and localization are not explicitly mentioned in the references.

MiNT-m is a IEEE 802.11b testbed using mobile nodes [12]. The MiNT-m mobile nodes are based on Roomba robots. As in Mobile Emulab, the robots are localized using cameras. The mean localization error is 2.4 cm in a small deployment and approximately 5.9 cm in a larger deployment. The difference is due to the need to increase the height of the cameras in the larger deployment.

Testbeds for Mobile Ad-hoc Networks (MANETs) bear some similarity to WSN testbeds with mobile nodes. A survey of MANET testbeds can be found in [16]. Our own testbed APE [2] is based on individuals carrying laptops with movement instructions on the display.

In wireless spectrum survey systems, mobile robots may be used to automatically assess the spectrum at different locations. While such systems are not testbeds, their approach to mobility often shares some similarity with testbeds that include mobile nodes. The Sybot [17] system uses robots to assess the WiFi spectrum, and claims a localization error less than 10 cm. Similar to our work, the authors also address the aspect of repeatability.

### 3. VARIANCE IN TESTBED EXPERIMENTS

Repeatabile testbed experiments are challenged by both natural and system variances caused by radio noise, mobility and hardware/software variations. A too high variance may mask significant events that instead will be perceived as added noise. Nodes are exposed to background radio interference that varies over time, as well as between locations. Such noise can be measured and reduced by shielding but not controlled.

There are also variances in the nodes themselves, due to imperfections in hardware and software. For example, temperature-dependent components may cause unpredictable variations in signal strength readings and drifting clocks may cause race conditions. Operating systems have time dependent behaviors, caused by unpredictable order of events, which may manifest themselves as variance in measurements.

#### 3.1. Mobility variations

One possible approach to evaluate scenarios with mobile nodes is to instruct humans to perform a sequence of movements while carrying the nodes. Such experiments are comparably easy to set up, since no special calibration of technical equipment (such as localization devices) is required, and movement instructions can be expressed at a high abstraction level (e.g., "Walk to the end of the corridor, then wait 10 seconds, then walk back."). This approach has been used previously to evaluate scenarios including mobile nodes, e.g., in the evaluation of the Whirlpool routing protocol [1], or in our own APE testbed [2].

However, there are several potential sources of signal strength variance when humans carry nodes: (1) there is a natural variation in human gait. When a movement experiment is repeated, a person carrying a node may move a bit faster or slower than before, or deviate slightly from the path she/he took in previous runs. Hence, a node may be at different positions at the same point in time in different runs of an experiment and experience different signal strengths. (2) The human body partly absorbs electromagnetic radiation, and the amount of absorbed energy depends – among other things – on the person’s physique and pose, and the radio frequency [18].

#### 3.1.1. Mobility precision

With repeatable mobility we mean both the ability to precisely follow the same path from one run to another, as well as the ability to achieve the same speed at all points on the path. Instead of a human walking, different types of vehicles can carry nodes. Then the path precision follows from the mechanics of a vehicle. A track bound vehicle, like a train, is likely to have better precision than a robot on wheels moving over an uneven floor. A significant advantage with a robot-based vehicle compared to a track bound is that it requires very little or no infrastructure support, such as a track. The follow-on questions can then be formulated as: "How accurately can a robot recreate speed, acceleration and to what precision can a path be followed?" and "Is the movement precision and variance acceptable for evaluating and comparing protocols and applications?" The answer to the latter question is that there is no single number – the acceptable variance depends on the application, the radio propagation, the accuracy of the sensing coverage, and the physical size of the sensor nodes and robot. A side observation to the first questions is that the accuracy in the geographical position is important for experiments with sensing accuracy, as the sensor data may be highly sensitive to the location.

Another major challenge for repeatability with a moving node is that the received signal strength $P_r$ depends on the transmission distance, the speed of mobility, the radiation pattern of the antennas and their orientation, the physical propagation environment, and the transmit power $P_t$.

The antennas and the environment together form the radio propagation channel. Small changes in geographical locations may cause large differences in signal strengths at the receiving node due to reflections and attenuation from the environment. When a node is moving it will therefore be affected by fading phenomena. The fading pattern depends on the radio wavelength, and the combined physical structure of the antennas and the environment. This environmentally dependent fading is very hard to predict with good accuracy or even impossible to do in real time. It is therefore very important that the robot has a movement
precision that is better than the distance between fading points. Otherwise we risk that the fading will be interpreted as a large uncontrollable variance instead of a repeatable phenomenon. In this paper, we will demonstrate with real measurements the spatial and temporal accuracy of our robot approach and that we in a repeatable way can capture fading.

3.1.2. Fading model

In order to understand precision requirements when capturing fading we will use three common propagation models. The issue is how sensitive the received signal power $P_r$ is to position errors – that is, how much the received signal strength can be affected by a small deviation in robot position. We use a widely adopted channel model [19, 20] comprising three modeling scales: (1) a large-scale propagation loss model where the average signal strength follows an inverse power-law (super-wavelength scale). (2) a medium scale where a shadowing model describes the impact of obstructions (i.e., at wavelength-scale presently 12.5 cm). (3) a small scale fading model that captures constructive/destructive interference between reflected radio waves (i.e. at sub wavelength scale). In Appendix A we give more details of the models, which follow textbooks in the area.

3.1.3. Sensitivity to small movements

Using the models and our parameters, the sensitivity analysis can be summarized as follows. (For complete derivation of rate-of-change models, see Appendix A).

Propagation loss model. In this model $P_r \propto d^{-\kappa}$, where $d$ is the transmission distance and $2 \leq \kappa \leq 4$ (typically) is the propagation loss exponent. In a pessimistic, worst-case, scenario the RSSI sensitivity is about 0.2 dBm/cm. More realistic rates of change are an order of magnitude smaller, that is 0.02 dBm/cm. Therefore, as expected, the large-scale propagation loss can safely be neglected as long as the positioning error is on the order of centimeters.

Shadowing model. Here, a pessimistic scenario is a receiver passing 1 cm from a shadowing (metal) plate, which gives a rate of change smaller than 4 dBm/cm. A more likely scenario, with a receiver passing 10 cm from an obstacle, gives around 1 dBm/cm. This is still pessimistic in general, but it corresponds to the typical RSSI resolution of radio chips, e.g., the CC2420. This means that a positioning accuracy on the order of centimeters is desirable to detect a change.

Small-scale fading model. In this model, destructive interference can completely cancel out the radio signal, i.e. cause $P_r = 0$. Actually, according to the model the dips could be infinite and there is no limit on the RSSI rate of change when given in dBm. Still, even if this theoretical infinite rate has limited practical interest, we see in Figure 1 that both the theoretical model and the real measured values indicate a change of up to 30 dBm/cm, and dips about 1 centimeter wide.

When comparing the sensitivity models it is obvious at the small-scale fading is the most profound. To conclude, in order not to mask such fading dips entirely, centimeter precision is required and every improvement towards the millimeter range is desirable.

![FIGURE 1: Two theoretical small-scale fading models (solid and dash-dotted lines) together with a measured channel in the Ångström building. All curves are normalized to 0 dBm maximum for comparability. Two values of the reflected amplitudes are used, $a_2 = 1.5a_1$ and $a_2 = 1.1a_1$. When the amplitudes are very close to each other the interference is most pronounced.]

3.1.4. Sensitivity of logarithmic metrics

The signal strength given in dBm relates to power $P_r$ in the following way:

$$P_r \text{dBm} = 10 \log_{10} \left( \frac{P_r}{10^{-3}} \right) = \frac{10}{\ln(10)} \ln(P_r) + 30. \quad (1)$$

From the recognition that $P_r$ depends on the distance $d$ between the sender and the receiver, we can differentiate (1) with respect to $d$ and obtain

$$\frac{dP_r \text{dBm}}{dd} = \frac{10}{\ln(10)} \frac{1}{P_r} \frac{dP_r}{dd}. \quad (2)$$

An interesting fact to note is that the logarithmic scale introduces a factor $P_r^{-1}$ that shows that the sensitivity will increase the smaller the received power is (and decrease the larger $P_r$ is). Hence, the sensitivity for absolute values can be distinctively different from that for dBm values.

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4 Observe that the scale classification serves practical purposes and is not strict. There are no sharp boundaries at which one effect disappears and the other takes over.

5 Observe that this singularity is entirely an effect of the logarithmic dBm scale and not an inherent property of the small-scale fading.

6 Therefore, also, the reasoning and numerical indications we give here pertain to the use of RSSI values only, and should not be carried over to other metrics – for example LQI, PER and BER – without care.
4. TESTBED DESIGN

Sensei-UU is designed to be relocatable, and to be easy to reproduce by other researchers. To be relocatable, a testbed and its infrastructure need to be simple to set up and tear down. To reach this goal, but also to make the testbed reproducible, it cannot include hard to configure infrastructure. An easily reproducible testbed has to be built with commonly available and affordable hardware and software.

To make Sensei-UU relocatable, it is designed around a wireless control channel described in Section 4.1. Using a wireless control channel makes it easy to set up and position nodes when a testbed instance is deployed at a new location. Mobile robots are used to support evaluation of systems with mobile nodes. The robot solution is based on a line-following approach for navigation. This facilitates relocating the testbed, because it only requires putting a new tape pattern on the floor in the new location and calibrating the robot’s color sensors. The approach is described in more detail in Section 4.2.

To make Sensei-UU reproducible by others, the management software is released under GPL. It is based on the OpenWrt [21] Linux distribution, which is available for a wide selection of hardware. The robot solution is based on Lego NXT [22] which is affordable and easily available.

Sensei-UU follows the general architecture of testbeds as depicted in Figure 2. Sensor nodes, e.g., TelosB nodes, are attached to management machines called sensor hosts, which are typically small Linux machines. The sensor hosts communicate with the site manager over the control channel. The site manager acts as the user’s gateway to the testbed and the sensor nodes. The control channel and sensor hosts are used to reprogram sensor nodes, control and monitor experiments, and collect log data. By design, the sensor nodes and their sensor hosts are considered mobile, even though it may be the case that most of them do not move during an experiment. Each sensor host tracks the positions of the sensor nodes attached to it and reports them to the site manager. By leaving it up to the sensor hosts to keep track of sensor node positions, Sensei-UU is not tied to one specific external positioning system, such as GPS.

4.1. Control channel

Sensor nodes are attached to a control channel via their sensor host, and can be addressed and controlled individually. Currently, IEEE 802.11g is used as the control channel, but the design is not limited to IEEE 802.11g; a wired Ethernet can also be used. The range of IEEE 802.11g 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 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 802.11g and IEEE 802.15.4, a popular choice for radio communication in sensor networks. We have previously analyzed interference between the two radio standards and concluded that both can coexist if non-overlapping channels are chosen and care is taken how and where nodes are placed [5].

4.2. Mobile nodes

Mobile nodes in Sensei-UU are built from 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 4a, the Lego robot carries a smartphone and a TelosB sensor node. Although a custom hardware solution for 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 that is defined by tape on the floor. The robot follows the track and can be started and stopped by the testbed user at arbitrary positions. The track system also contains specially marked positions on the track called waypoints, which aid the robot in navigation. If the robot passes a waypoint, it can turn if requested by the testbed user.

The robot is built with two downward-facing color sensors that are positioned so that they can detect the edges of the track so 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. The robot continuously estimates the traveled distance on the basis of wheel rotations, 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 the position estimate can be corrected whenever a waypoint is passed. Hence, localization errors only accumulate between adjacent waypoints. The smartphone acts as a sensor host and can have multiple USB devices attached.
5. EVALUATION

In this section we evaluate the impact of different sources of variance on experiments with mobile nodes in Sensei-UU. Three major sources of variance were described in Section 3: imperfections in robot movement, imperfections and variation in hardware and software components, and external radio interference. First we evaluate the timing and localization precision of the robot system. Next, we present a set of experiments in an anechoic chamber to understand the variance that is caused by the testbed components. Then, to understand the benefits of using a robot for mobility, we present experiments in which either a human or a robot carries a mobile node. Finally, we consider how external sources of interference (people in the experiment area, microwave ovens) affect experiments.

5.1. Mobility precision

The mobile nodes can travel along any path that can be realized with tape (although if a path has sharp turns, the speed of the robots is limited). The overall mean localization error is less than 5 mm over a 2 m straight line and less than 17 mm over a 2 m curved line. 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. The timing is also highly accurate: The standard deviation between the arrival times on a 3 m path is approximately 0.2 s.

To measure the timing and localization error of our Lego NXT-based approach, we set up a small path system in which the distance between two adjacent way points is 0.5 m, 1 m, 2 m or 3 m. The robot moves along the the track system, and timing and localization errors are logged. Since the robot knows exactly where it is every time it reaches a waypoint, it logs the arrival time at each waypoint to measure timing errors. In between each waypoint, the robot estimates the position by using the built-in rotation sensor in the Lego NXT motors. When the robot reaches a waypoint, it logs the the localization error by comparing the waypoint position to the estimated position from the robot. The results represent a worst case scenario as the measurements include starting and stopping.

5.2. RSSI measurements

We evaluated the Received Signal Strength Indicator (RSSI) and its variance in in an anechoic chamber, and two different corridors of buildings on our campus. In this paper, we focus on the experiments in the anechoic chamber and in the corridor of the Ångström building (Figure 4b-4c). An evaluation of the testbed’s relocatability, in which measurement results between the two corridors are compared and discussed, is available in [5].
5.2.1. Experimental setup

The setup for the experiments in the corridor is shown in Figure 5. The robot’s path is 32 m long and straight. We use 17 waypoints on the path with a distance of 2 m between consecutive waypoints. Three stationary sensor nodes are placed 0.5 m from the track at 0 m, 16 m, and 32 m. Each of the stationary nodes is placed 82 cm over the ground. The sensor node on the robot is placed at a height of 42.5 cm from the ground. TelosB sensor nodes are used for both the stationary sensor nodes and the mobile sensor node.

We set up a similar experiment in the anechoic chamber (Figure 4b). Due to the layout of the chamber, the setup there is constrained to a 8 m path with restrictions to where stationary nodes can be placed. The waypoints are positioned 2 m apart as in the full size experiment. The robot travels the path that corresponds to the first 8 m of the 32 m path described in the previous paragraph. We also put the sensor hosts and other testbed hardware, including the IEEE 802.11g control channel, inside the anechoic chamber since we want to see their effects on the results.

In order to compare results from the anechoic chamber and the corridor, stationary node 1 has the same relative position with respect to the path in all setups. Node 2 and 3 had to have different positions due to the smaller space in the chamber. Therefore, in our comparison we only include the measurements from node 1.

5.2.2. Method of data analysis

We measure the RSSI at the mobile node along the path of the robot and study the mean and standard deviation of measured RSSI between runs. To study how repeatable experiments are, we use the sample standard deviation (SD) as a metric. A small SD indicates good repeatability as it means that link quality is similar between different runs of the same experiment.

We treat the RSSI measurements from each run as a spatially discrete signal \( S_n \) that maps a position of the mobile node to an RSSI value. The index \( n \) identifies the run (\( S_1 \) to \( S_{10} \) in this case). The signal \( S_n \) is defined only for positions at which an RSSI measurement has been made during run \( n \). This complicates comparison of signals from different runs, because measurements in different runs may not be perfectly aligned in position, and some measurements are missing due to packet loss. To deal with this complication, we construct a spatially continuous signal \( S'_n \) from each signal \( S_n \) by linearly interpolating between two consecutive RSSI measurements. This new signal \( S'_n \) is defined over the whole distance the mobile node travels.

For each position \( i \), the mean \( \overline{S'}(i) \) is calculated as

\[
\overline{S'}(i) = \frac{1}{N} \sum_{n=1}^{N} (S'_n(i)),
\]

and the sample standard deviation, \( SD(i) \), as

\[
SD(i) = \left( \frac{1}{N-1} \sum_{n=1}^{N} (S'_n(i) - \overline{S'}(i))^2 \right)^{\frac{1}{2}}.
\]

5.2.3. Anechoic chamber measurements

The measurements in the anechoic chamber aim to study the impact of the testbed components and the robot’s mobility on experiments. The purpose of an anechoic chamber is to reduce reflections of RF signals since reflections cause fading effects. It also shields the experiment from external...
measurements are prone to quantization error, which can some quantization of the signal strength. This means RSSI a continuous value, and hence the chip internally performs the unit dBm \[25\]. The true signal strength in dBm is a

\[
\text{RSSI values as integers from the interval }
\]

transceiver. As many commercially available transceivers, amount to the variance visible in Figure 6a. we conclude that localization error only contributes a small and from our evaluation of localization error in the robot, scale propagation loss model (Section 3.1.3, Appendix A) contains no shadowing obstacles, the RF signal is mainly the anechoic chamber minimizes reflections and since it eliminated whenever the robot encounters a waypoint, and for the variance seen in the measurement results. This source of variance (quantization error, hardware imperfections) will affect all RSSI measurements.

We ran another experiment in the anechoic chamber in which the mobile node was replaced by a stationary node that was placed at different positions in different runs. This experiment allows us to eliminate the effect of robot mobility on the SD. The observed sample standard deviation of RSSI ranged from 0.2 dBm to 2 dBm (depending on position), which is in the order of the SD we observe for communication with a mobile node instead of a stationary node.

5.2.4. Impact of different types of movements

To study the benefit of robots carrying nodes, we assess the repeatability of an experiment in which a human carries a node, and contrast it to our approach using robots. This experiment was performed during the early evening in Ångström corridor, shown in Figure 4c. We ran an experiment in which a person carried a node along the track described in the experimental setup, essentially taking the role of the robot. The person was instructed to complete the track in 100 seconds, and was provided with a stop watch to control their own speed. Since the walking person did not carry a localization device, it was not possible to get their position while walking. Therefore, we assumed a constant walking speed and linearly interpolated the person’s position from the total track length and the duration of the walk.

Figure 7a shows the mean RSSI of packets sent by node 1 as received by the node carried by the person. As in the previous plot, the mean signal strength of ten runs of the experiment is shown, along with the standard deviation at each position over the ten runs. As expected, the mean signal strength decreases as the distance of the mobile node to node 1 increases. Yet, only this general trend (the signal strength decreasing with the distance increasing) that is to

radio interference. In theory, in an anechoic chamber the RSSI should decrease logarithmically with the distance between the sender and the receiver increasing. In practice, such a chamber is not perfect and a small amount of background noise as well as reflections will always be present. Still, our conservative hypothesis is that any variance between runs or any deviation from the theoretical model is caused by imperfections of our testbed and variances in hardware. In other words, variance observed in the anechoic chamber is assumed to be independent of the environment, and therefore is assumed to add to the variance measured outside the chamber.

Figure 6a shows the mean RSSI of packets from node 1 received at the mobile node. The mean is calculated from ten runs. The figure also shows the mean plus and minus one sample standard deviation. As expected, there is still some variance and the RSSI does not fall perfectly with distance.

We attribute the variance seen in the figure to two sources. First, errors in the robot’s localization may cause the obtained signals to be slightly shifted between runs at some points. Recall, however, that the localization error is eliminated whenever the robot encounters a waypoint, and that the localization error is generally fairly low. Since the anechoic chamber minimizes reflections and since it contains no shadowing obstacles, the RF signal is mainly affected by large scale propagation loss, whereas shadowing and small-scale fading have little impact. From our analysis of the effects of localization errors on RSSI under a largescale propagation loss model (Section 3.1.3, Appendix A) and from our evaluation of localization error in the robot, we conclude that localization error only contributes a small amount to the variance visible in Figure 6a.

A second source of variance is the sensor nodes’ radio transceiver. As many commercially available transceivers, the ChipCon CC2420 chip on our sensor nodes returns RSSI values as integers from the interval \([-100, 0]\), with the unit dBm \[25\]. The true signal strength in dBm is a continuous value, and hence the chip internally performs some quantization of the signal strength. This means RSSI measurements are prone to quantization error, which can cause variance if the true signal strength is near the border of two quantization intervals. Further imperfections in the chip and in the other sensor node hardware, such as noise in the analog/digital conversion, may further contribute to the variance seen in the measurement results. This source of variance (quantization error, hardware imperfections) will affect all RSSI measurements.

FIGURE 6: RSSI measurements for node 1 from the anechoic chamber and the Angstrom building.
be expected from a large scale propagation loss model, is preserved in the mean. Radio propagation effects that happen on a shorter scale, such as fading due to multi-path propagation, cannot be observed, and the standard deviation is large all along the track when compared to the measurements made in the anechoic chamber. It seems likely that these two observations – the mean only preserves general trends, large variation in signal strength between runs – stem from the previously mentioned issues with humans carrying nodes. The fact that the person carrying the node may have moved slightly differently in the individual runs means that at some points, the linear interpolation of position may give a large localization error. We showed in Section 3.1.3 that, under a small-scale fading model, even a small difference in position may cause a large difference in received RSSI. Since in a corridor environment experiments are exposed to such small-scale fading effects, we believe that ultimately the localization errors and variations in human movement contribute to a large amount of the observed variance. The effect of the body shielding RF communication is also likely to contribute to the variance.

The experiment was repeated with a robot instead of a human carrying the mobile node. The mean RSSI and its SD at the mobile node are shown in Figure 7b. In comparison, there are two important observations to be made: When a robot is used to carry the node, radio effects from the environment are preserved; in the figure, the mean signal strength clearly shows dips in certain positions, which are fading points. Furthermore, the standard deviation at each position is much smaller.

We can see effects that correspond to the theoretical analysis in Section 3.1.3. First, there is a general tendency of larger variance for small RSSI as predicted by Equation (2). The effect should thus not be interpreted as a deterioration of the positioning accuracy with increasing distance. Second, the RSSI variance increases in the fading dips. This can be seen in Figure 6b, which shows a close-up of meter 1 to 3 traveled by the robot in the corridor. (The data shown in the figure has been obtained in a different experiment with the same settings, and hence cannot be directly compared with Figure 7b.) As the measurement environments contained no sharp shielding objects close to the robot’s path, the effect is most likely due to the small scale fading as shown in Figure 1.

5.3. External interference

The measurements in the anechoic chamber and in the corridor demonstrate what variance we can expect to get when we take precautions to avoid interference. During office hours there is an increase in external interference, due to more radio activity and rapid changes in the environment.

(a) RSSI as the mobile node is carried away from a stationary node by a person. The movement is timed with a stop watch and the experiment is repeated ten times. The mean and one standard deviation of RSSI are shown in the plot.

(b) RSSI from Node 1 when a robot carries the mobile node.

FIGURE 7: Comparing walking with a node to robot measurements.
5.3.1. Microwave ovens
When investigating indoor wireless networks, a frequent concern is: "How is the operation of the testbed affected by the presence of microwave ovens in close proximity?" Microwave interference is likely to affect any wireless communication using radio frequencies that overlap with the wide-spectrum microwave oven. In the context of a wireless sensor network testbed, the relevant question is rather whether it is possible to reproduce experiments with sufficient precision in the presence of external interference caused by a microwave oven.

As it happens, the indoor path in the Ångström building passes by a small pantry equipped with microwave ovens. To investigate the effect, we ran a series of experiment with an oven turned on at 600 W. The effect of the oven was not detectable in the measurements. This finding agrees with other empirical studies of the influence of microwave ovens on 802.15.4 communication [26]. To understand why no effect of the microwave oven could be seen, we used a spectrum analyzer to measure the interference from the microwave oven. The spectrum analyzer showed that IEEE 802.15.4 channel 26, which we used, was rarely affected by the microwave oven at 2 m distance. We could find short spikes when the noise level increased to approximately -80 dBm from previously -90 dBm. If we would have used a lower channel we might have experienced more interference as we saw noise levels of up to -50 dBm but as our goal is to have repeatable measurements, we rather avoid those channels.

5.3.2. People in the experiment area
Another common concern when wireless measurements are performed in a lab setting is that people walking in the experiment area will affect the variance. To study how people affect the repeatability of experiments, we ran experiments in daytime with people walking in the corridors. The physical setup was identical to previous experiments, but arranged so that between one and three persons walked along the path during each run, either passing the robot or meeting it.

Measurement results from this experiment can be found in Figure 8. The overall trends are similar to the experiments performed in the evening, where no other people were present. However, the variance in the deep fading points is sometimes higher. Inspection of individual runs shows that the greatest impact of people in the experiment area is that the deep dips in RSSI sometimes get even deeper compared to when no people are walking by. The reason for this is that people can block the line-of-sight part of the signal and that part of the signal has greater impact in the fading points.

6. CONCLUSIONS
The Sensei-UU WSN testbed supports repeatable experiments that include mobility at walking speeds in an affordable and easily relocatable design. Inexpensive Lego robots are used to carry sensors and to create repeatable movements. The ability to relocate the testbed makes it possible to easily evaluate applications and protocols in different environments.

We have presented a theoretical analysis of what precision is required to claim repeatable mobility and in our experimental evaluation we conclude that the mobility precision of Sensei-UU is sufficient 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.

In the experiments in the corridor, as well as in the anechoic chamber, we have different fading patterns, but the important result is that the variances are in the same order. These measurements increase our confidence that the testbed itself adds insignificant, controlled variance to an experiment. Altogether, this confirms that our approach to mobility – chosen to be able to easily relocate the testbed, enable reproducibility of experiments and yet inexpensive to deploy – provide sufficient precision to claim the ability of repeatable experiments that include mobility at walking

FIGURE 8: Node 1 with people in the corridor

\[\text{Mean RSSI (dBm)}\]

\[\text{Distance (m)}\]
7. FUTURE WORK

We are currently designing an experiment to evaluate how well different data collection protocols work with a mobile sink. 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 and build instructions for the robots.

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APPENDIX A. INFLUENCE OF POSITION ON THE RECEIVED SIGNAL STRENGTH

Appendix A.1. Large-scale propagation loss

The radio waves from the sender’s antenna propagates in many directions, and the waves’ power density decreases with propagation distance. For an isotropic antenna in free space, the transmit power spreads over a growing sphere, and the power $P_r$ at the receiver therefore decreases with the area $4\pi d^2$ of the sphere: $P_r \propto d^{-2}$. From empirical studies, the slightly generalized model

$$P_r \propto \left( \frac{d}{d_0} \right)^{-\kappa} \quad (A.1)$$

has been developed to account for obstructed environments. Here, the distance dependence is with respect to the empirical reference distance $d_0$ and the impact of non-free-space propagation is captured by the loss exponent $\kappa$. The latter is typically in the range $2 \leq \kappa \leq 4$, although values outside this range occasionally are encountered. From (A.1) we obtain

$$P_r, \text{dBm} = \text{const.} - \frac{10\kappa}{\ln(10)} \ln(d). \quad (A.2)$$

Differentiating with respect to the distance $d$, we get an expression for how small changes $\Delta d$ – or likewise small errors $\Delta d$ – in position affect the RSSI values:

$$\Delta P_r, \text{dBm} = -\frac{10\kappa}{\ln(10)} \frac{\Delta d}{d}. \quad (A.3)$$

This effect is clearly largest at small distances $d$. However, with a positioning error $\Delta d = 0.01$ m at a transmitter-receiver distance $d = 1$ m the RSSI error is merely 0.17 dBm if $\kappa = 4$. This small error should be considered a worst-case type of error as the propagation loss at small distances is most likely free-space with $\kappa = 2$.

Appendix A.2. Medium-scale shadowing

A detailed and realistic description of the impact of shadowing objects on the received signal strength is complex. Due to refraction and the impact of object size and uneven surfaces, a detailed model of shadowing becomes highly specific to a certain physical propagation path. There exist numerous models on different levels of granularity, but the simplified knife-edge diffraction model will serve our purposes well as it describes the first order effects of the shadowing phenomenon.

FIGURE A.1: Simple knife-edge diffraction scenario, with sender and receiver shown as the black dots separated by $d_1 + d_2$ m.

Consider the scenario in Figure A.1, where the shadowing object is at distance $d_1$ and $d_2$ from the sender and receiver respectively. The edge is at a distance $h$ from the line-of-sight path. From diffraction theory [20], the excess propagation loss

$$L(\nu) = \frac{P_r, \text{shadow}(\nu)}{P_r, \text{free space}} \quad (A.4)$$

over the free space scenario is given by

$$L(\nu) = \frac{(1 + 2[F_s(\nu) - 1]F_c(\nu) + 2[F_c(\nu) - 1]F_s(\nu))}{4}, \quad (A.5)$$

where $F_c$ and $F_s$ are the Fresnel cosine and sine integrals, and

$$\nu = h \sqrt{\frac{2(d_1 + d_2)}{\lambda d_1 d_2}} \quad (A.6)$$

is the Fresnel-Kirchhoff diffraction parameter with $\lambda$ being the carrier wavelength. We are now interested in how this excess loss changes with distances. Let us fix $d_1$ and $d_2$ and vary $h$ to capture the effects of transition between a shadowed and a free propagation path. By differentiation of $L(\nu)$,

$$\frac{dL(\nu)}{d\nu} = \frac{\cos\left(\frac{\pi \nu^2}{2}\right) (2F_c(\nu) - 1) + \sin\left(\frac{\pi \nu^2}{2}\right) (2F_s(\nu) - 1)}{2} \quad (A.7)$$

and the use of (2) and (A.6) we obtain the result displayed in Figure A.2 and Figure A.3. We note that if the mobile

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amplitudes and phases, and antenna movements will affect the phases $\phi_n$ and thereby how much constructive and destructive interference that will occur. Consequently, the impact on the received signal strength is introduced by sub-wavelength movements. Depending on the environment, different degrees of fading can be encountered. In line-of-sight scenarios, one term is dominating with an amplitude $a_k \gg a_n$ for all $n \neq k$. There will still be short term fading but no severe dips, and these conditions are captured statistically by models such as Rician and Nakagami-$m$ fading. If there are many terms of similar amplitude, which can be the case in a non-line-of-sight scenario, the fading becomes more severe. In the worst case we get so-called Rayleigh fading.

A general position vs. signal strength analysis of the small scale fading as given by (A.8) is not feasible, but important insights can be gained from a simplified analysis. Assume that the receiver sees two incoming radio waves so that $N = 2$ in (A.8). From well-known trigonometric identities, we can rewrite the resulting two-term sum as

$$s_r(t) = \sqrt{a_1^2 + a_2^2 + 2a_1a_2 \cos(\phi_1 - \phi_2) \cos(2\pi f_c t + \theta)}, \quad (A.9)$$

where $\theta$ is a phase shift we need not analyze here. The power of this signal is

$$P_r = \frac{a_1^2 + a_2^2 + 2a_1a_2 \cos(\phi_1 - \phi_2)}{2}, \quad (A.10)$$

which has maximum and minimum values $P_{r,\text{max}} = (a_1 + a_2)^2/2$ and $P_{r,\text{min}} = (a_1 - a_2)^2/2$ respectively. To connect the phases $\phi_1$ and $\phi_2$ to movements and distances we have to make assumptions about the angle of arrival. Let us assume the worst case, in which the direction of movement is along the diametrically opposed directions of arrival, so that

$$\phi_1 = -\phi_2 = 2\pi \lambda^{-1} d. \quad (A.11)$$

Here, $\lambda$ is the carrier wavelength. By combining (2), (A.10) and (A.11) we obtain

$$\frac{dP_r}{dBm} = \frac{10}{\ln(10)} \frac{2a_1a_2 4\pi \lambda^{-1} \sin(4\pi \lambda^{-1} d)}{a_1^2 + a_2^2 + 2a_1a_2 \cos(4\pi \lambda^{-1} d)} \quad (A.12)$$

First, note that when $a_1 \neq a_2$ the expression is non-singular and can be evaluated at all distances $d$. In particular, the fading dips occur according to (A.10) at $d = (k+1/2)(\lambda/2)$ for integer $k$, and at these points the derivative in (A.12) is zero. Second, note that it is close to the fading dip that the derivative can become very large in magnitude, and that its magnitude depends on the depth of the fading dip. We illustrate this in Figure 1 (shown in Section 3) and Figure A.4 where the fading dips and the corresponding derivative are shown for the cases when $a_2 = 1.5a_1$ and $a_2 = 1.1a_1$ respectively.

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