A Numerical Study of Propagation Effects in a Wireless Mesh Test Bed

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Abstract: - The present layout of the indoor wireless mesh network test-bed build at the Meraka Institute is introduced. This is followed by a description of a numerical electromagnetic model for the complete test-bed, including the coupling and diffraction effects, as generated with WIPL-D Pro. The results of numerical simulations are compared with the measurements. The findings help to quantify errors and provide grounds for suggestions towards improving the test-bed's design.

Key-Words: - electromagnetic propagation, wireless mesh network, wireless test-bed.

1 Introduction

A wireless network test bed is a group of computers that are able to communicate with each other wirelessly and intended as a test platform for experimental work with various new communication protocols. There are a number of wireless test beds around the globe. Perhaps the most well known examples are CUWin [1], Orbit [2], Roof Net [3] and Kansei [4]. Some of the test-beds were unplanned and established as a collective effort of independent individuals (e.g. MIT RoofNet), and some were set up by organizations.

These test beds emulate larger wireless networks and are used to develop, test and evaluate new routing protocols for wireless multi-hop mesh networks.

The Meraka Institute seeks innovative solutions to provide wireless broadband Internet access to rural areas in Africa [5], and uses the indoor laboratory test-bed it has established to evaluate and compare various wireless protocols [6], [7].

It should be mentioned that, in modeling complex wireless networks, one may choose to use computer-only simulators like NS2 [8]. Such simulators use simplified models for both networking and physical layers, often leading to inconsistent results [9], and requiring a validation [10]. Under these circumstances, a laboratory test on real-world equipment provides a solution to provide more realistic results.

Protocols designed for large communication distances typical in rural areas, able to utilize the information about the signal level and possibly direction of arrival are typically based on an assumption of propagation close to the log-distance path loss model [11] or on a simple Friis free-space loss equation [11].

The validity of the latter equation is determined by the absence of obstructions, a sufficient distance between nodes, and polarization match [11], [15]. The validity of the former equation adds a requirement of uniformity in the obstacle's profile, and also on the independence of the source on the surroundings.

These factors play an important role in the ability to predict the propagation characteristics [11], [12]. When applied to the results obtained from the test bed simulations, the ability to understand and control the propagation determines the scalability of the simulation outputs [10], and thus the applicability to real-world scenarios.

In this work an accurate method for solving electromagnetic coupling problems [13],[14] is applied to the test bed of Meraka Institute. To the best knowledge of the authors, an investigation of this detail applied to a full-scale wireless network test-bed has not been done before. The findings aim to help in quantifying the errors in the simulations, and pave a way to suggest improvements to the test bed set-up.

The paper is structured in the following way. Section 2 describes the physical layout, main features and electromagnetic characteristics of the test-bed. Section 3 shows the results of a numerical electromagnetic simulation of the complete 7×7 grid of PC cases with attached antennas. The Conclusion finalizes the paper with a discussion and a summary.

2 Test-Bed Description

The laboratory test-bed of the Meraka Institute is configured as a square 7 by 7 grid of small PCs connected into a network. Figure 1 shows an overview of the set up, installed in a 6 m by 12 m room.

Each PC is equipped with a wireless network card and a 5 dB omni-directional antenna, shown in Figure 1. The antennas are connected to respective adapters via 30 dB attenuators. This effectively limits the maximum communication range at the lowest speed (of 1 Mbps) from 17 km to 17 m. Thus introduced restriction on the communication range permits localization of the experiments to the room where the test bed is set up. In addition, the 30 dB attenuation helps to reduce the amount of external interference.

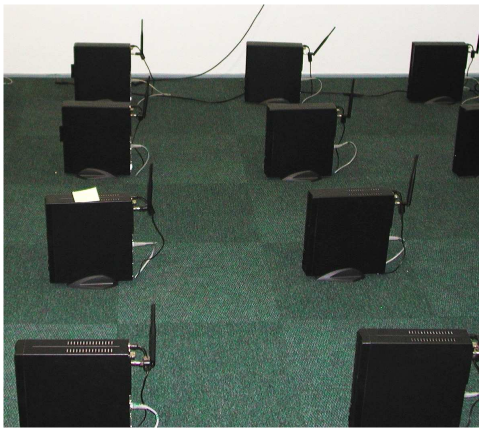
The Meraka's laboratory test bed may be compared against the Orbit mesh laboratory. Both test beds were set up as a dedicated facility. This enhances reproducibility of the results. The Orbit test bed has two large grids of size similar to Meraka's. The Orbit laboratory uses Atheros wireless chipset that supports 802.11 protocols, as does Meraka. The key difference between the Meraka's and Orbit's laboratories is the way they limit the communication range. In the Orbit's wireless test bed, the noise floor is raised by adding white Gaussian noise. Meraka's laboratory uses attenuators.

2 Dimensions and Related Effects

Several effects related to wave propagation mentioned in the introduction are quantified with regards to Wireless Africa's test bed.

2.1 On Formation of a Plane Wave

The distance between nodes is 0.8 m. This distance is dictated by the need to model free space propagation, where the propagating waves are sufficiently close to plane waves. This requires that the distance between antennas R is much larger than both the wavelength λ, and the product of the electrical size of the antenna D/λ and its physical size D, as per [15]. The latter restriction is on the maximum phase error (herein 22.5°) and may be written as $R >> 2D^2/\lambda$. At the lower 2.5 GHz wireless fidelity (Wi-Fi) bands, the wavelength is 12 cm. The antenna has length of about 14 cm, and the PC case is 30 cm tall. It is easy to calculate that a spacing of 0.8 m is sufficient if antenna alone is considered. However, as it will be shown in the next subsection, the PC cases influence radiation, and it would be better (especially at higher Wi-Fi bands) to have the inter-node spacing larger than 0.8 m. In practice the choice has been limited by the ability to fit all the nodes within the space available.



(a)

(b)

(c)

Figure 1. (a) Wireless mesh network test-bed. Only 10 out of 49 nodes are shown. Nodes are arranged in a rectangular grid and spaced 0.8 m from one another. (b) View of a single node. PC case is 40 cm tall. Antenna is 14 cm long and is spaced 3.5 cm away from the PC case. (c) Inside the antenna.

2.1 On Diffraction Effects

The current set up permits for a limited field of view between nodes. The clearness of the field of view may be expressed with the concept of the Fresnel zone radius [11]. The maximum radius r_n of the n-th zone (in the middle between 2 antennas) may be written as $r_n = \sqrt{n\lambda R/4}$. This means that at the frequency 2.5 GHz, the 1st Fresnel zone has 0.45 m radius, measured with respect to the centers of the

radiating structure. The radiating structure includes antennae but, where an antenna is in proximity of metallic structures (such as PC case), these structures alters the radiation, and should also be taken into account.
Presently, as it may be seen in Figure 1b, the centers of the antennas are less than 4 cm above the PC cases. The antenna's feed point is even lower. This means that the PC cases must produce diffraction effects. In addition, the PC case is expected to produce near-field effects (such as altering the radiation pattern), since the distance of 3 cm is less than a third of the wavelength.

3 Numerical EM Simulation and Related Physical Measurements

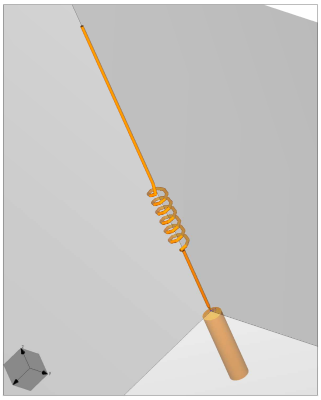
The numerical model for electromagnetic (EM) simulations was prepared in several steps, with a state-of-the-art modeling package WIPL-D [13]. The theory behind the method of moments used in WIPL-D to do the calculations is comprehensively described in [14].
In all models, the network scattering (*S*) parameters [16] were estimated and referred to as coupling coefficients. All single frequency simulations were done at the frequency of 2.45 GHz that is in the middle of the lower Wi-Fi band.

3.1 Model of Antenna

As a first step, a model of the antenna was made, as shown in Figure 2a. The geometry of this model was made to match the physical antenna shown in Figure 1c. The feed point is at the junction of a thick conical wire with the thin wire. A delta-gap generator model [15], [14] was used as a source.
The radiation pattern produced by the numerical model was compared with the pattern measurements done in an anechoic chamber for the physical antenna (without the PC case) shown in Figure 1b. In the horizontal plane the radiation pattern is very close to an ideal omni-directional pattern. The small deviations from the omni-directional patter were observed. These are due to the asymmetry introduced by the antenna's matching coil.
A comparison of the normalized patterns in vertical plane is shown in Figure 3. The modeled and measured patterns match well. The angular shift is attributed to the pole the antenna was mounted on during the test.

3.2 PC Case with Antenna

In the next step, the PC case shown in Figure 1b was approximated with a rectangular box made of a perfect conductor. The antenna was placed according to the physical geometry, transferring the physical structure of Figure 1b into the model shown in Figure 2b.
The numerical model of the structure has shown a deviation of up of 1.5 dB from the omni-directional pattern. This deviation is along the direction of the PC case, and is therefore considered as caused by the PC case.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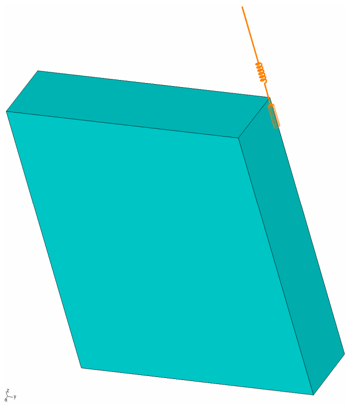
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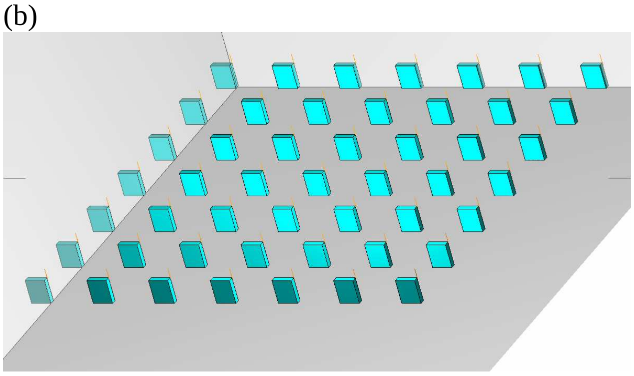

(c)

Figure 2. (a) Wire model of antenna. (b) Model of a PC case with an antenna. (c) Complete model of the 7×7 network.

The measurements done in an anechoic chamber confirmed that the radiation pattern of the antenna attached to a PC case is not omni-directional any more. The measured a deviation from an omni-directional pattern did not exceed 4.5 dB. The measured and modeled patterns have similar features and profile. The difference in the magnitude of deviation between measurement and simulation is attributed to a simplified model of antenna mounting. It is expected that this simplification may soften the diffraction effects, especially for the direction along the PC case.

The measurements have also shown that, in the horizontal plane, the gain of the antenna mounted on the PC case varies within ±0.5 dB for most of the directions, except for the -4.5 dB dip, where the variation rises to ±1 dB.

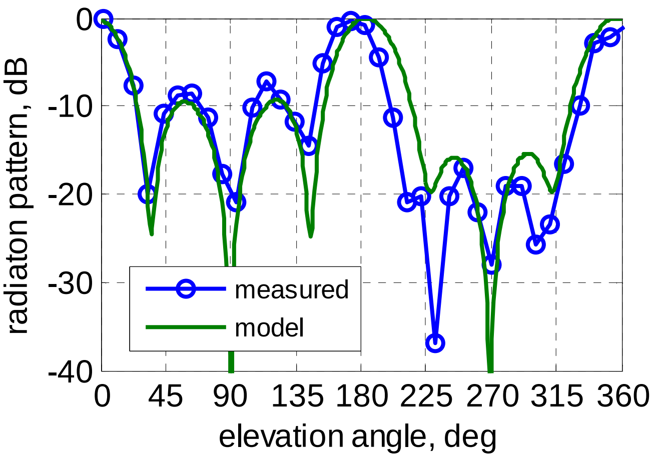


Figure 3. Measured and modeled radiation patterns for the dipole antenna without a PC case.

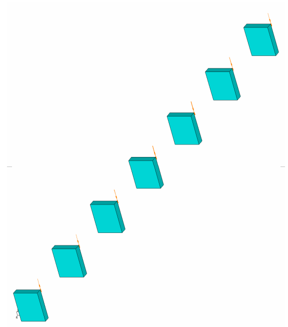
3.3 Linear Arrays of PCs

As an intermediate step, two types of linear arrays were modeled. A linear array is a one dimensional structure and is expected to have a simpler set of effects compared to a full two dimensional array required for modeling the actual test bed.

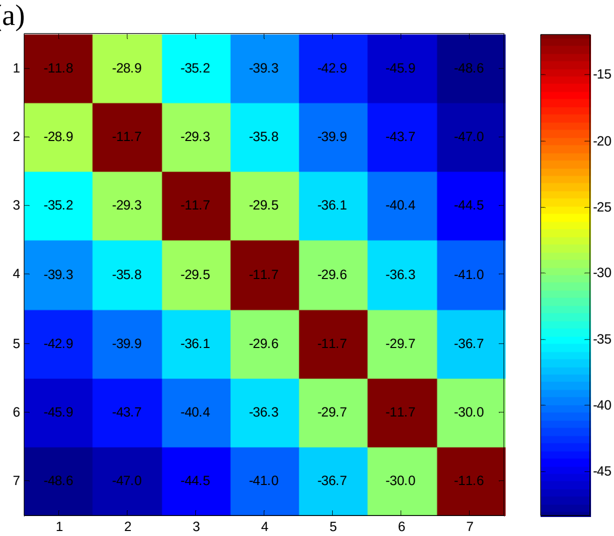
The distance between the centers of the PC cases was kept 0.8 m, the same as in the actual test-bed.

The first scenario is shown in Figure 4, where the PC cases were oriented to correspond to a single row of the test-bed's grid.

A close look reveals that propagation in one direction along the array is slightly different to the propagation in the opposite direction. This effect is particularly pronounced at the edges (first and last nodes) of the array. The maximum difference is between the coupling of the 4th to the 7th node (S_{47} or S_{74} in terms of the scattering matrix [16]) and to the 1st node (S_{41} or S_{14} in terms of the scattering matrix), and equals 1.7 dB. The difference in coupling between first and last elements is attributed to the asymmetry in the placement of the antenna with respect to the PC case (as may be noted in Figure 1b).



(a)



(b)

Figure 4. Linear array of PCs placed with wide sides parallel to each other. (a) Geometry overview. (b) Coupling level (in dB) between antennas in the array. Indexes along the horizontal and vertical axes correspond to the position of the respective PC in the array.

The second scenario is shown in Figure 5. The PC cases were oriented to correspond to a single column of the test-bed's grid.

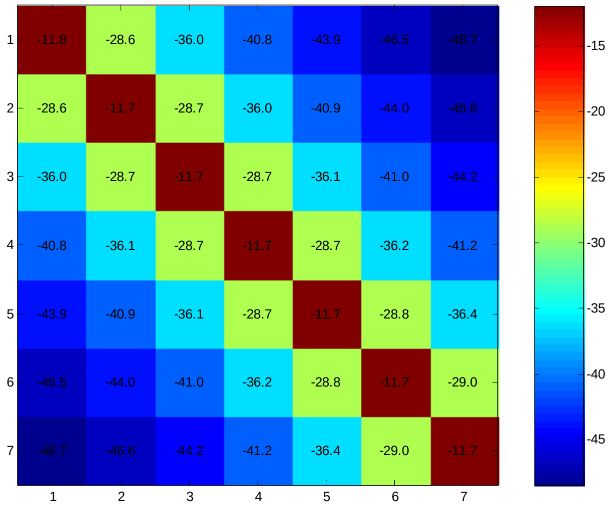
Many of the same remarks may be made on the variation of the coupling between the different elements of the array depending on their positions.

Comparing the two scenarios, it is possible to observe that the second scenario shows up to 1.3 dB less attenuation at small distances (within one or two hops between nodes). For larger distances, the second scenario introduces a marginally larger attenuation (up to 0.4 dB).

It should however be noted that a more accurate numerical model should show a larger attenuation at large distances.

These indicate that the propagation characteristics along rows and along columns of the test bed grid are somewhat different.

(a)



(b)

Figure 5. Linear array of PCs placed with wide sides along the same line. (a) Geometry overview. (b) Coupling level (in dB) between antennas in the array. Indexes along the horizontal and vertical axes correspond to the position of the respective PC in the array.

3.3 Complete Model

A model of the complete 7×7 grid of PCs with attached antennas is shown in Figure 2c. It is based on the template already described in subsection 3.2, which was placed on a rectangular grid with spacing of 0.8 m.

The nodes are numbered 11, 12, … , 76, 77, where the first digit denotes the horizontal position (row), and the second digit denotes the vertical position (column) in the grid. The node 11 is the most top-left node in Figure 2c (at the origin).

The results of the electromagnetic simulations may be represented as an intensity plot for each of the PCs with relation to all other PCs (nodes). This is shown in Figure 6. There, the most top-left plot shows the coupling between the node 11 and all the other nodes. The units of the color-bar are dB. The color-bar was normalized to have 0 dB correspond to the sensitivity threshold of the wireless cards.

Asymmetries present in the radial distribution seen in Figure 6 reveal that, in the test-bed under evaluation, the ability of nodes to communicate with each other does not just depend on the direct line-of-sight distance, as predicted by the log-distance path loss model [11]. This may also be observed in Figure 7. This figure shows power-averaged results summarizing Figure 6. The averaging was done by adding the relative powers from all plots in Figure 6, where the transmitting node is always placed at the center of Figure 7.

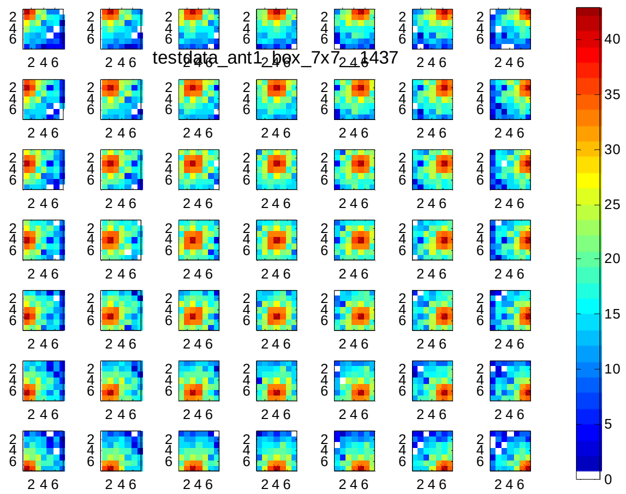


Figure 6. Strength of coupling (relative; in dB) between each node and all other nodes. Coupling of the node 11 is on the most top-left intensity plot. White blocks stand for levels below the communication threshold.

The results show that in the present realization of the test bed the path loss is influenced by the complex diffraction phenomena due to several factors. The main contributors include: (a) the closeness of the antennas to the PC cases, causing strong asymmetry in the horizontal radiation pattern of the antennas; (b) the line-of-sight between the antennas is close to the metallic PC cases, causing angle-dependant diffraction effects (e.g. different for *x*- and *y*- axes in the grid, as considered in Section 3.3); (c) array effects due to periodic placement of antennas.

The effects (a) and (b) may be mitigated by installing the antennas on sufficiently high non-metallic stands. The minimal height of the stands is defined by the clearness of at least the 1st Fresnel zone (i.e. 0.45 m at 2.45 GHz). This upgrade work is planned at our (Meraka Institute's) laboratory.

The effects of arraying has been estimated by modeling a 7×7 grid of the 0.8 m spaced bare-dipole antennas (without any PC cases or other elements). This model has shown a deviation in the inter-antenna coupling (with respect to the Friis equation) up to +1…-3 dB (with standard deviation of up to 1.5 dB). The numerical model that includes the PC cases has shown a much greater standard deviation, of up to 3.5 dB. These results indicate that spacing antennas away from the PC cases may lower the standard deviation by at least 2 dB.

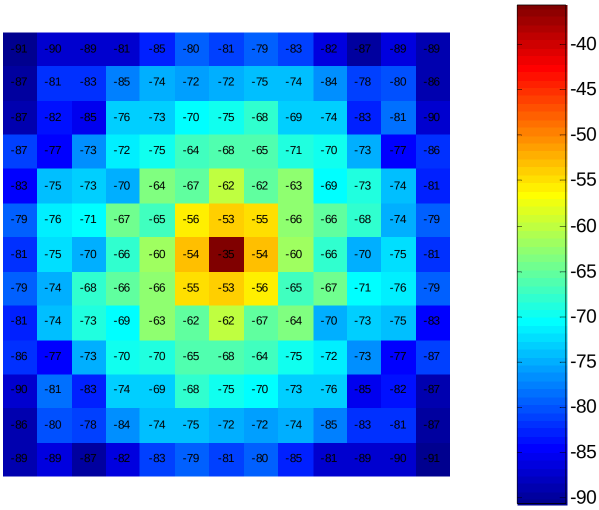


Figure 7. Intensity plot (dB) of the average coupling coefficient per node in the array.

Judging from the pictures provided in some of the above-mentioned research papers (see for example [2]), most of the above conclusions with regards to the effects due to antenna mounting and positioning may also apply to other laboratory wireless test-beds.

4 Conclusion

The electromagnetic coupling of nodes in a full scale model of the Meraka Institute's wireless mesh network test-bed has been modeled using a method of moments. The modeling explicitly included near field and diffraction effects, and has indicated the error boundaries of the results that would come out of simulations run on the test bed. It was also concluded that it is desired to separate the antennas from the metallic objects such as the PC cases. Such a separation is expected to improve the precision of the simulation results.

Acknowledgment

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