A Novel 3D-Based Network Simulation Platform for Wireless Indoor Networks

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***Abstract*—In this paper, a novel 3D-based network simulation platform for wireless indoor networks is proposed. The purpose of the platform is to improve the accuracy of radio propagation modeling and to offer designers a virtual workspace for testing their systems. Radio propagation models are investigated by performing path-loss calculations and Fresnel zone geometry estimation in a research laboratory environment.**

***Keywords*-3D Locationing; Sensor Networks; Simulation; TOSSIM; ZigBee.**

I. Introduction

This paper is an extended version of our conference article [1] containing additional backround information, extended testing and a more comprehensive explanation of the proposed simulation environment.

Sensor networks are comprised of small wireless devices capable of sensing their environment and dynamically communicating with their neighbors [2][3][4]. These networks are characterized by short link distances, limited system resources and low battery consumption [5][6]. Popular applications include intelligent home automation, monitoring and short range wireless communication [7][8][9].

Sensor network technologies are deeply rooted to their hardware platforms [10][11], limiting the things a developer can do before getting access to the actual devices. Testing programs designed for sensor networks without simulation becomes difficult due to the need of deploying actual hardware to the target environment during testing [12]. A versatile and efficient simulator would definitely benefit the research and development community. The simulation of sensor network programs is also important for the purposes of determining the requirements for hardware before committing funds for prototyping on actual devices, which might normally be unsuitable for the task or the amount of nodes in the prototype might not be sufficient.

In our previous research work [13][14], we examined the TOSSIM simulator [15][16] packaged with the TinyOS system [17][18]. We found out that it was a useful tool for sensor network developers, but lacked simulation of radio propagation, path-loss and small-scale indoor fading. Moreover, the simulation of ad-hoc networking was not supported at that time [19]. As a continuation of our previous research work, we started to investigate different methods of modeling path-loss in an indoor environment and to design a simulation environment that would best serve the needs of sensor network design and administration.

Modeling radio wave propagation is a mature field and closely related to acoustics. For example, one model that will be discussed in this paper, Rayleigh fading, dates back to 1880's when Lord Rayleigh observed the behavior of sound propagation of an orchestra [20]. Even though the principles of radio wave modeling are a mature field, finding novel applications for old models is relevant to today's science. In the field of simulation, a more complex combination of suitable propagation models can be used, since computing capabilities are increasing rapidly.

The rest of the paper is organized as follows. Section II gives a brief overview of ZigBee and wireless indoor communication. Path-loss modeling in sensor networks is covered in Section III. The section also contains results of some experiments we performed on a simple log-distance path-loss model to investigate the relation between the model and in-lab reality using ZigBee-enabled Wireless Personal Area Network (WPAN) devices. Section IV describes the Fresnel zone equation, which can be used to determine Line-Of-Sight (LOS) between two transmitting radios. Tests were performed based on this equation. The potential of using the Fresnel zone equation to improve path-loss calculations is discussed and the need for a 3D simulation environment to achieve these benefits is explained. Different problems related to 3D simulation is discussed in Section V. A novel 3D network simulator, which can act as a sandbox for network developers and administrators, is proposed in Section VI and concrete results of the experiments that are relevant to the proposed simulator are also discussed. This proposal concerns a prototype in an early design stage. Moreover, essential functions and possible technologies are discussed in the section. Finally, Section VII proposes some new ideas that will be used in our future research work and concludes the paper.

II. An Overview of ZigBee Communication

ZigBee [21] operates in the 2.4 GHz band with maximum transmission speed of 250 kb/s. It uses 16 channels ranging from 11 to 26. Each channel uses 5 MHz of bandwidth. The center frequency of each channel is $F_{\mathrm{C}} = (2405 + 5 \times (k - 11))$ MHz, where $k = 11, 12, \ldots, 26$. ZigBee is based on the Direct Sequence Spread Spectrum (DSSS) technique and Offset Quadrature Phase Shift Keying (O-QPSK) modulation.

The ZigBee node listens to a chosen channel before transmitting. If the channel is occupied, the node waits for a random amount of time. After this waiting period, the node listens to the channel again and if it is free, the node can transmit data. This technique is called as Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA).

When the data has been sent to the destination node, it sends an acknowledgement message to the source node to confirm that the data transmission has been successful. If the source node does not receive the confirmation in a certain interval, it resends the data to the destination node. Moreover, in ZigBee mesh topology, the node can send message through an alternative route if the first route fails.

In our research laboratory experiments we used Sensinode Nanorouters and Nanosensors [22] as the first hardware set and Texas Instruments CC2530 evaluation boards [23] as the second hardware set. Figure 1 illustrates Texas Instruments' devices used in the second hardware set.

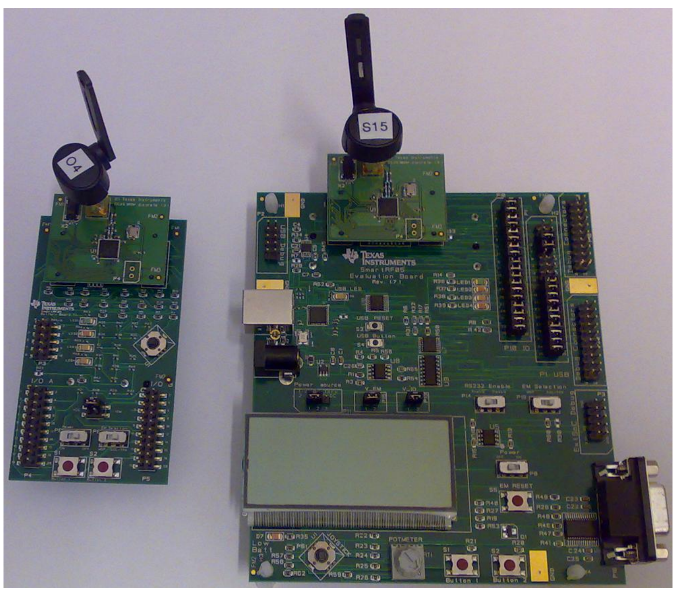

Fig. 1: Texas Instruments CC2530 evaluation boards [23] were used as the second hardware set in our research laboratory experiments.

ZigBee was chosen for our testing technology, because it is a good representative for modern wireless personal networks and it includes a lot of features to test in our research work.

III. Path-Loss Modeling

Radio transmissions traveling through space disperse and attenuate in a manner that can be, to some extent, predicted through path-loss modeling. Under ideal conditions, such as a LOS vacuum with no interference, radio propagation can be modeled by using the Friis free space equation [24]:

$$P_r(d) = \frac{P_t G_t G_r \lambda^2}{(4\pi)^2 d^2 L} \tag{1}$$

In the equation, $P_r(d)$ is the strength of the received signal at distance d from the transmitter, P_t is the transmitted signal strength, G_t and G_r are the antenna gains at the transmitter and receiver, λ is the transmission wavelength, and L is an artificial system loss factor accounting for loss caused by, for example, hardware. However, these ideal conditions are extremely rare on our planet. Radio waves travel through matter with different properties and are reflected by electromagnetic fields of objects creating a multipath signal. The equation can be regarded useful for sensor network modeling only as a starting point. In the log-distance path-loss equation, the Friis equation can be used to help determining a priori loss values for an experimental system [24]:

$$\overline{PL}(dB) = \overline{PL}(d_0) + 10n\log(\frac{d}{d_0}) \tag{2}$$

In the equation, $\overline{PL}(dB)$ is the predicted signal loss in decibels at distance d, $\overline{PL}(d_0)$ is the path-loss at a reference distance determined by the user, and n is a path-loss exponent determined through experimentation. In a small scale indoor environment, a reference distance of one meter is perhaps the most practical.

Our focus in this paper is on the practical applications for path-loss models. In our research work, we are interested in determining the path-loss at the reference distance as well as the path-loss exponent. These variables have a significant role in the reliability of the model.

It has been suggested in [24] that the Friis equation can be used to determine the path-loss at the reference distance, if the user has no access to better reference values. Values for the path-loss exponent can be found from various sources [24] and the user can use a value that best seems to reflect the surroundings she attempts to simulate.

In our experiments, the main focus was to determine the accuracy of the model. A single link was tested in our research laboratory to see how close the values of the model would come to the measurements. A transmitted signal of 100 mW (0 dBm) was used at the 2.4 GHz frequency. Two sets of ZigBee-enabled hardware were used in our experiments. The first set was comprised of devices with a small ceramic antenna integrated to the chip [22], while the other set used larger detachable antennas [23].

Our research laboratory is a typical office environment with desks, computers and electronics (see Figure 2). The surroundings are sure to cause multipath propagation and several wireless networks were present to cause interference. Over 10 Wireless Local Area Networks (WLANs) were in the vicinity with one WLAN-router close to the test setup.

Tests with a spectrum analyzer revealed interference values with an average of -65 dBm and with spikes up to -40 dBm caused by WLAN transmissions. Interference was therefore significant enough to impact the results. Figure 3 illustrates a spectrum image taken in the research laboratory. The spectrum image shows the range between 2400 MHz and 2485 MHz, spanning the entire ZigBee range.

In the measurements, we used a Rohde & Schwarz FSH6 (model .26) Handheld Spectrum Analyzer [25] (100 kHz – 6 GHz) with an Empfänger receiver, made for measuring signals between 500–3000 MHz band. The center frequency in the measurements was 2.4425 GHz and the channel bandwidth was 85 MHz. Figures of power characteristics were captured

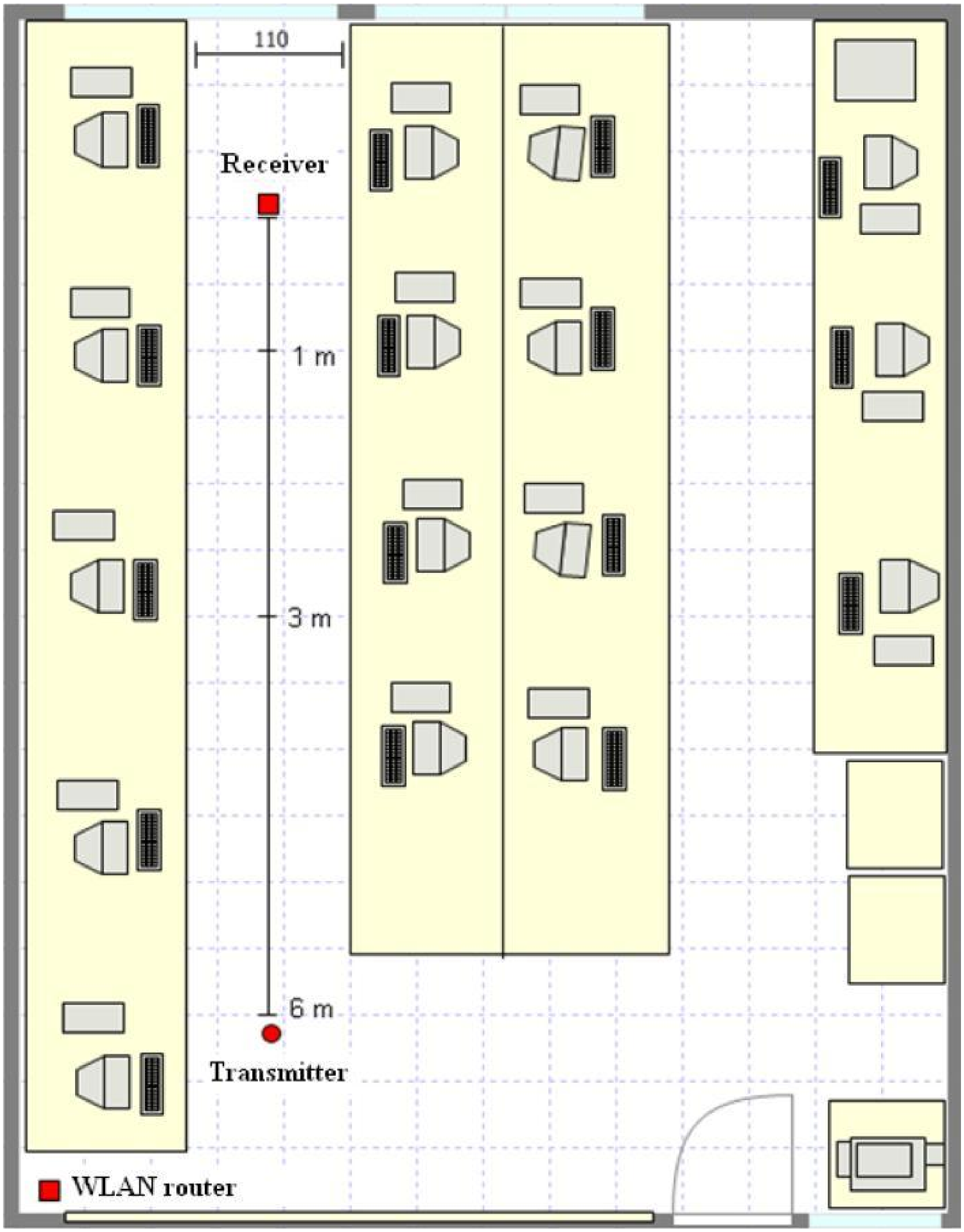

Fig. 2: The layout of our research laboratory used in the experiments, drawn using Room Arranger. [26]

with FSHRemote Program [25]. The same spectrum analyzer was successfully used also in our previous research work on ZigBee and Bluetooth interference measurements [27]. The equipment used is illustrated in Figure 4.

Path-loss was tested at distances of 1, 3 and 6 meters. The received signal strength and average packet loss was measured at these distances with clear LOS.

Tests revealed that on a 1 meter distance, using the Friis equation as an estimate for the reference distance, will not give a realistic value compared to the measurements. On the first hardware setup [22], an estimated received signal strength of -44 dBm versus an actual received signal of -77 dBm was observed. On the second hardware [23], the difference between the estimate and the measurements at the reference distance was smaller: an estimated received signal strength of -44 dBm versus an actual received signal of -48 dBm was observed.

However, when the measured path-loss at the reference distance was used instead of the Friis equation value, the estimates became accurate to ± 2 dBm at the distance of 3

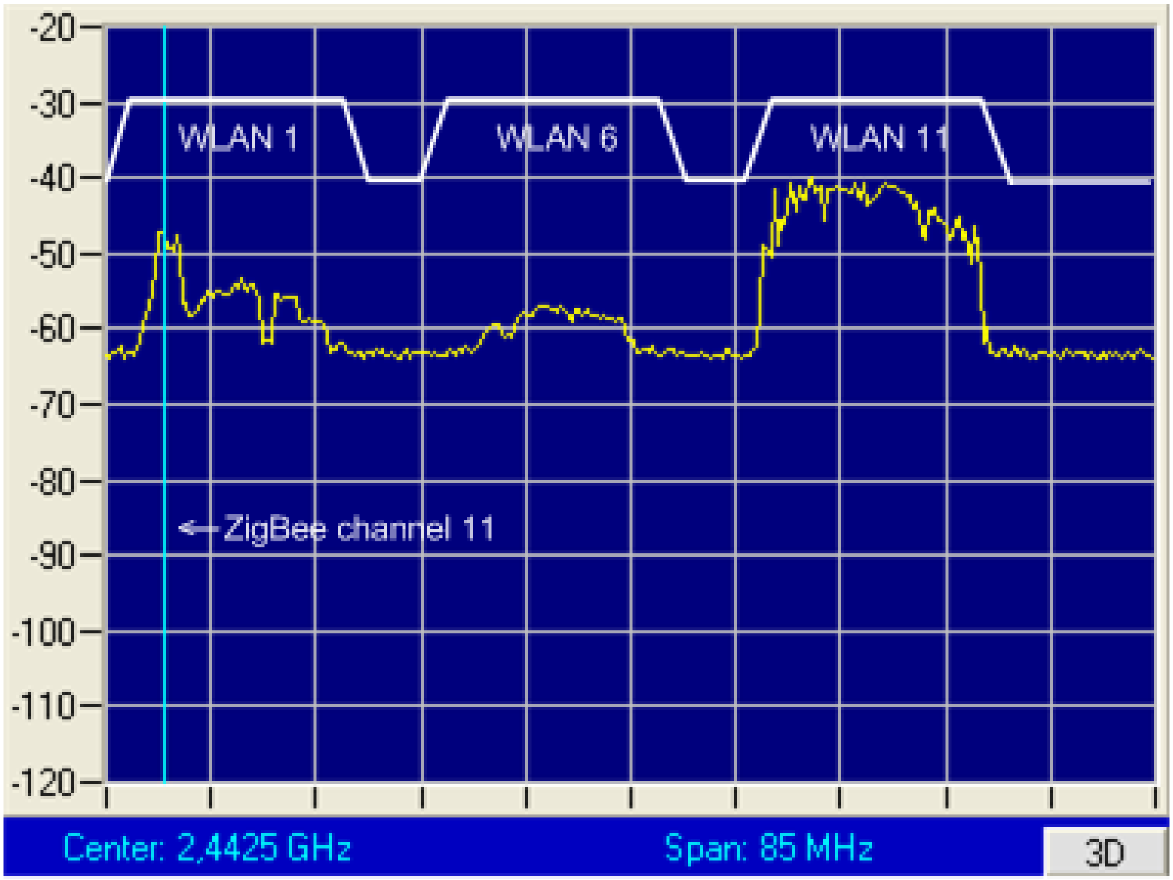

Fig. 3: Spectrum analyzer output from the laboratory: Three non-overlapping channels used by WLAN networks can be seen as pronounced humps. The spike marked with the vertical line is a ZigBee device transmitting on channel 11. The spectrum range of this image is from 2400 MHz to 2485 MHz encompassing the entire ZigBee range.

and 6 meters. An average received signal strength at 3 meters was $-86\ dBm$ on the first setup and $-58\ dBm$ on the second. At 6 meters, a signal strength of $-92\ dBm$ on the first set and $-62\ dBm$ on the second set was observed. This suggests that the use of the path-loss exponent values available (for example in [24]) work adequately. However, the determination of the loss at the reference distance leaves something to be desired. Using the equation for free space loss does not account additional loss caused already on 1 meter distance, or by the hardware used. Therefore, the reference distance must be modeled more accurately even for simulations.

It is worth noting that the signal strength at 6 meters on the first setup was actually below the announced receiver sensitivity limit of the ZigBee-enabled device used, although the manufacturer's specification promises a link distance of $10-30$ meters for indoor environments. Due to the use of the small integrated antenna, the overall link distance was not nearly as good as when using the devices equipped with larger antennas in the second setup.

Tests conclude that the log-distance path-loss model requires either actual reference distance measurements or a more accurate estimate than what the Friis equation can provide in a short range indoor environment. Using the model to get more realistic link estimates in TOSSIM simulations has been tested with some success in [28]. However, if a path-loss model is based solely on the distance between the nodes with an average modifier for additional loss caused by the environment, the model cannot function in a changing environment. A path-loss model, used in an indoor network simulation with mobile nodes, needs information whether the LOS between the nodes is clear or not.

Other, more sophisticated attenuation models are also available. Our focus in this paper is on small-scale indoor networks. Therefore, models accounting for multipath reception are especially relevant. Two models are prominent in especially this regard: Rayleigh fading and Rician fading. Rayleigh fading assumes that the majority of the signal is composed of Non Line of Sight (NLOS) multipath signals without a dominant LOS signal available. In Rayleigh fading, the signal is assumed to contain a degree of scattering and jitter caused by the multitudes of reflected signals, and it is modeled using Gaussian distribution. Rician fading is otherwise similar, but a dominant LOS signal complemented by multipath signals is assumed. Rayleigh fading is suitable especially in heavily built urban areas, while Rician fading might be more suitable to our focus area. [24]

IV. Fresnel Zone Modeling

Whether two communicating devices have a clear LOS to each other or not is significant in predicting the signal loss

Fig. 4: Rohde & Schwarz FSH6 (model .26) Handheld Spectrum Analyzer [25] with an Empfänger receiver was used in our research laboratory experiments.

between them. For this, the Fresnel zone equation can be useful [24]:

$$F_n = \sqrt{\frac{n\lambda d_1 d_2}{d_1 + d_2}} \tag{3}$$

In the equation, F_n is the radius of the n:th Fresnel zone at the point where the distance from the transmitter is d_1 and the distance to the receiver is d_2, while λ is the transmission wavelength. Our interest is in the first Fresnel zone, as it can be used to determine if a clear LOS exists between the two devices.

The first Fresnel zone forms an ellipsoid between the two antennas with the high point being in the middle, where $d_1 = d_2$ (see Figure 5). If the zone is at least 55 % free of obstruction, the LOS can be considered free. If the LOS is obstructed, the path-loss calculations should be adjusted accordingly. We experimented on the validity of the model in our research laboratory by placing a partially blocking metal barrier between the devices at 3 and 6 meter link distances. Initially the results seemed valid with attenuation between the devices increasing as the barrier blocked a greater portion of the Fresnel zone. These experiments were conducted with the Nanorouter devices. However, further experiments using the CC2530 radios with more efficient antennas revealed that multipath propagation is a significant factor in the results. This time, when we used the partition to block the line of sight between the devices, we failed to notice an appreciable change in the received signal strength. This is likely due to multipath propagation occurring in the laboratory. Tests with the Fresnel Zone equation conclude that multipath propagation makes reliable experimenting on the model in an indoor environment difficult, if a signal traveling by the shortest path between the devices cannot be distinguished from a multipath signal. However, it does not mean that using the model as a simulation tool is pointless in an indoor network.

A wireless network simulation using the Fresnel zone in an outdoor environment has been implemented in [29] by using the ns-2 simulator. However, the required calculations were processor intensive and required a long time to complete. This is an issue that needs to be addressed as sensor networks, even in indoor link distances, transmit a great volume of packets with a large number of non-static nodes. However, the system resources of modern computers continue to increase rapidly. Thus, even the most processor intensive calculations become possible over time. Unless a method distinguishing direct signals from indirect multipath signals is available, multipath propagation must be taken into account in the modeling. In practice, it means performing the Fresnel calculations not only to the direct signal, but also to reflected signals.

Using the Fresnel zone in a simulation is not effective unless a 3D simulation environment is available. In a 2D simulation, it is not possible to apply the equation in a realistic manner. Therefore, we need a 3D sensor network simulation environment.

V. Simulation Problems

Our proposal, a novel 3D-based network simulation platform for wireless indoor networks, is intended to address many problems found in the field of WPANs.

First and foremost, the physical properties of radio wave propagation in WPANs are not simulated in a way that a developer would find very useful. Simulators with 2D-based simulation and visualization qualities, such as TOSSIM, are available. However, we feel that a simulation limited to only 2D representation is an oversimplification, albeit a convenient one.

2D spatial representation limits the modeling methods that can be used to create more accurate estimations of the behavior of radio waves. The Fresnel zone cannot be modeled in a 2D space nor the effects of many objects interfering with the transmission. Moreover, the visualization and handling of networks in multi-floor buildings becomes difficult in a 2D model.

Furthermore, wave reflection such as ray-tracing, which could be used for the benefit of physical modeling, cannot be effectively used in 2D spaces either. Two dimensional ray-tracing may have been used for the purposes of radio wave propagation prediction, but using two dimensional ray-tracing, although useful in heavily built urban areas and large scale models, is too simplistic to be useful in small scale indoor environments.

3D-based simulation is available in the form of, for example, Actix's Radioplan RPS software [30], which makes some of the proposed features available. For example, using ray-tracing and designing 3D-spaces is possible. It provides a good

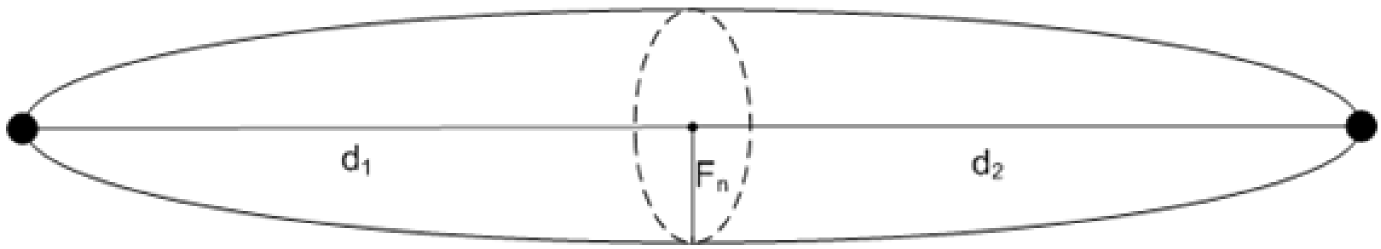

Fig. 5: The Fresnel Zone.

starting point, on which to take example of when designing a more full-bodied simulator. [30]

VI. Novel 3D Simulation Environment

To make 3D sensor network simulations plausible for development and administration, a common platform should be established. Our platform is independent from sensor network technologies themselves: it can be configured for a wide variety of devices on the market. Next we will go through the properties of the proposed system and present an outline of its structure.

The simulation platform is a base component running the simulation of the properties of radio communication and phenomena of the physical space. This platform component is connected to separate components running virtual devices representing wireless network nodes and other applicable devices. The user interface of the platform is also a separate component interfacing with the platform so that maximum flexibility in modifying the system is achieved. The component based model along with the central functions of each component is illustrated in Figure 6.

Section VI-A describes the simulation platform component. The user interface component is explained in Section VI-B. Section VI-C describes the virtual device component. Finally, Section VI-D explains how to use the simulation environment for studying and modeling the propagation of radio waves.

A. Simulation Platform Component

The simulation platform component contains the simulation of the physical world. It contains the three dimensional space, in which all objects and devices are placed. This space contains the physical phenomena and characteristics the real world does: temperature, moisture, lighting, and the passage of time. Gaussian white noise is generated to account for background noise, which may negatively impact on connectivity. Everything that affects on the radio communication or sensor data of devices within the simulation should be implemented as realistically and feasible as possible. Aspects, such as lighting, may not affect on radio communication, but they are useful for simulating sensor stimulae with the device components.

The environment must be able to simulate different physical mediums. A variety of materials will all be implemented with appropriate effects on radio waves, and the simulation of radio waves is the most important aspect of the proposed environment.

A radio wave traveling through an indoor environment is subject to many effects, which should be accounted for in an accurate three dimensional simulation. A signal will attenuate over distance. A wave coming into contact with an object will, depending on the situation, experience reflection, diffraction or scattering.

Reflection is caused by the wave coming into contact with objects, which have much larger dimensions compared to the wavelength of the transmitted wave. For the 2.4 GHz ISM (Industrial, Scientific, and Medical) frequency band, the wavelength is approximately 12.5 centimeters, so an object need not be large to cause reflection. When a reflection occurs, the wave will change its direction much in the same way as a wave of light would do, and it possibly lose a part of its energy depending on the object.

Diffraction occurs when the transmitted wave comes into contact with obstructions with sharp edges, such as corners. In indoor environments these features are understandably common and thus diffraction must be accounted for in the most accurate systems. Diffraction causes the transmitted wave to bend around the edge and form secondary waves.

Wave scattering is caused by objects smaller than the wavelength of the frequency of the wave. Objects like this are also common in indoor environments. A scattered signal multiplies and reflects in a fashion that is very difficult to model accurately, and it is usually represented by a gaussian multipath effect.

Reflection, diffraction and scattering all affect on how far the signal of a radio device will carry, how long it travels and how strong the signal will be in the point of reception. Several different methods of modeling the behavior of radio signals are available with a variety of accuracy, some of which have been presented in this paper.

The behavior of signals can be modeled by using, for example, ray-tracing in a three dimensional space. Ray-tracing is a method, in which the path of the ray is plotted in three dimensional space by utilizing vectors. The ray is traced through the medium and its direction and strength is modified. In three dimensional indoor radio wave propagation, ray-tracing can be utilized by using ray tubes emanating from a transmitter. This tube expands over distance in a way a signal would spread, and the ray tube can be reflected, multiplied and passed through obstacles appropriately. This has been tested with success, for example, in [31]. The receiver is surrounded by a sphere having the contact with a ray tube and receiving the transmitted signal, which strength should be strong enough for decoding. As such, accounting for reflected

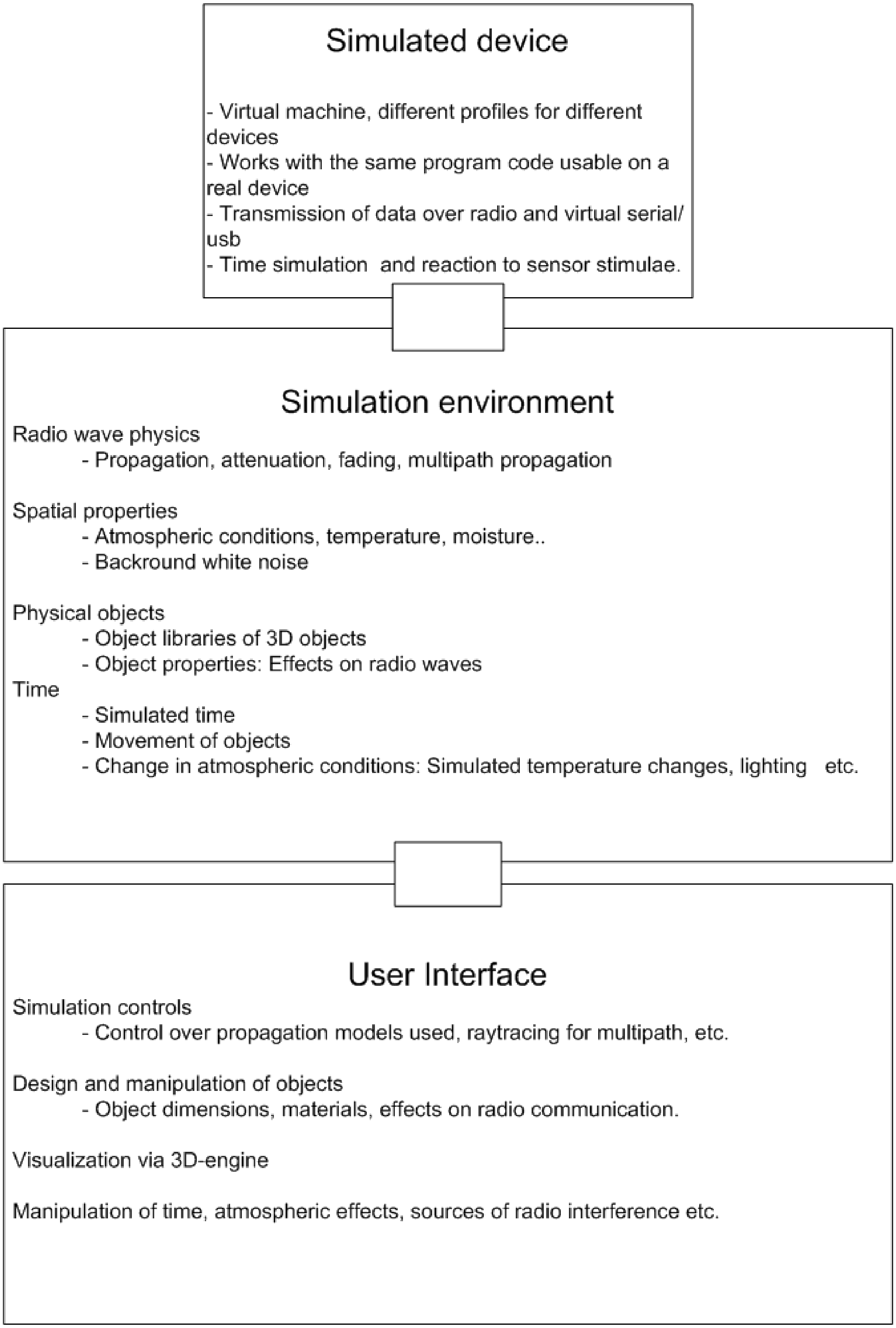

Fig. 6: A component model outline of the proposed platform with a list of its central features.

signals is possible with ray-tracing and has also been tested, for example, in [32]. A ray-tracing model should be optimized so that a minimum of computation is required for sufficiently accurate simulation. For accurate ray-tracing, a large amount of ray tubes need to be sent to every direction from the transmitter, but rays becoming irrelevant to the simulation can be eliminated. For example, the simulation system can keep track on the distance the ray has traveled and apply path-loss calculations on when the transmitted signal strength weakens beyond the receiver sensitivity of the receiving devices, and eliminate such rays. Rays traveling beyond the simulated spacial domain may also be removed. If the computation still proves to be too demanding, rays which have reflected for a certain amount of times may be eliminated. [33]

B. User Interface Component

The user interface component should contain the tools for viewing and manipulating the simulation. The user can design an indoor environment, select wall materials, and place objects, such as furnitures, from a library of premade generic items. The tools make it possible to model an entire building with objects inside. Alternatively, it should be possible to use a simplified attenuation model instead of placing objects by defining properties to a room. For example, a room could be defined to be ”a room with office furniture” and the model could adjust attenuation properties accordingly so that users content with a simpler modeling solution can save time in layout design.

The user can then select the modeling algorithms used for the simulation or optimally, import one manually. For example, the log normal path-loss model presented earlier could be used for path-loss calculation and ray-tracing and Fresnel zone determination to bring additional accuracy to account for multipath signals and partially blocked line of sight. The simple path-loss model could be easily substituted with Rayleigh or Rician fading. Signals traveling through walls and large objects will suffer additional attenuation with their own specific attenuation factors based on the material of the medium. The user can also manipulate the passing of time, as fast forwarding or slowing down time to observe the simulation in action, which can be beneficial. A suitable 3D-engine will be used to present the final model in operation.

C. Virtual Device Component

The device components will be virtual devices interfacing with the platform. The device component will be responsible for the inner workings of a network device. Program code working on an actual device should be made to work on the virtual device with as little modifications as possible. The virtual device will communicate with the platform via its interface by sending and receiving radio signals and by receiving sensor stimulae from the simulation environment. The device could, for example, sample its temperature sensor and receive a temperature value present in the simulation platform in the coordinates of the device. As part of the interface, the device will have to be able to provide for the simulation platform not only the messages it sends but also the frequency used, the signal strength of the transmitted signal, and antenna characteristics, such as antenna gain and receiver sensitivity. Transmission methods, such as DSSS, will have to be considered and functions, such as Clear Channel Assessment (CCA), supported. The creation of the virtual devices for different types of wireless devices is left to third party developers and interested parties wishing to add support for a certain device. Support for virtual serial or Universal Serial Bus (USB) communication for further levels of simulation can be considered.

D. Platform in Operation

Once the simulation environment is set with required structural elements and objects in place, and the radio wave models chosen, the device components can be started up much in the same way as in the real world. The user controls the speed, in which the time progresses and the devices should resume same functions they would do in reality. During the simulation, the user has access to debug tools displaying the traffic of transmitted signals and a graphical representation of the flow of radio messages. A message packet transmitted from a device is stored and the chosen attenuation/ray-tracing model determines the devices that are reached. The packet is then transferred to those devices and the device component will determine independently how to react on it. Messages arriving below a device's receiver sensitivity level are not transferred. This enables debugging of a network on a level that is not available in most simulators.

Although the creation of a simulation with all the objects and properties of 3D space can be time consuming, the advantages of using such a system can outweigh the additional work required. Figure 7 illustrates a mock-up of what the simulated space would look like on a platform.

An important aspect of the simulator is the possibility to test the code during the development. As in TOSSIM, developers can test their programs before installing them on real devices. This saves time and effort since it is much easier to test a new piece of code virtually than to deploy a real life network to see the results. However, TOSSIM does not support ad-hoc network connections. All connections are predetermined manually at a certain received signal strength and as such the simulation is lacking the ability to determine whether the tested program operates as required or not.

By using the proposed simulation platform, the designing of network deployment becomes easier. It would help those responsible for the deployment of the network, if they can see how densely the devices should be deployed to achieve optimal network coverage. By testing ad-hoc networking and getting a sufficiently realistic estimate on required amount of nodes, the optimal density can be achieved.

Developers can also stress test the network to make sure it works when a lot of activity is present. Great amounts of network traffic in the same frequency can cause transmission problems, which are difficult to predetermine. Foreseeing traffic problems in the design and development phase can save money, as it is done before committing funds to sensor devices because a fairly accurate amount of required nodes can be determined.

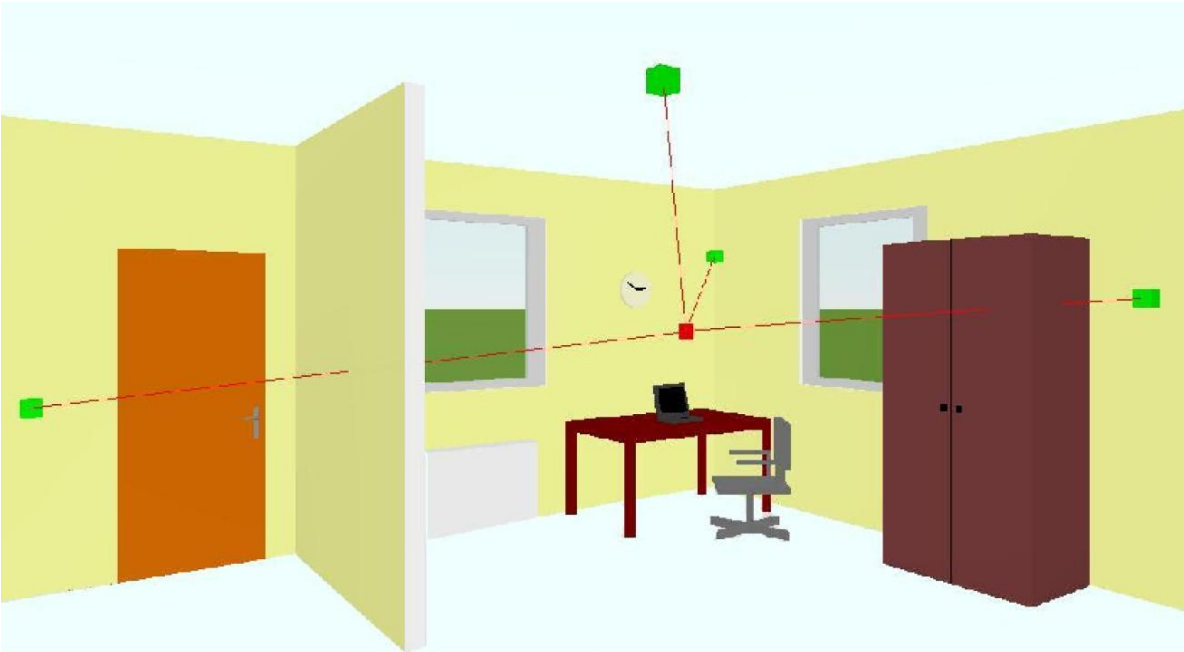

Fig. 7: Mock-up of a 3D simulation space, drawn by using Room Arranger. [26]

The simulation platform could also be used in conjunction with real world data. By replacing device components with the message flow of actual devices from, for example, packet sniffer data and with the radio model removed in the favor of actual on-site information of received signal strengths, one can create a network visualization tool of an actual network for administration purposes. A network consisting of hundreds or even thousands of nodes, perhaps in a large building complex, is difficult to monitor. Administrators can use the simulator tools in conjunction with actual data flow of the deployed network to oversee connectivity and diagnose problems more easily. The visualization would also help in tracking mobile nodes, but would require accurate positioning methods.

Visualizations of radio nodes in two dimensional networks are commonly shown as circles describing the maximum link distance available. This method of visualization is often observed, for example, in wireless locationing, since the locationing algorithms are often based on calculations using circle geometry. This is an oversimplification especially indoors, since the range of the available radio link changes dramatically based on the physical medium the wave is in contact with.

By using the simulation environment to study and model the propagation of radio waves, it might be possible to design better positioning algorithms by using methods such as ray-tracing. Moreover, since a 3D space is used, modeling of the Fresnel zone becomes possible in the determination of LOS between two devices, and this can potentially be used to improve the accuracy of path-loss calculations.

VII. Conclusion and Future Work

A novel 3D-based network simulation platform for wireless indoor networks was proposed based on a project under design and development. Moreover, radio propagation models were investigated by performing path-loss calculations and Fresnel zone geometry estimation in our research laboratory environment.

In our experiments, we tested the feasibility of using the path-loss equation and Fresnel zone calculations in small scale indoor environments. The usage of the Friis free space loss equation proved inaccurate in determining path-loss at the reference distance of one meter due to the hardware used and the environmental factors unaccounted for by the equation as discussed in Section III.

By using measured reference loss values in a laboratory environment, the inaccuracies were eliminated and the simple path-loss equation became a reliable method in predicting path-loss under the test conditions. Tests with the Fresnel zone equation suggest that it can be used to create more precise path-loss predictions in the proposed environment once the effect of multipath signals can be accounted for, as discussed in Section IV.

The simple path-loss equation can be used to simulate the weakening of a radio signal in indoor environment when it is combined with real world test data for the reference loss. The Fresnel zone equation with multipath signals taken into account can be used to analyze whether obstruction between simulated nodes is enough to warrant further loss to the signal. Therefore, both equations should be implemented in the simulation environment.

We stress that the simulation environment proposed in this paper is the result of a pen and paper feasibility study, and not yet a realized software. We are in the initial stages of development of the prototype for the simulator and as such, there are no system validation results nor is the prototype available for scrutiny. However, we strongly believe that the proposed idea is of technical and scientific relevance and interest already at this point of its development.

During our research work, we found out that a design and simulation environment, such as our novel 3D-based network simulation platform for wireless indoor networks, is sorely needed for improving effective sensor network design, simulation and implementation. The rapidly increasing capabilities of computing create new possibilities to model and simulate physical radio wave properties more accurately using very intricate and sophisticated methods. A generic, standardized platform would be required for the sake of greater interoperability between different technologies within the platform.

To summarize, the potential key benefits of the simulation platform are:

- Easier testing of code in development.
- More efficient network deployment design and visualization.
- Simulated network stress testing.
- Administrative uses in conjunction with real world data.
- Scientific modeling purposes.

A logical next step in our future research work is to create a prototype of a 3D simulation environment by combining existing simulators and available 3D modeling software. A proper implementation of the simulation framework is necessary to evaluate the validity of the proposed system. We will also look into other models to use in simulating path-loss and assess their validity for small scale indoor use. Our further experiments on radio propagation models and positioning algorithms will ultimately show how much benefit the platform can create for design, simulation and implementation of wireless sensor networks.

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