Accurate Radio Transmission Using Photon Mapping

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***Abstract*—Accurate simulation of wireless radio signals is a challenging problem. While primary effects can easily be calculated, second order effects are numerous and will often substantially alter the range of the radios. Many modern simulators such as ns-3 use a simple, overly conservative calculation known as the Friis [1] equation.**

This work demonstrates a more accurate estimate of radio waves via photon mapping[2]. By utilizing photon mapping we can predict where photons will travel as well as the objects they will strike. By collecting the number of photons to strike an object (e.g. an antenna) the effective signal strength can be determined. If the signal strength is above a pre-specified cutoff then the receiving node can hear the transmitter.

We show that this approach generates a higher fidelity estimate in most scenarios. As expected, buildings and obstacles impact radio transmissions in ways that cannot be modeled by the Friis equation. While the resolution of radio transmissions is increased, the amount of computation required for this result has grown considerably, i.e. A straightforward formula has been replaced with computing the paths of thousands of photons.

***Index Terms*—wireless networking, 802.11, simulation, photon mapping, ray tracing**

I. Introduction

Wireless radio communication has become ubiquitous and, in fact, necessary for many purposes ranging from widespread wifi hot-spots for web browsing to critical military applications. Whether or not one node is capable of hearing another is an essential question, the answer to which will determine the effective ability to communicate.

Efficiency is critical when establishing a communication mesh between the nodes. Implementing this decision problem in a naive manner will produce an $O(n^2)$ algorithm. In a mobile ad-hoc network this would need to be performed before every transmission.

An oracle for deciding whether or not node x can hear node y would be useful in this situation. Unfortunately, such an oracle does not exist and we must fall back on approximating an answer. One such method adopted by ns-2 and ns-3 is the Friis [1] equation. The Friis equation assumes idealized conditions and that no other objects interfere with communications. Clearly this is an oversimplification; many materials impact radio wave transmission in some, oftentimes significant, manner.

In this work we propose an improved method of approximating radio transmissions. By modeling the radio communications as photons, determining the signal strength is simply a matter of gathering photons which impact a region of interest. A variation of photon mapping is applicable in this scenario. By enclosing radio receivers in bounding spheres, the number of photons to impact the sphere and, in turn, the signal strength of the radio signals, can be determined.

The photon mapping algorithm was developed by Jensen [2] to improve upon deficiencies in classic ray tracing approaches. It is a realistic two-pass global illumination algorithm which consists of shooting photons into the scene and then performing a local collection step. Photon mapping is applicable to determining accurate radio transmissions due to the fact that visible light and radio waves are essentially the same phenomenon.

II. Overview

Our approach begins by emitting photons from our radio transmitter in a directional manner. The output of this transmitter is 250 mW. We chose this value in our aim to mimic something along the lines of a typical Wifi base station such as a Linksys wireless router.

It would be constructive to examine the Friis equation for any possible simplifying assumptions. A modern extension to the original Friis equation [1] is

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

We can assume a unity value for both the transmission gain G_t and reception gain G_r as ns-3 also makes these assumptions. This reduces the equation to

$$RX_{dB} = TX_{dB} + 10\log_{10}\frac{\lambda^2}{(4\pi d)^2 L} \quad (2)$$

P_r	reception power (W)
P_t	transmission power (W)
G_t	transmission gain (unit-less)
G_r	reception gain (unit-less)
λ	wavelength (m)
d	distance (m)
L	system loss (unit-less)
RX_{dB}	received power (dB)
TX_{dB}	transmitted power (dB)

The central frequency of Channel 6 of a 802.11b g router is 2.437 GHz. This frequency will be used in all test cases for convenience as it is the center channel of 802.11 and is a popular default for most routers as it is one of the three non-overlapping channels. The power of

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a photon can be determined with the following formula: $E = h\nu$

In the case of 2.437 GHz photons, $E \approx 10^{-25}$J, which would require $\approx 10^{22}$ photons to simulate a second of RF traffic at 250 mW. Since mapping that number of photons is infeasible, we make an approximation that the power in each photon is based on the number of photons emitted from the base stations antenna for our simulation. $E = \frac{250mW}{\#\, photons}$. This is the same approximation that is implicitly made in visible photon mapping.

To properly receive a signal, a mobile station must receive at least -100 dBm of signal. This works out to be 100 femtowatts as shown below.

$$-100\text{dBm} = 10 \log \frac{\text{Power}}{1\text{mW}} \tag{3}$$

$$10^{-10} = \frac{\text{Power}}{1\text{mW}} \tag{4}$$

$$10^{-13} = \text{Power} \tag{5}$$

When a photon collides with an object of interest, e.g. a bounding sphere, we record that photon's energy. After all photons have been emitted, each receiving object i has x_i photons which impacted it. For each i, we can sum the energy of all x_i to find the total estimated energy received. At this point we can make a determination as to whether or not enough energy was received to consider this a strong signal. Minimal code modifications were required to track photon-object collisions.

The above process can be calculated simultaneously as the first step, photon emission. It also replaces the need for a second step, namely photon gathering, which is not as easily parallelized. The reason the second step can be bypassed is that our aim is not to display the image resulting from the photons but rather to answer the question, "Can these objects (primitives) hear my radio signal?" This is a far simpler question to answer as the photons of interest have already been sorted into various buckets, i.e. those contained within each object.

A. Additional Work

While not strictly required by this project, we did run into a small problem: our entire code-base was built upon quads while our model of Amos Eaton was triangles. After several failed attempts at using modeling software (Rhinoceros, Blender, etc.), we decided to simply write our own tool for the job. Using the first few steps of Catmull-Clark [3], we derived three quads from every triangle, a reasonable tradeoff. Soon after we were happily running our code on the Amos Eaton model but emitting valid .obj files can be a little tricky!

Additionally, the given .obj file implementation was slightly lacking for our needs. Specifically, when declaring material properties, our photon mapping implementation required a coefficient for the transmissive property of the material in addition to the emissive and reflective properties. Adding this without breaking existing .obj files (without the transmissive property specified) was our goal and we were successful.

III. Experiment & Results

Our first assumption is a unity gain antenna. If the antenna were to impart a large gain or loss, this would need to be factored in as photons were transmitted.

To test the plausibility of our model, we used an object file provided by Professor Cutler of the Amos Eaton 1st floor, which we quadrangulated to allow our code to properly process the file.

The test involves a unidirectional antenna in the center room of the Amos Eaton first floor object model. This antenna is an area light source which emits 250 mW via 10,000 photons. Using fewer photons was shown to cause accuracy problems as each photon was contained too much energy. The light is "monochromatic" as we are using only one frequency. The model could be trivially extended to support 3 frequencies as we extended code using the RGB light model.

We chose to make Amos Eaton out of a material that was 30% Reflective and 10% transmissive which we based on assumptions of an average of typical building losses.

As we can see in Figure 1 the photons spread out well among the AE model, however the transmitted power differs greatly. Six spheres were placed in various locations around the building. The number of photons crossing a one unit sphere were counted and their total unit energy was calculated. This was then multiplied by the energy per photon which provided us with a received energy in watts. We then calculated the signal power in dBm and mapped the expected range to a red-green continuum. The expected range of signals was from -100 dBm to 24 dBm, as -100 dBm was the weakest signal a radio can "hear" and 24 dBm is roughly the power of the source. Anything below -100 dBm was colored pure red and above 24 pure green. Below -100 dBm is a common possibility but over 24 dBm would indicate an error condition, which is displayed. The results of our calculations are shown in Figure 2.

Since the transmissive model was a major addition to the code, a run with no transmissive materials was run. As is shown in Figure 3, all photon transport must take place using the doors in the model. As such, when the power calculation pass was run (Figure 4), we see a marked decrease in the amount of radios that can "hear" the antenna. This is contrary to what we would expect in reality, and thus realism in our model can be shown to have increased.

The Friis equation (Equation 2) approach assumes a vacuum and perfect line of sight. This leads to highly inaccurate results in most situations, including long distances in air. For example, in our model, Friis would estimate a received power of 19 dBm for any spheres within 10 meters of the antenna. In our model we do not see a received power this high even for the sphere in the same room as the antenna. Indeed, from a quick experiment in MRC 330D, my laptop received only -33 dBm despite the fact that I sit next to the access point. Clearly, our model is far more accurate.

IV. Optimizations

The bulk of our time is spent in the photon emission stage. Each photon is independent from all others which allows for simultaneous tracing of all paths. While parallel computation was not originally within the scope of this assignment, we felt our time would be better spent parallelizing a small amount of code than waiting many times longer for results.

OpenMP [4] was designed for code bases just like ours: pre-written and tested code requiring performance improvements beyond a single core, ideally needing few modifications to the existing code base. OpenMP worked well for us with very few code changes: less than 10 lines of code were changed and our tracing step went from 100% of one core to 100% of all four cores on our iMac, substantially decreasing the runtime of this step.

Beyond OpenMP, few other changes were required. Most of these were correcting race conditions in the non-threaded kd-tree. There are two locations in the kd-tree where photons are added. Wrapping these locations in recursive mutexes solved this particular race condition. While stating that the kd-tree is now thread-safe may be premature, the crash has not been seen since this modification to the kd-trees were made.

V. Future Work

Our first task will be integration with the ROSS [5] framework, a high performance parallel optimistic simulator. ROSS has been used in the past to primarily simulate large wired networks. However, recently a need for well-performing wireless simulations has arisen. It was within this context that the idea for this very paper was conceived. We expect integration with ROSS to be non-trivial, although a simple first approach would be to run our photon mapper at each Global Virtual Time (GVT)[1] interval. During GVT, progress is effectively stopped and each processor knows the locations of all radios at a given time. It is therefore possible for photon mapping to take place at a given instant in time with no wireless node movement. A table could then be built to determine which nodes are able to hear other transmitting nodes. This table would be consulted until the next GVT interval and corresponding photon mapping step.

Our current model assumes that when photons are transmitted through a material, they are merely attenuated, and their angle and other properties do not change. For maximal realism our model should take into account for both refraction and diffraction though when transmitted through materials, as well as near openings and corners that approach the size of our modeled photons. In the case of the 2.4 GHz photon, which has a wavelength of 12.5 cm, this could be a common effect.

A natural improvement for optimizing the photon emission would be adding GPU support. This task was originally in our proposal but was cut at some point as it was overly ambitious. However, our code was written with parallel computation in mind and therefore should not be too difficult to add as an enhancement. From a funding perspective we should clearly target GPUs as early as possible as the Department of Defense, more specifically the Army, have thousands of GPUs that are largely idle.

An additional performance improvement is likely through the use of Russian Roulette [2][6]. For each bounce in our system we may create up to three additional photons. So, for example, our initial emission of 500 photons (a relatively small amount), each of which may bounce up to 5 times (a constant in our simulator), may yield up to $500 \times 3^5 = 121,500$ photons. Russian Roulette deviates from this approach; instead the material properties are used to determine whether the photon is diffusely scattered, reflected, transmitted, or dropped as a whole. In other words, the energies of the photons are not scaled down according to the material. The result will still be correct; as McGuire states, "one photon carrying energy 100X is just as powerful as one hundred photons with energy X each."[6]

VI. Get & Run the Code

Please visit `https://github.com/laprej/photons` for code viewing and downloading. There is a `README` in the repository describing how to run the code. This README can be viewed at the bottom of the above link as well.

References

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[6] Morgan McGuire, "Homework 0x01: Russian roulette," `http://graphics.cs.williams.edu/courses/cs371/f08/reading/Homework1-Russian.pdf`.

[1] GVT is a coordinated "pause" in processing to determine the lowest unprocessed timestamp of any event in the system. Any events "older" than GVT can be reclaimed.

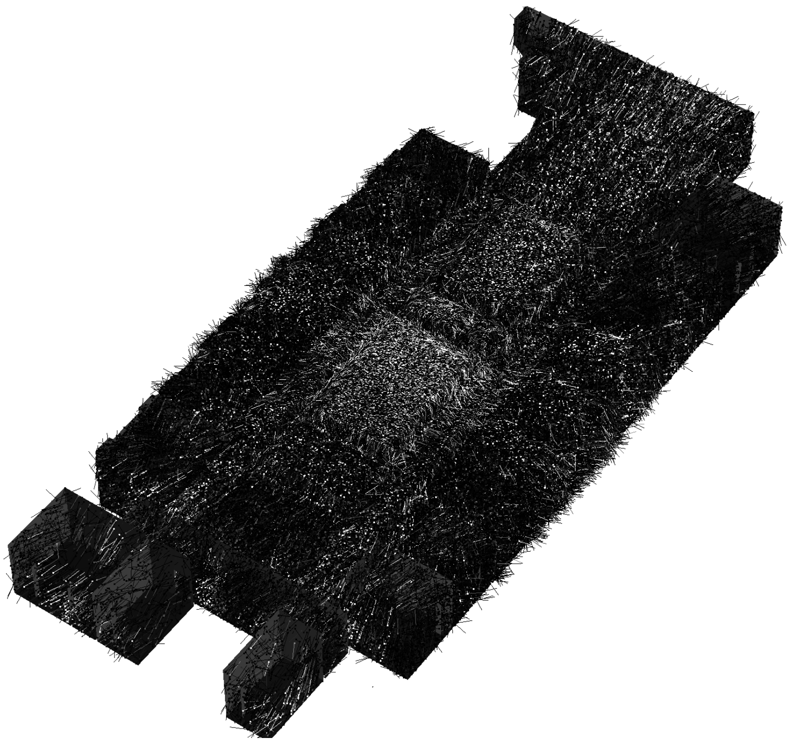

Fig. 1. Photon scatter patterns on the first floor of Amos Eaton with transmissive walls.

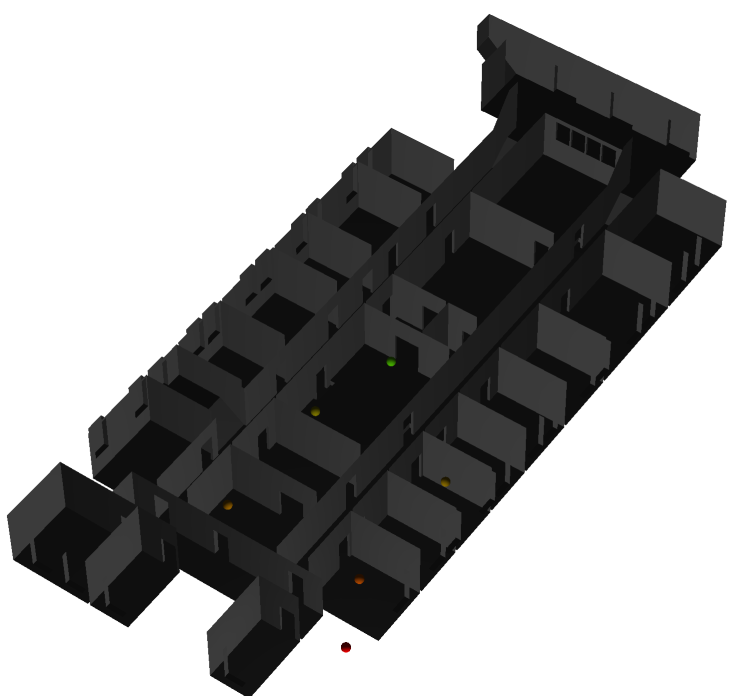

Fig. 2. Bounding spheres at various locations on the first floor of Amos Eaton with transmissive walls. Color values range from red (no reception) to green (good reception).

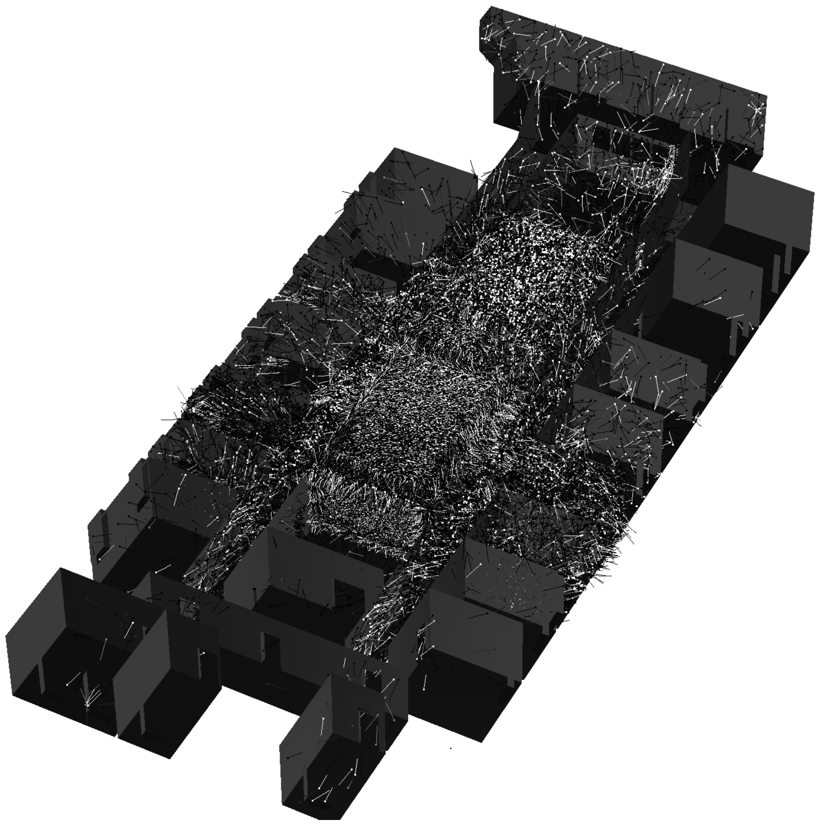

Fig. 3. Photon scatter patterns on the first floor of Amos Eaton with non-transmissive walls. The photons do not blanket the entire model as they do in the transmissive scenario.

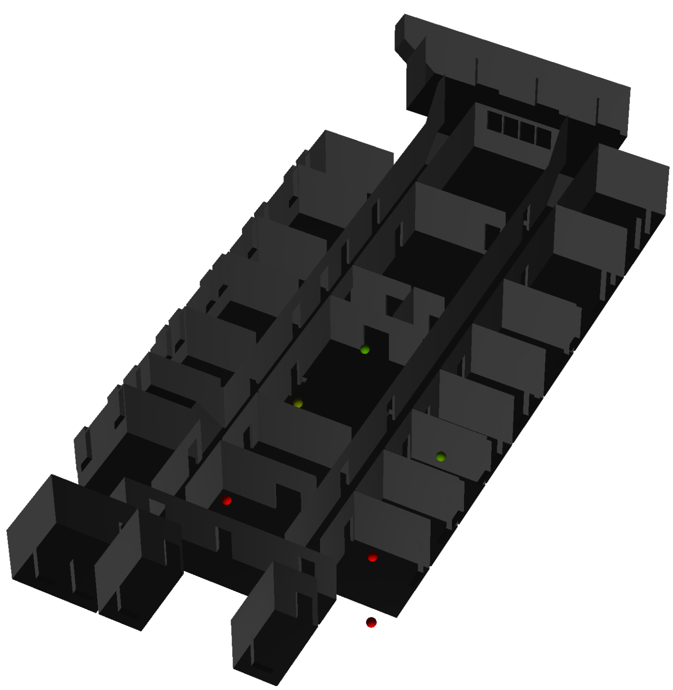

Fig. 4. Bounding spheres at various locations on the first floor of Amos Eaton with non-transmissive walls. Color values range from red (no reception) to green (good reception). Less photons implies weaker signal strength.