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Efficient model for indoor *radio paths* computation

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ABSTRACT

This paper presents a radio paths modeling framework for simulating *RF* coverage in complex indoor environments. We propose an algorithm which utilizes a geometric visibility graph of a building to traverse all possible bounded radio paths. These paths are needed for the computation of signal strength captured at a given receiver location. We have implemented the suggested algorithm and conducted a set of experiments to evaluate its performance in complex environments. The main conclusion is that the new algorithm is both (i) Accurate: predicts the signal strength inside complex buildings. (ii) Runtime efficient: requires only few seconds to compute all relevant radio paths, even when operating on complex structures containing thousands of walls.

1. Introduction

In order to meet the growing appetite for wireless communication, an increasing number of antennas need to be deployed in urban areas. Nonetheless, factors such as cost of installation and health-related concerns place effective limitations on providers' ability to serve the demand by merely deploying more and more antennas. It is for this reason that the communication research community is preoccupied with predicting the required throughput and quality of signals. Furthermore, *LTE* [1], *WiMAX* [2,3], *WiFi-MIMO* [4] and Beam Forming technologies are all characterized by greater bandwidth and range than the commonly used WiFi, emphasizing the importance of the problem hereby discussed.

Most simulation systems for *RF* coverage are based on empirical propagation characteristics of the environment. Such designs usually implement statistical models for the geometric environment that describe the expected performance of a propagation path (see [5] for an extensive survey on statistical propagation models). To enable efficient interpolation at the field-estimation stage, a high-performance database featuring advanced indexing and caching is usually required. The propagation prediction model, also named Radio Frequency (*RF*) model, provides two types of parameters: *large-scale path loss* and *small-scale fading statistics*. The first is used to determine and optimize the coverage of a base-station placement, while the second provides tools to improve the receiver's design. Another approach is a ray-tracing-based radio wave propagation prediction model (e.g., [6]). Systems employing this model consider each ray path as a sample, while the union of all ray paths between the transmitter and receivers forms a sample space. Since each such sample relates to different path components (like reflections and diffractions), each sample illuminates different sets of receivers and contributes differently to the final prediction results. Thus, for an RF prediction system which employs this model, the termination conditions should be considered with great care.

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The matter of approximating the strength of a signal received from a given transmitter in urban surroundings has been extensively studied (e.g., [5,7–10]). One notable shortcoming of approximation methodologies discussed in the literature is that they typically need to utilize RF-propagation model computations. In turn, simulating such complex networks requires significant computing resources as well as running time (e.g., [11]). An important observation, which could assist in that regard, is that, for most practical purposes, it is only required to estimate the radio field in a sub-space. For example, there is normally little motivation to calculate the radio field close to the ceiling. By effectively identifying and characterizing the particular sub-space which is of-interest, it is, therefore, possible to improve efficiency and shorten computational time.

We may, therefore, regard a point-to-point ray tracing approach as a pure geometric spatial *billiard* problem as follows: Given a building structure, a billiard ball's initial position and a target hole's fixed position, compute all directions at which one can target the ball towards the hole, transversing a predetermined upper-bound path-length. This is essentially a subproblem of the one we consider here. That is because, while addressing a radio path one should consider not only reflections but also penetration phenomena.

In this paper[1] we suggest a new simulation framework specifically designated to approximate the signal strength in complex urban environments. The new *In Door Radio Paths algorithm* (*IDRP*) computes the set of significant *radio paths* between the transmitter and the receiver using pure geometric properties of the building itself. Then, this set of radio paths is used by our *RF* model to allow accurate and efficient signal strength prediction.

The remainder of this paper is organized as follows: In Section 2 we present an overview of the basic *RF* models applied for predicting a signal strength at a given point. In Section 3 we present the geometric properties of a radio path between a transmitter and a receiver, with respect to the walls between them. We then introduce the new *IDRP* algorithm for predicting all radio paths, followed by a short discussion on the algorithm's asymptotic runtime. Thereafter, in Section 4 we present an implementation of the suggested algorithm and discuss simulation results and field experiments. Finally, in Section 5 we draw some conclusions and suggest future research directions.

2. RF Propagation model outline

Henceforth we refer to the sub-space which is of interest as the **building** (denoted by $\mathcal{B}$). That is to say, the relevant portion of space for which RF signal power should be taken into consideration. Explicitly, a building is the set of all its building elements.

Definition 1. A building element is either a rectangular or a triangular shaped planar element that is a part of a wall, floor or ceiling, or the absence of such (like a window or a door opening).

Definition 2. The visibility graph of a building ($VG(\mathcal{B})$**)** is the set of vertices V, together with the set of arcs E, where V is associated with the set of geometric building elements, and E is associated with the set of all possible direct paths between vertices. In other words, arcs correspond to the existence of line(s) of sight (LOS) between building elements.

When a signal travels within a building it bounces off (**reflectance**) and penetrates (**transmittance**) the building elements it crosses on its way. We refer to both reflectance and transference as *bounces*. A signal transmitted through a building element simply transverses its original incidence direction vector $\hat{k}$ after penetration takes place. The signal reflection geometry, on the other hand, resembles a mirror-like light ray incidence geometry; that is: (1) The reflected ray and the normal to the reflection surface $\vec{n}$ at the point of the incidence lie in the same plane and (2) The angle between the incident ray and the normal is equal to the angle between the reflected ray and the same normal.

Obviously, the signal power does not remain constant throughout. Instead, only a portion of a signal bounces back while a complementary portion (these should sum up to be the incidence signal power) transmits through the building element. In order to explicitly formulate our model, we introduce the following physical concept:

Definition 3. Polarization: polarization vector $\vec{E_0}$ is the property of a propagating signal that encloses the amplitude, phase and orientation of its oscillations. $\vec{E_0}$ is situated on the plane perpendicular to the signal propagation direction $\hat{k}$.

Thus, for a transmitted signal we may formulate:

$$\frac{\vec{E_t}}{\|\vec{E_0}\|} = t_{TE} \cdot cos\beta \cdot (\hat{k} \times \hat{n}) + t_{TM} \cdot sin\beta \cdot ((\hat{k} \times \hat{n}) \times \hat{k}). \tag{1}$$

Similarly, for the reflected signal:

$$\frac{\vec{E_r}}{\|\vec{E_0}\|} = r_{TE} \cdot cos\beta \cdot (\hat{k} \times \hat{n}) + r_{TM} \cdot sin\beta \cdot ((\hat{k} \times \hat{n}) \times \hat{k}) \tag{2}$$

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[1] Preliminary version of this paper appeared in [12].