Efficient Model for Indoor *Radio Paths* Computation

**Boaz Ben-Moshe**  
*Computer Science, Ariel University Center, Ariel 40700, Israel*  
Email: benmo@ariel.ac.il Tel: +972 54 7740272

**Paz Carmi**  
*Computer Science, Ben Gurion University, Beer-Sheva, Israel*

**Moti Shani**  
*Electrical Engineering, Ariel University Center, Ariel 40700, Israel*

**Nir Shvalb**  
*Industrial Engineering, Ariel University Center, Ariel 40700, Israel*

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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.

**Keywords:** RF Simulation, Ray-Tracing, Wireless Coverage Prediction, Visibility Graph, Urban Propagation Model.

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1. **Introduction**

In order to meet the growing appetite for wireless communication, an increasing number of antennas need to be deployed in urban areas. Nonethe-
less, 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.

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, 8, 9, 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 subspace. For example, there is normally little motive 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 sub-problem 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 introduced 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).*

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\(^1\)Preliminary version of this paper appeared in [12].
**Definition 2.** The Visibility Graph of a Building \((V G(B))\) 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 \(\hat{n}\) 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:

\[
\frac{\vec{E}_t}{\|\vec{E}_0\|} = t_{TE} \cdot \cos \beta \cdot (\hat{k} \times \hat{n}) + t_{TM} \cdot \sin \beta \cdot ((\hat{k} \times \hat{n}) \times \hat{k}).
\]

(1)

Similarly, for the reflected signal:

\[
\frac{\vec{E}_r}{\|\vec{E}_0\|} = r_{TE} \cdot \cos \beta \cdot (\hat{k} \times \hat{n}) + r_{TM} \cdot \sin \beta \cdot ((\hat{k} \times \hat{n}) \times \hat{k})
\]

(2)

Where \(\beta\) is the angle between \(\hat{k} \times \hat{n}\) and the incident polarization vector \(\vec{E}_0\). \(t_{TE}, r_{TE}\) and \(t_{TM}, r_{TM}\) are well known penetration and reflection coefficients.
associated with different TM and TE vector components of $\vec{E}_0$ (these are referred to as the Transverse Magnetic and Transverse Electric components, the polarization components whose associated fields are not in the direction of propagation). These depend on the building element material, thickness and geometric structure as well as the signal frequency. For a comprehensive survey on RF propagation models refer to [13].

3. Geometric algorithm for Radio-Paths computation

In this section we introduce an algorithm for computing the direction at which a directed signal from the transmitter $T$ is received by the receiver $R$. When a signal hits a wall we consider both the reflectance and transmittance phenomena described above. Notice that, if a signal received by $R$ penetrates a wall, the direction of the signal path is defined by the straight extension between $T$ and $R$. In this case the path can be easily extracted. Assuming there exists an oracle informing us of a given sequence of walls $W$ (an ordered set), the following observation significantly simplifies computations related to reflectance phenomena:

**Observation 4.** Consider a signal bouncing off a wall $w \in W$. Reflecting the image of $B$ through the wall $w$ will result in a straight line presentation of the signal between $T$ and the $w$-reflected $R$ (within the $w$-reflected building).

**Proof.** The proof is by induction on the number of signal bounces $b$. Since we use the same paradigm for the induction hypothesis we begin by demonstrating our claim on the somewhat trivial base case. For the base case where $b = 1$: denote by $w_1$ the wall hit by the signal path and further denote $p_1$ to be the hitting point. The signal paths $(T, p_1)$ and $(p_1, R)$ are both straight lines. Thus we can ignore all other walls ($b = 1$). Denote the plane defined by the triangle $\triangle(T, p_1, R)$ by $P$. Notice that $P$ would intersect the reflected $R$ denoted by $R'$ as well. Furthermore, notice that the segment extending from $T$ and $p_1$ includes $R'$. Assume $b > 1$ and let $w_b$ be the last wall from which the signal bounces off, with point $p_b$ the last bouncing point. Before the last bounce, the induction hypothesis implies that the signal path from $T$ to the reflected $p_b$ (with their respective reflections) is a straight line. Therefore, we can consider the first $b - 1$ bounces as penetrations. Finally, base case 2 implies that reflecting through $w_b$ concludes the proof.
Since the number of walls that a signal may hit is physically bounded we can examine all possible sequences, dismissing the need for an oracle.

We will now introduce our algorithm for computing a building Visibility Graph ($V\Gamma(B)$). Next, given a desired path length (i.e., the number of signal bounces) we extract from the $V\Gamma(B)$ all bounded length paths between the transmitter and receiver\(^2\). Then, for each such path we compute its virtual reflected structure and conclude whether such a path can be realized. Finally we compute the total contribution (power, phase of $\vec{E}$) of all realizable paths.

3.1. Preprocessing: computing the visibility graph

We now describe the preprocessing stage in which a Visibility Graph ($V\Gamma(B)$) of the building $B$ is computed. The set of vertices $V$ is associated with all building elements (i.e., facets of walls, ceilings and floors). To be more accurate, each building element is associated with two vertices in $V\Gamma(B)$ (i.e., face-facet and back-facet). However, $n$-polygonal (with $n > 4$) elements, as well as non-simply-connected elements (such as doors or windows) are not included in $V$. Instead, these are divided into several simply shaped elements; each is associated with a vertex in $V\Gamma(B)$. Each pair $v_1, v_2 \in V$ is connected by an arc $e_{12} \in E$ if and only if there exists a spatial LOS between their associated building elements (that is, without intersecting any other building element along the way). In the planar case there are few efficient algorithms for computing $V\Gamma(B)$ (e.g., $[14]$). Yet, computing the $V\Gamma(B)$ of a building is a rather complex task, both theoretically and practically. S. Teller and M. Hohmeyer $[15]$ showed that four lines with general Plücker coordinates determine a single line incident on the four input lines. One can use this property in order to design an $O(n^3)$ algorithm for computing the exact $V\Gamma(B)$ in a general position. In practice, however, input degeneracies may result in 0, 1, 2, or even an infinity number of incident lines for a given set of four walls. Figure 1 presents an example of all the walls which are visible from a point.

Observation 5. General position assumption is not applicable for real-life buildings. Indeed, most buildings have many parallel walls and grid based

\(^2\)In the actual implementation each building element is associated with a path loss value, and we bound the signal power loss, rather than the path length.
coordinate values. Moreover, walls are almost always parallel to the Z-axis (and floors are perpendicular to it).

In light of the above observation, the algorithm runtime is hardly practical for large buildings (with hundreds of walls). In addition, special handling is required for degenerate input lines. Yet, a careful examination yields the following:

**Observation 6.** Every path in the $V_G(B)$ corresponds to a unique spatial geometric radio path, or to no path at all, in the actual building.

**Proof.** Recall that we only consider planar building elements. Further recall that each building element corresponds to a pair of vertices in $V_G(B)$. Therefore, since $V_G(B)$ is constructed via successive building reflections (which reflect the receiver as well), we can regard the geometric radio path connecting $T$ and the reflected receiver $R$ as a straight line (i.e., all wall bounces may be thought of as penetrations).

**Observation 7.** We may compute a relaxed approximation of $V_G(B)$ which represents ‘over-visibility’. Yet, we must ensure that if there exists a direct LOS between two building elements, there will be an edge between their corresponding vertices in $V_G(B)$.

Motivated by the room-structure of most buildings and the observations we have made, we define a more practical algorithm for computing the $V_G(B)$.

The actual algorithm is somewhat more complex. For example, consider staircase visibility computation. Dividing a building into rooms requires several technical approaches. Given the transmitter $T$ and the receiver $R$ loci, we add them to $V_G(B)$ by connecting each with the room vertices they are in. In other words, any geometric element in $B$ which can directly ”see” $T$ will be arc-wise connected to it in $V_G(B)$. We then denote the *extended visibility graph* by $V_G(B, T, R)$. Note that $V_G(B)$ should only be computed once. Furthermore, if the $T$ and $R$ loci are to be altered they can be added to $V_G(B)$ and reconnected to the building elements in the room they are in, making our strategy time practical.
Figure 1: The visibility property is presented using straight lines. All visible walls from the middle point are marked in yellow. Observe that the visibility may go through windows and doors.

**Algorithm 1**: The Visibility Graph pseudo-code

**Data**: Geometric structure of $B$; $T$ and $R$.

**Result**: A relaxed visibility graph of $B$ with $T$, $R$.

1. Transform each simple building element into a pair of connected vertices;
2. Divide the building into rooms;
3. Divide each floor and ceiling into patches according to each room projection;
4. Define each door or window in the room as a virtual wall (of zero width);
5. Connect all the inner elements of each room (walls, floor, ceiling, doors and windows);
Figure 2: The IDRP algorithm: (A) A simple example of a 2D building is given; for simplicity we present each building element using a single node and a connected pair of vertices. (B) The building visibility graph: $\mathcal{V}G(B)$. (C) Adding $T$ and $R$ to the recomputed visibility graph. (D) Consider the graph path between $T$ and $R$ in the visibility graph $\{T, a, k, d, h, R\}$. (E) The virtual building which is correlated with the path and the validation algorithm: connecting $T$ and $R$ with a straight line, making sure the line intersects all the graph path nodes (the walls along the path are dashed). (F) The actual radio-path of the visibility graph path $\{T, a, k, d, h, R\}$.
3.2. Computing all bounded length radio paths over the visibility graph

In practical signal power computations the number of signal bounces can be upper-bounded (i.e., we only need to consider paths in $V_G(B)$) which are at most $c$-hop length). Given a bounded length $c$, we traverse $V_G(B, T, R)$ and compute all possible paths between $T$ and $R$ of length $\leq c$. For each such path $\gamma \subseteq V_G(B, T, R)$ we compute its virtual reflected structure $V_{RS}(B, \gamma)$.

**Algorithm 2**: The IDRP strategy pseudo-code

**Data**: Geometric structure of $B$; The visibility graph $V_G(B)$.

**Result**: All possible paths $\gamma$ between $T$ and $R$.

1. Given $T$ and $R$, add two corresponding nodes to $V_G(B)$;
2. Compute all bounded-length paths $\gamma$ between $T$ and $R$ over $V_G(B)$;
3. for each path such $\gamma$ do
   4. Construct the virtual reflected structure $V_{RS}(B, \gamma)$;
   5. if the direct spatial line between $T$ and $R$ in $V_{RS}(B, \gamma)$ hits all
      (and only) the building elements that correspond to vertices in $\gamma$
      then
      6. Compute $\gamma^*$: the real radio path induced by $\gamma$;
      7. Add $\gamma^*$ to the set of radio paths;

For each computed radio path $\gamma$ (a valid geometric path between $T$ and $R$) one can compute the signal received at $R$ (referring only to $\gamma$), taking into consideration the properties (reflection, penetration, thickness, density, angle) of each wall $\gamma$ passes through.

3.3. Modeling RF diffraction

Geometric modeling of RF-propagation in urban regions should also address the case where some radio paths are not intersecting straight walls but sharp edges or corners such as metal-doorposts. This case is often referred as **RF-Diffraction** [16, 17]. In this subsection we present an efficient method for considering **RF-Diffraction** based on the following observation.

**Observation 8.** Diffraction points can be modeled as weak omni-directional transmitters [13]. Therefore, a receiver is mainly affected by diffraction-points close to it. In other words, in most cases it is sufficient to consider diffraction-points which are visible from the receiver.
In order to find the main diffraction-points which affect the receiver, we need to find the set of radio paths which are close enough to corners and edges near the receiver. We defined two algorithms for modeling the RF diffraction at the receiver side. The first algorithm is runtime oriented while the second one is a more accurate.

**Efficient diffraction points computation**

1. Find the set \( (DP) \) of all possible diffraction points/edges which are close-enough and visible from the receiver.
2. For each validated radio path \((rp)\) find the distance between \( rp \) and the \( DP \) member \((dp)\) which is closest to it.
3. If this distance is smaller than some value, consider the intersection point between \( rp \) and \( dp \) to be a diffraction point.
4. Address each diffraction point as a weak omni-directional transmitter (according to the corresponding radio path.)

In case we are not limited by runtime performance we can use the following diffraction model:

**Accurate diffraction points computation**

1. Sample several points \((DP)\) which are (i) near and visible-from the receiver. (ii) on scattering surfaces (i.e., diffraction points/edges).
2. For each point \( dp \in DP \) find the main radio-paths (from the original transmitter).
3. Extrapolate the radio paths computed over \( DP \) to all possible diffraction points/edges/surfaces which are close-enough and visible from the receiver.
4. Address each diffraction point as a weak omni-directional transmitter (according to the corresponding radio path.)

Figure 3 presents an example for computing few diffraction points out of many possible radio paths.

**3.4. Complexity and practical runtime**

In this section we present the runtime complexity of the algorithms followed by the practical runtime over common inputs. Assuming \( |\mathcal{B}| = n, \frac{|E(V(\mathcal{B}))|}{n} = k \). Computing \( VG(\mathcal{B}) \) can be done in \( O(kn^2) \). Note: this preliminary stage (preprocessing) is only computed once per building. Adding
Figure 3: Modeling RF-diffraction: only four diffraction points were found (on the doorposts near $Rx$) out of over a hundred possible radio paths between $Tx$ and $Rx$ (for better readability, the regular radio paths are not drawn in the room where $Rx$ is located).

$\mathcal{T}$ and $\mathcal{R}$ to $VG(\mathcal{B})$ can be done in linear time $O(n)$ (the algorithm simply finds the rooms in which $\mathcal{T}$ and $\mathcal{R}$ exist). Computing all relevant $c$ bounded length radio paths over $VG(\mathcal{B}, \mathcal{T}, \mathcal{R})$ is $O(2^{\max(c,k)} + nk)$. Note: for all practical scenarios one can assume $k, c < 20$ and $k << n$. For common buildings in which $\mathcal{B}$ has 20 rooms, $n = 2000$, $c = 20$, $k = 7$, the algorithm has calculated an average of 550,000 possible radio paths within less than 10 seconds. Then, subsequent to a pruning stage, as little as 100 radio paths are left to be considered.

4. Experimental results

We have implemented a software package for computing the visibility graph and all bounded length radio paths. As discussed, our implementation also includes a sophisticated RF model in order to allow realistic propagation models such as WiFi. The software was implemented in Java 1.6, while the 3D models were generated using Google sketch-up. We have tested the application on several models including large building structures with thousands of walls and several floors. As an example see Figure 4 which is an implementation of IDRP on a campus building. In order to empirically validate the suggested RF model, we have used experimental results of Indoor measurements from the ISRC consortium [18, 19].
These measurements were carried out in a single floor building with sixteen rooms, using Agilent’s N5230 network analyzer, connected to two omnidirectional antennas (Electro-Metrics EM-6865) with amplifiers.

We have then used a 3D model of the same building and perform a simulation using the same positions for the transmitter and receiver. We followed [20] for the exact permeability parameters (for frequencies 2.412−2.462GHz).

The comparison between the physical and the simulated results are shown in Figures 5,6. Figure 5 presents almost similar behavior of the impulse response in dB scale. Figure 6 presents a reasonable correlation between the physical and the simulated results comparing the signal strength peaks along time on a \( \text{[Watts/Meter]} \) scale. It should be noted that we did not use any kind of normalization factors, i.e., the results shown here were computed directly without any kind of fitting function.

In order to further test the suggested radio paths model we exchanged the transmitter and the receiver positions and compared the simulation results - naturally the same radio-paths were computed (see Figure 7). In some cases a minor difference between the simulations was found - due to different diffraction behavior).

After validating the simulation signal strength, we moved to test the angular accuracy of the simulation with respect to actual field measurements with directional antenna. Figure 8 presents two such examples, the amplitude
Figure 5: Comparing the impulse response of real signals (in red) and simulated signals (green) in 2.4GHz.

is presented according to the distance from the center and the horizontal angle given in 0-360 degrees.

Finally, we conducted a set of advance simulation experiments which include the following scenarios:

- Mobile ad-hoc network (MANET) [21]: In this scenario each client may also be a relay station (or a hot-spot). Therefore, the task is to be able to simulate the routing-tree of the ad-hoc networks with respect to the dynamic location of the clients within the building. Figure 9 presents a simulation of HWMP routing protocol [21] simulated in a 1Hz sampling rate.

- Advance material of walls simulation, in which several types building materials where used. For each type of material the corresponding dielectric parameters were used (see [13, 20] for a list of such values. We associate each building element (i.e., wall, floor, roof) with a material and perform a simulation according to the RF properties of each material. Figure 10 presents such simulation.
Figure 6: Two arbitrary positions simulation versus experimental results, in 2.4GHz. Notice: that the experimental and theoretical peaks are concurrent and agree by value. Discrepancies may be a result of modeling and measuring errors.

Figure 7: Exchanging the transmitter and the receiver is leading to the same radio paths. Left: the transmitter is located at the first floor. Right: the transmitter is located at the second floor.
Figure 8: Field experiment: comparing the horizontal signal strength as received by a directional antenna (blue) and simulated results (red). Left: the actual simulated results of the radio paths. Right: simple spline of the simulated radio paths.

Figure 9: Simulating a mobile ad-hoc network: Left: simulating the radio paths among each two clients. Right: the optimal routing tree based on the radio path simulation.
Figure 10: The Radio Paths implementation: 35 different radio paths between T and R (located at the lower and upper floor). The simulation took into consideration several different materials and width of walls (presented by colors).

5. Conclusions

Our experimental results demonstrate that the suggested IDRP framework holds a promise of greater efficiency in the area of RF propagation models inside buildings. In terms of practical run-time, the simulation framework was able to compute all significant radio paths within complicated buildings in a meter of seconds. Traversing such set of significant radio paths enables us to predict the signal strength at the receiver side. Moreover, appreciating the actual geometric paths enables us to predict the signal phase and direction. The suggested algorithm was able to sufficiently evaluate an indoor radio impulse. Thus, computing the superposition signal sum is made possible. This property is essential for simulating MIMO technology (such as [1, 3, 4]). The runtime efficiency of the algorithm allows us so simulate dynamic MANET networks (such as 802.11.s [21]) in almost real-time mode - the building Visibility Graph was computed in preprocessing stage while the radio-paths between the clients were computed in real-time (according to the dynamic location of the clients).

For future work we plan to generalize this simulation platform to support several Tx sources. This is intended allow a user to simulate wireless communication in urban regions. In turn, this course of development may be applicable for facility location problems such as 4G Femtocells layout design [22, 23].
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