Abstract:
This deliverable summarizes the activities and achievements of investigations of WP1 Task 1.2 in the first year of the project. In this deliverable current evolutions of ray-tracing tools in order to fulfill the new needs coming from the radio positioning community are addressed. First investigations on introduction of time-variation related to human activity are presented. Then an innovation that aims to locally correct the prediction with the insertion of measurement data is introduced. Lastly, a band-divided UWB ray-tracing technique as well as new methods and concepts for dynamic multi node channel simulations are detailed.

Keyword list: Multi-link channels, positioning, ray-tracing, time-variant channels, human activity, mobility models, UWB, measurement insertion, mobility models, graph-based modelling.
EXECUTIVE SUMMARY

In this deliverable D.1.5 the intermediate research results conducted in WHERE2 WP1, for the purpose of evolutions of ray-tracing tools for dynamic positioning are presented. This report is structured in two parts, a main part summarizing the outlines of the reported activities organized topic-wise, and an extended appendix containing reports providing to the readers more detailed information on the last addressed topic.

Non stationarities of the channel related to human activity are addressed in Section 2. First, a targeted literature survey on deterministic human body modelling is provided. Then, several approaches are envisaged to get a ray-tracing solution embedding a realistic modelling of time-variant human activity for fixed radio links. For instance, the adaptation of the method presented in the Deliverable 1.4 for the LOS direct path calculation to all dominant paths or the creation of additional scattered multi-paths (based on physical or empirical modelling) for each snapshot of human crowd activity (i.e. persons location at a given time). A measurement campaign is currently specified in order to compare these different approaches.

An innovation based on refinement of ray-tracing simulations by measurement insertion is introduced in Section 3. This innovation proposes not only to enhance the prediction where measurements were carried out but also to alter the prediction in the surrounding of the measured data. The maximal distance as well as the weighting factor for the local correction will have to be determined. Thus, investigations from WHERE1 indoor measurement campaigns are going to be used to further evaluate the requirements of the method and determine the best parameters to consider.

Section 4 presents a method in order to introduce UWB capability into a ray-tracing solution. This method consists first at dividing the spectrum into chunks of narrow bands, then at carrying out a conventional ray-tracing simulation in each sub-band and finally at concatenating the individual channel frequency responses into one UWB frequency response. Following a validation step notably based on UWB measurements, it is expected that this new feature will be embedded in an extended prototype of an existing ray-based tool in order to provide the realistic simulations needed by the other WPs.

Ray-tracing simulations for a dynamic multi node channel scenarios is summarized in Section 5. The concept of multi-graph description of the environment layout as well as the notion of ray signature are introduced. The proposed multi graph structure allows a high level representation of an indoor layout and thus the extraction of useful metadata information such as the visibility graph (i.e. the visibility relationships between all vertices of the layout; useful for a fast ray paths determination) or the graph of rooms (i.e. the distribution of rooms and their possible communication through a door; useful for mobility model purpose). Besides, the ray signature aims at representing the interactions that are predisposed to be encountered by a group of rays. It is symbolized by a sequence of structure identifier (i.e. a specific number that links each interaction/vertex of the ray signature with the building layout structure through the structure graph).

Thus, the multigraph oriented description of the layout will be exploited to get realistic simulation of autonomous entities mobility (in combination with an extended version of the Python “SimPy” package: an agent-based mobility model) as well as to speed up incremental determination of ray paths (in combination with the notion of ray signature). A detailed description of the multigraph oriented description of the layout and their exploitation for incremental ray determination can be found respectively in Appendix A.1 and A.2.

The presented results and the ongoing activities presented in this deliverable, together with the results from D1.3 on the statistical dependency of multi-link channels as well as from D1.4 on non-stationary channels form the basis for the characterization of a multi-link channel model.
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## AUTHORS

<table>
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<th>Partner</th>
<th>Name</th>
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</tr>
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</table>
| SIR     | Julien Stéphan     | Phone: +33 223 480 500  
Fax: +33 223 480 599  
e-mail: jstephan@siradel.com |
|         | Yves Lostanlen     | Phone: +1 416 572 7677  
Fax: +33 223 480 599  
e-mail: ylostanlen@siradel.com |
| SIG     | Marios Raspopoulos | Phone: +357 22 32 52 40  
Fax: +357 22 32 52 41  
e-mail: m.raspopoulos@sigintsolutions.com |
| URI     | Bernard Uguen      | Phone: +33 223 236 033  
Fax: +33 223 235 616  
e-mail: bernard.uguen@univ-rennes1.fr |
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1 INTRODUCTION

Ray-tracing tools are very accurate solutions to predict propagation effects in mobile indoor and outdoor environments and are very widely used in radio communications. Nevertheless, these tools need to be adapted in order to fulfill new needs coming from the radio positioning community. Notably from the indoor propagation channel modelling in which very realistic situations scenarios must be considered. For instance multi-link mobile environment scenarios are composed of mixed Line of Sight (LOS) and Non Line of Sight (NLOS) conditions with time-variant effects due to moving people and furthermore the presence of furniture cannot be neglected. Investigations led in within WHERE2 WP1 research activities are more specifically focused on multi-link radio channel modelling for cooperative localization purposes. In this context and in order to address realistic positioning simulation scenarios involving several nodes with independent mobility models each, new modules must be implemented and embedded in existing ray-tracing tools. The three partners involved in this task already have their own ray-tracing tool for indoor application: SIRADEL through their indoor ray-tracing model based on the Volcano technology, SIGINT with their 3DTruEM simulator and UR1 with their PyRay simulation tool. In the frame of the WHERE2 project, the development of the new required features will be divided among the partners in order to take advantage of complementarity of each solution.

First of all, the development of a module that introduces a realistic mobility model in indoor is required. In such a model, each entity (i.e. every element potentially mobile) is commonly considered as autonomous (agent-based modelling) and aims at following a “real” trajectory according the used environment description (i.e. the building layout for an indoor environment). The notion of multigraph description is notably introduced in this deliverable, which aims at taking advantage of the environment description for both ray-tracing simulation and mobility modelling. Then, in connection with the simulation of dynamic wireless network scenarios, the non stationarity of the channel related to surrounding human (i.e. agent) activity was identified as a key feature that need to be accurately modelled by ray-tracing solutions. Besides, in order to provide the most realistic predictions as possible to feed specific needs of other WHERE2 WPs (such as the prediction of location dependent channel parameters for different bandwidths including Ultra-Wide Band (UWB) in an indoor realistic synthetic environment to develop and verify the positioning algorithms in WP2 or the calculation and updating of realistic fingerprinting databases and coverage maps to evaluate the need for a vertical handover as this is studied in WP3), an innovation based on refinement of ray-tracing simulations by measurement insertion and the introduction of UWB capability are also proposed.

In the following the intermediate research results, conducted in WHERE2 WP1, for the purpose of evolved ray-tracing for positioning are presented. The document is structured in the following way: various already or future addressed research activities are summarized; and detailed descriptions on tools and concepts used to adapt ray-tracing simulators for dynamic multi node channel simulations can be found in form of reports in the appendix. The summaries provide short introductions, first results and address open issues of the various research topics.

Section 2: A method was proposed in deliverable D1.4 to introduce indoor time-variant channel properties related to human activity into a geometry-based stochastic channel model (i.e. WINNER2). Investigations in order to adapt this method into ray-tracing solution are presented. A state of the art on the existing solutions is detailed as well as several envisaged approaches for modelling the obstruction of propagation paths by human body.

Section 3: Even if ray-tracing tools are based on a deterministic approach, some approximations are made for the determination of the propagation mechanisms (such as diffraction over furniture). These approximations introduce modelling errors between simulation and the reality, thus a proposed innovation that aims at locally correct the ray-tracing prediction with the insertion of measurement data is presented.

Section 4: In order to feed the specific needs of WHERE2 WP2 and WP3, a ray-tracing solution will be
used to simulate an UWB mobile environment. The selected method in order to introduce UWB capability into a ray-tracing solution is detailed. This method is based on band-divided predictions of impulse response and a frequency domain concatenation of individual channel frequency responses.

Section 5: New concepts and tools are under development in order to adapt a ray-tracing simulator for dynamic multi node channel simulations. The notions of multigraph description of the building layout and ray signature are presented, which aim at speeding up determination of ray paths. Besides, the multigraph representation is going to be exploited in combination with an extended version of the Python “SimPy” package in order to get a realistic simulation of autonomous entities mobility (agent-based modelling).
2 INTEGRATION OF TIME-VARIATIONS IN RAY-TRACING TOOLS

2.1 State of the art on the existing solutions

Typical deterministic wireless channels are modelled through techniques that do not capture temporal variations. Besides, the accuracy of deterministic propagation tools is highly depending to the available description of the environment. The simulation process will always contain a part of uncertainties coming from:

- Time-independent data. Objects not included in the original modelling of the environment;
- Time-dependent data. Moving objects, mostly human-driven for which the position evolves with time.

The main contributors for indoor static details are pieces of furniture. It is conventional that indoor furniture is neglected in deterministic radio propagation predictions since it implies too much computational cost and relies commonly on unknown geo map data. However, in a more confined environment (e.g. indoor femtocell), any object of significant length can be a source of scattering through diffraction or non-specular reflection (diffusion). Thus, by considering the main contributor, we get a richer propagation spectrum as well as more realistic spatio-temporal properties of the channel. Fujimoto in [1] denotes that "The influence of furniture and the movement of people can have a significant (and time-varying) effect on coverage". Although the main trend was to discard those pieces of furniture, a few studies were conducted to see what could be the impact of furniture, and how it could be modeled if it was important enough. In [2], a mean difference of 6 to 7 dB was observed between measurements with and without people and furniture. It was also observed that furniture influences more the propagation channel than people especially at higher frequencies. For example in the detailed 60 GHz work of [3], where it was concluded that main paths were attenuated whereas new paths were added, giving birth to a wider spectrum but with less powerful contributions, even being under the detection threshold.

In Indoor, the main moving scatterers are moving people (e.g. employees in an office). People and their movements used to be also neglected by common ray-tracing tools. However, with the growth of indoor nomadic wireless applications, new modelling approaches have been proposed. Thus, physical human body representation have been introduced in a couple of ray-tracing tools. These deterministic tools may be used in two different simulation processes:

- Realistic simulation of the time-variant channel properties, already including the human traffic impact (i.e. physically-based);
- Realistic simulation of the time-invariant channel properties, plus estimation of the multi-path obstruction probabilities. The time-variant channel simulation is then generally obtained from a Markov process.
The Body-shadowing model presented in [4] is cited as reference although it is designed for 60 GHz propagation predictions. A physical model of the obstruction of a ray by a person was developed by Künisch et al. in [5] relying on a double vertical knife edge diffraction plus a phase and amplitude correction to determine the path-loss. In this model, derived from channel measurements in the range from 4 to 10 GHz, a human body is represented as an infinite length and constant width stripe S (see Figure 1). Therefore the diffracted field is the sum of two knife-edged fields: one diffracted by the front and one by the back of the person. It was found that a better match with measured data was obtained if the stripe was aligned in the main body axes. The result section of the paper details that in most cases, the overall shape is reasonably reproduced, including the oscillations before and after the main shadowing.

Figure 1: UWB Human body model [5]
(a) Perspective view (b) Top view, person walks along the x direction.

Other models have been developed to include humans as scatterers, for example in [6, 7] where Khajafi et al. present a Human body model as a cylinder containing salty water, circumscribed within a parallelepiped as pictured in Figure 2. The presented results are in agreement with those based on channel measurements in the literature and confirm the impact of bodies on the radio propagation.

Figure 2: 60 GHz Human body model [6].

Authors in [8] also propose a complementary modelling approach. The fading is predicted from a three-knife-diffraction method, i.e. from the sum of the three following components: knife diffraction at one edge of the human body; knife diffraction at the other edge; and knife diffraction on the top of the human body (see Figure 3). The Ricean K-value, when obstruction occurs, is given by the ratio between the faded direct path power and the power of other contributions. The validity of this three-knife-diffraction method is proved by comparison to CW measurements at 2.4 GHz with controlled person movements.
2.2 Modelling of time-variant human activity for fixed radio links

A method was already proposed and introduced in Deliverable 1.4 in order to simulate indoor time-variant channel properties related to human activity. This method is currently integrated into a geometry-based stochastic channel model (i.e. WINNER2). Future works will be focused on adaptation of this method into a ray-tracing solution. Objective is to get relevant statistics for time-variant channel models. The envisaged prediction process is depicted in Figure 4.

After defining a particular scenario based on a SISO radio link, prediction of ray-tracing multi-paths and a snapshot of human crowd activity (persons are modelled by a vertical cylinder of width 40cm and height 170cm.) are combined in order to determine the “obstruction state” (i.e. the number of obstructions of path and the list of obstructing persons). As the exact geometry of each path is fully known, the determination of the “obstruction state” results from a simple geometry analysis. It is envisaged then to predict the shadowing loss in a very realistic way. Several approaches will be analyzed as the adaptation of the method presented in Deliverable 1.4 (inspired from [8]) for the LOS direct path calculation to all dominant paths simulated by the ray-tracing solution. Creation of additional scattered multi-paths (based on physical or empirical modelling) for each snapshot will be also analyzed. These different approaches will be compared to measured data. A measurement campaign is being specified in order to characterize simple radio links with controlled human activity. These measurements will be carried out in the SIRADEL premises and could be thus easily reproduced by deterministic radio wave propagation models. Besides, as illustrated in Figure 4 and reported in Deliverable 1.4, ray-tracing solution is also used to get statistics on paths obstruction. In this process, persons are uniformly distributed over the propagation environment. Thus, a large number of path-person pairs is obtained and used to derive the obstruction probability function used to feed the elaborated method for time-variant GSCM predictions.

2.3 Anticipating impact on positioning

Fading caused by the movement of people or the presence of furniture degrades the performance of communication systems operating indoor. In the same way, their influence on the radio propagation channel must be considered by localization method in order to provide realistic estimation of the mobile station
location. Besides, most of the current localization methods consider data from the indoor propagation channel, such as the received signal strength (RSS), the direction of arrival (DOA), the time of arrival (TOA), the time differences of arrival (TDOA), etc. It was proven that these parameters are strongly impacted by the obstructed or generated multipath due to moving people or the presence of furniture.
3 REFINED RAY-TRACING SIMULATIONS BY MEASUREMENT INSERTION

3.1 Purpose of the measurement insertion

Propagation models based on a deterministic approach (such as ray-tracing solutions) are very accurate, especially when they are coupled with a realistic representation of the environment (e.g., high resolution map data in an outdoor context or a fine representation of the building structure in indoor). Yet given the many possible details actually present in a scene (pieces of furniture, details of the building structure), some differences between the reality and simulations may be observed. Some approximations are made for the determination of the propagation mechanisms (e.g., diffraction over furniture or reflection on walls) introducing modelling errors between the simulation and the reality. The realization of measurement campaigns is the only way to get a reference for power levels, provided that the measurement process is perfectly controlled. If a measurement set obtained in a specific environment is available, it is possible to globally adjust the simulations with the measurements. However, even if the propagation model is statistically centered for an entire set of measured data, it is unlikely that, for a specific point, the predicted value will match the measured data. Thus, the proposed innovation aims at locally correct the coverage map with the insertion of measurement data, taking into account though some local correlation of the signals.

3.2 Investigations from WHERE1 indoor measurement campaigns

The correction, based on the prediction error surrounding a specific simulated point, will be propagated for various points of the coverage map. Therefore the process will enhance not only the coverage map where measurements were carried out but also alter the prediction in the surrounding of the measured data. The maximal distance for the correction will have to be determined (by a thorough analysis of the correlation) as well as a weighting factor taking into account the number of bins considered for the correction. Investigations from WHERE1 indoor measurement campaigns [9] are envisaged in order to first evaluate the minimal set of measurement required to enhance the simulation and second to determine a method for estimation of the correlation distance in indoor environments (heuristic method is envisaged).
4 UWB RAY-TRACING

UWB communication recently attracts significant attentions in commercial or scientific sectors [10] and has become one of the key technologies in short-range communications due to its potential to provide high data rates in multi-user networking environments. UWB consists of narrow time signals (pulses) that occupy a wide range of the spectrum (BW>20% of the central frequency or >500 MHz). These narrow time signals provide very good temporal resolution and can be used for accurate positioning and ranging. The interest in UWB communication has also stimulated the need for UWB channel modelling which mainly focus on indoor environments due to the short-range nature of this kind of communication. There exist various empirical/statistical models in literature like [11, 12, 13, 14]. Besides, deterministic UWB Channel modelling is commonly tackled via two options: either by time-domain techniques like in [15] or by dividing the spectrum into chunks of narrow bands and carrying out conventional ray-tracing simulations and then concatenating the individual channel frequency responses into one UWB frequency response. We currently envisage to employ the second approach as this has been presented by Sugahara in [16] to convert a ray-tracing simulator into UWB without modifying its calculation engine. This technique allows notably to incorporate the frequency dependence of the electrical parameters of building materials which in many cases might be significant.

The algorithm to be used for the development of this "Band-Divided" UWB ray-tracing technique is shown in Figure 5.

1. Firstly the UWB spectrum is split into narrow sub-bands which would allow to use conventional narrowband ray-tracing techniques in order to calculate the impulse responses;

2. Then, for each of these impulse responses, a Fourier transform is performed to calculate the narrowband channel frequency response. A filter is used to filter out the sub-band of interest;

3. The filtered individual sub-band frequency responses are combined in order to obtain the UWB channel frequency response;

4. Inverse Fourier transform is performed on the UWB channel frequency response to obtain the UWB impulse response.

After a validation step with UWB measurements, investigations of the effect of different divisions of the spectrum on the accuracy of the method will be conducted. It is then expected that this new feature will be used to provide realistic UWB simulations needed by the other WPs.
Split the UWB spectrum into sub-bands and use conventional Ray Tracing for each sub-band to obtain the impulse response for each sub-band.

Use Fourier Transform to transform the impulse responses into the frequency domain.

Filter out the respective sub-band in the individual frequency responses and combine them to get the channel UWB frequency response.

Inverse Fourier Transform to obtain the UWB Impulse Response.

Figure 5: UWB Ray-Tracing Algorithm.
5 Dynamic Ray-tracing Simulation

5.1 Overview

Usually, traditional propagation tools are designed in order to evaluate radio channel features on a predefined grid. This is a perfect approach for coverage purposes but when dealing with more time-variant sophisticated scenarios, this gridding approach results in strong combinatoric limitations. In fact, it happens difficult to anticipate all possible multi-link channel situations. Thus, it would be desirable to proceed to the electromagnetic calculations only for this very set of radio links involved at one time step of a dynamic simulation.

Ray-tracing simulations for a dynamic multi node channel going to be exploited in the WHERE2 project for predicting the evolution of the channel impulse response along trajectories. In that kind of situation, either one (AP to mobile) or two (mobile to mobile) extremities of the link are moving. This situation requires the calculation of almost the same geometrical information from successive time steps. Thus, it makes sense to determine what is the strictly necessary computation load in that context. We based our approach on the new concept of a multigraph description of the building layout which is detailed in the Appendix A.

This has been the seminal idea and motivation of the introduction and definition of the complementary concept of the ray signature which is detailed shortly in A.2.4. A ray signature presents the advantage over a ray of being more conservative or stationary during the time evolution of a radio channel due to motion of radio link. A given signature can provide either:

- A valid ray (which is then exploited for predicting the CIR);
- Or a new muted signature if the derived ray happens to be not valid.

Each individual node (or agent) is implemented as an independent thread running sequentially the list of inner processes described in Figure 6.

![Figure 6: Dynamic ray-tracing simulation - Overview.](image)

Note that an AP is also modeled as an agent without mobility capabilities.
5.2 Current investigations on indoor pedestrian motion

We found in the literature that modelling pedestrian mobility in virtual world is a problem which has been extensively studied in the context of video games and virtual reality field [17],[18],[19]. The idea is to proceed simulation for autonomous entities in realistic indoor environment described by the multigraph description introduced in the previous section. The behaviors of user agents must be determined not only by external sources (steering behaviors), but also with regard to their internal state. In that respect the knowledge of the introduced graph of rooms $G_r$ is a precious asset which has been exploited. The simulator also relies on pre-existing packages especially the python SimPy package.

The interest of using a discrete event simulator as SimPy is that it not required for each subtask of the agent to have the same time step. This is a free parameter, the recalculation of network neighborhood can be done for example on a larger time step than the channel impulse response evaluation.

The motion is obtained though a combination of steering behaviors as described in [17]. It has been adapted from a SimPy implementation developed by Ken Mac Leod of the Steering behaviors for autonomous characters: http://www.mcs.vuw.ac.nz/cgi-bin/wiki/SimPy?SimPyTransit. The proposed implementation exploits the adopted multigraph Layout description described in the Appendix.

5.3 Status of the Implementation

At that point of the project, the software development work has well progressed for both channel and mobility modelling. The important building blocks necessary to achieve the targeted objectives have been either developed or identified. A significant part of the preliminary work has been consisting in redefining completely the data structure exploiting a multigraph description of the layout.

The current implementation allows to instantiate several agents in the layout. One can monitor in real time the position of each agent. The used high level mobility scheme is currently as follows:

- Each agent draws randomly a room number $N_r$.
- Exploiting the Dijkstra’s algorithm the shortest path from the current room and the targeted room $N_r$ is determined.
- The agent is steered from room to room along the determined trajectory. In a future implementation it is foreseen to assign each agent a graph oriented building profile. The profile will provide prior probability for each room and a Poisson parameter for describing transition from one room to another in a more realistic manner. Then, it should be possible to simulate a more realistic indoor pedestrian mobility scenario to observe the influence of increasing user density on positioning performances.

Note that the obstacle avoidance is not fully functional and that the actual connection with the ray-tracing solution is not included in the current state of the implementation. Figure 7 is a snapshot of those moving agents at one time step of the simulation including in black lines the corresponding trace.
Figure 7: Example of 5 agents moving randomly from rooms to rooms inside the SIRADEL building.
6 CONCLUSIONS
This intermediate deliverable summarizes the ongoing activities of T1.2 in WHERE2 WP1 on the topic of multi-link channel models. The focus in this deliverable is put on the evolution of ray-tracing tools in order to fulfill the new needs coming from the radio positioning community. The ongoing research activities described in deliverable D1.3, D1.4, D1.5, and D1.6 will be synthesized in the intermediate report D1.7 (M24) and final report D1.8 (M34) about the WHERE2 channel model.
Investigations on the introduction of time-variant channel properties related to human activity in indoor ray-tracing solutions were presented in Section 2. Following a targeted literature survey on deterministic human body modeling, several approaches have been envisaged; a measurement campaign is being specified in order to compare these different approaches. In Section 3, an innovation based on refining of ray-tracing simulations by measurement insertions was proposed. Investigations from WHERE1 indoor measurement campaigns are going to be used to further evaluate the requirements of the method and determine the best parameters to consider. A “band-divided” UWB ray-tracing technique is detailed in Section 4. It is expected that this implementation will be used to provide UWB simulations needed to the other WPs. In Section 5, dynamic ray-tracing simulation is addressed. The concept of multi-graph description of the environment layout was introduced. This structure will be exploited to get realistic simulation of autonomous entities mobility (in combination with an extended version of the Python “SimPy” package: an agent-based mobility model) as well as speed up incremental determination of ray paths (in combination with the notion of ray signature).
The presented results and future activities are the basic foundation for the description of a multi-link channel model. Together with the results from D1.3 on the statistical dependency of multi-link channels and from D1.4 on non-stationary channels, a description for multilink channel models for localization purposes will be prepared and shared with the other work packages in WHERE2.
A APPENDIX

A.1 Multigraph oriented description of the layout

The proposed multigraph description of the layout relies on the Python graph analysis package NetworkX (http://networkx.lanl.gov/). NetworkX is a Python package for the creation, manipulation, and study of the structure, dynamics, and functions of complex networks. The data structure of the Indoor layout has been modified by introducing and exploiting graph structures, and in taking advantages of existing methods from NetworkX library. This section lists the graph oriented description of the layout which has been introduced and built. The adopted multi graph structure allows to extract useful meta information from the layout which will be later exploited for:

- incremental determination of rays using ray signatures;
- providing information to mobile agents (i.e. human or mobile radio nodes).

A.1.1 The layout structure graph $G_s$

We begin with defining the structure graph: $G_s(V_s, E_s)$. This graph describes the building layout structure. Where $V_s$ is the ordered set of vertices index and $E_s$ is the ordered set of edge index. We have:

\[
\text{card}(V_s) = N_n \\
\text{card}(E_s) = N_e
\]

and,

\[
V_s = \{n_0, \cdots, n_{N_n-1}\} \\
E_s = \{e_0, \cdots, e_{N_e-1}\}
\]

We define the two following functions: tail() and head() as functions which take an edge number as argument and return the vertex number associated respectively with tail and head of the edge.

\[
\text{tail}(e_k) \in V_s \\
\text{head}(e_k) \in V_s
\]

Equipped with those 2 functions, one can define two sets of points whose indexes are associated respectively to starting and ending points of the structure edges.

\[
A_s = \text{tail}(E_s) = \{\text{tail}(e_0), \cdots, \text{tail}(e_{N_e-1})\} \\
B_s = \text{head}(E_s) = \{\text{head}(e_0), \cdots, \text{head}(e_{N_e-1})\}
\]

Figure 8: The structure graph $G_s$.

In figure 8 black segments represented either a door or a window.
A.1.2 The visibility graph $G_v$

The second graph of the layout is the visibility graph $G_v$. Nodes of this graph are the same as those of $G_s$. Only the connectivity between nodes are defined differently. Two nodes are connected if they have an “optical” visibility relationship. This simply means that the electromagnetic energy can flow from one node to another. The graph structure is well suited and convenient to store exhaustively visibility relationships between nodes and edges. This graph is exploited for fast determination of ray signatures A.2.4.

![Figure 9: Example of a visibility graph $G_v$.](image)

A.1.3 The cycle (topological) $G_t$

For defining the mobility of mobile agents in the layout we need to analyze the topology of $G_v$. Exploiting the NetworkX API it is possible to determine all the layout cycles. This graph of cycles has been called $G_t$ as it contains valuable topological information. Each cycle contains various attributes as for example the set of nodes and edges of the cycle. This information is exploited once the position of $t_x$ or $r_x$ is known in order to connect directly to those leaves of $G_t$ which are associated with a given cycle. This data organization avoids tedious and slow search of edges and nodes to connect with. Naive approaches would require for example the calculation of a lot of segment intersections. With this graph available, geometrical calculations are reduced to a minimum. An example of graph $G_t$ is shown in Figure 10.

![Figure 10: Example of a graph of cycles $G_t$.](image)

A.1.4 The graph of rooms $G_r$

The graph of rooms $G_r$ is obtained simply in filtering the nodes of $G_t$ (cycles) which have at least one door. An example of a graph of rooms is shown in Figure 11. This graph is exploited to control high level mobility of agents inside the building. This graph is also exploited for fast extraction of the list of edges which constitute a given room.
A.2 Exploiting graphs for incremental ray determination

A.2.1 Ray tracing and graphs

The determination of rays is no more than a set of computational steps which establishes a link between a structure graph $G_s$ and another graph $C_N$ which is a set of $N_r(\gamma)$ rays or paths, all originating at transmitter $t_x$ and ending at receiver $r_x$, this will also denoted as a cluster of $N_r$ rays. Formally,$$C_N(\gamma) = RT(G_s, t_x, r_x, \gamma)$$The number of rays depends on various parameters and heuristic criteria in order to select only those rays carrying the most important part of the energy from the transmitter to the receiver. Obviously when the number of rays is limited, a potentially significant part of the energy which reaches the receiver by diffusion and reverberation is neglected. The parameter $\gamma$ controls the amount of total energy in the ray description. When $\gamma = 0$ one only gets the LOS component whereas when $\gamma = 1$, it corresponds to this idealistic situation where all the diffusion and reverberation effects would be integrated in the ray cluster $C_N(\gamma)$. This situation is both irrelevant and intractable because $\lim_{\gamma \to 1} N_r = \infty$. This doesn’t means that $\gamma = 1$ corresponds to a perfect situation, because the model itself is an oversimplification of any real environment and neglects a lot of details. Even if the geometrical descriptions were perfect, the problem of approximating material constitution parameters still remains and even in case of perfect knowledge of those parameters we should keep in mind that such ray approaches are only asymptotic approximations of Maxwell equations.

However, for positioning and localisation applications there is an interest in fast determination of those rays which contain the dominant part of the energy because they are strongly associated with predictable features of the propagation environment and are potentially a way for taking advantage of multipath in advanced positioning algorithms.

A.2.2 Structure identifier of a point (sid(\(p\)))

sid(\(p\)) is a function which takes a point in the plane (0,x,y) as an argument and returns an information relative to its belonging, either to the vertice set $\gamma$ or as a point belonging to the edge without its terminations. The following convention is used: If a vertex belongs to the $i^{th}$ edge the point structure id (sid) is given by the edge number $e_i$, if the point belongs to the structure, the structure id is defined as minus time the associated node number.

$$\text{sid}(p_{n_i}) = -n_i$$

if $\exists \alpha \in [0,1]$ $p = (1 - \alpha) p_{\text{tail}(e_i)} + \alpha p_{\text{head}(e_i)}$, $\text{sid}(p) = e_i$
A.2.3 Individual rays

Let's define a ray \( k \) as the ordered sequence of points
\[
R_k = \{ t_x, p^0_k, \ldots, p^{N-1}_k, r_x \} = \{ t_x, P_k, r_x \},
\]
where \( t_x \) and \( r_x \) are the points associated to transmitter and receiver and:
\[
\mathcal{D}_k = \{ p^0_k, \ldots, p^{N-1}_k \}
\]
is the ordered sequence of \( N^k \) interaction points along the \( k^{th} \) ray.

A.2.4 Definition of a ray signature

The signature of \( R_k \) is defined as the sequence of the structure id of \( P_k \).
\[
\mathcal{I}_k = \text{signature}(R_k) = \text{signature}(P_k) = \{ \text{sid}(p^0_k), \ldots, \text{sid}(p^{N-1}_k) \} = \{ s^0_k, \ldots, s^{N-1}_k \}
\]
\[
\text{sid}([tx, rx]) = \emptyset
\]
Notice that when at least one ending point of the radio link is moving all the points of \( P_k \) are moving correspondingly. This is not the case of the signature which remains steady in the vicinity region of the moving point. The signature is varying slowly and discontinuously. This is an interesting feature that the ray signature is a precursor of rays. This is the justification of the algorithm we are using which stores the signature graph once one of the link extremity is known. As an example one shows in Figure 12 a set of rays (in blue) which all share the same signature, which contains 4 reflections. \( t_x \) is static and is placed above-left the first segment. The signature for all these blue rays is
\[
\mathcal{I} = \{1, 2, 3, 4\}
\]
The figure has been produced by drawing randomly \( r_x \) in the plane. When the receiver \( r_x \) is misplaced the signature does not lead to a valid ray. When \( r_x \) belongs to the right portion of the plane there exists a valid ray associated with the signature. All those ray have in common their signature. It means that if one termination of the signature is static, either \( t_x \) or \( r_x \) one can associate to such a signature the set of points where the signature can produce a valid ray. Behind that, there is the concept that we only need to track evolution of signatures during the motion. The derivation of rays from signatures being geometrically straightforward.

One other interesting features of ray signature which is illustrated in Figure 13, is that it is possible to derive higher order signatures from a given low order signature. The order of a signature being defined as the number of interactions involved in the signature.
\[
\text{order}(\mathcal{I}) = \text{card}(\mathcal{I})
\]
For example if we have a signature of order 4:
\[
\mathcal{I}_0 = \{1, 2, 3, 4\}
\]
corresponding for example to the transmission through of 4 successive walls placed between \( t_x \) and \( r_x \), one can derive those 3 new signatures of order 6.
\[
\mathcal{I}_1 = \{1, 2, 1, 2, 3, 4\}
\]
\[
\mathcal{I}_2 = \{1, 2, 3, 2, 3, 4\}
\]
\[
\mathcal{I}_3 = \{1, 2, 3, 4, 3, 4\}
\]
Figure 12: Illustration of the concept of signature. Rays in blue have the same signature.

The rule being the following: once 2 successive transmissions (TT) are present in a given signature, one can introduce in the middle a double reflection sequence (RR) and derived several new rays of higher order.

We define the order distance between 2 signatures as:

$$d_0(S_{k_1}, S_{k_2}) = |\text{order}(S_{k_1}) - \text{order}(S_{k_2})|$$

We define an other distance between 2 ray signatures of same order $d_0(S_{k_1}, S_{k_2}) = 0$ as the number of distinct elements in the interaction sequence.

$$d(S_{k_1}, S_{k_2}) = \sum_{l=0}^{N_l-1} \mathbb{1}(s_{k_1}^l - s_{k_2}^l \neq 0)$$

When one extremity of a radio link is mobile a signature can:

- remain steady;
- mute. i.e:
  - a new segment number is involved (the signature order remains the same);
  - an extra extra segment is involved (the signature order increases);
  - a segment collapse (the signature order decreases).

An interaction is either a reflexion (R), transmission (T) or diffraction (D). The interaction type determination is required before transforming a signature into an actual ray. Notice that while the $r$ or $t$, is not precised the interaction type remains unknown, it can potentially become either a reflection or a transmission. The signature is independent from the extremities and can be exploited to derive a wide variety of rays in the vicinity of a given transmitter. This is particularly interesting when dealing with ray tracing in a mobility scenario where a radio link has only slightly changed. For a new time step, and then a new position of link extremities it remains just to check if a previous time step signature is still valid and if not in which new signature it has been muted.
Figure 13: Illustration of deriving higher order signature from a signature containing at least a double transmission (TT).
REFERENCES


