Optimal Placement of Base Stations in Wireless Indoor Telecommunication*

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*Work was done while at ECRC, Munich, Germany

Remarks

ABSTRACT

Planning of local wireless communication networks is about installing base stations (small radio transmitters) to provide wireless devices with strong enough signals.

POPULAR is an advanced industrial prototype that allows to compute the minimal number of base stations and their location given a blue-print of the installation site and information about the materials used for walls and ceilings. It does so by simulating the propagation of radio-waves using ray tracing and by subsequent optimization of the number of base stations needed to cover the whole building.

Taking advantage of state-of-the-art techniques for programmable application-oriented constraint solving, POPULAR is among the first practical tools that can optimally plan wireless communication networks.

Wireless Telecommunication

- Reachable everywhere
- Flexible - no cabling
- Improved quality and security

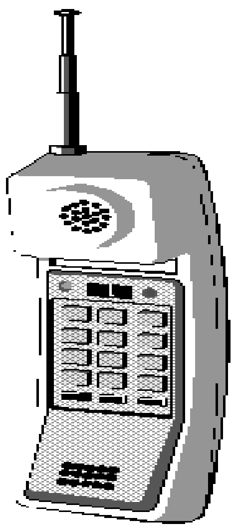
ECRC (Siemens, ICL, Bull)

Siemens Private Networks

Siemens Research and Development

RWTH Aachen, Communication Networks Dept.

- Indoor digital telecommunication
- Need sender stations
- Have to plan their location



Remarks

Project leader. Aachen: Prof. Dr. Walke, Hr. Hußmann

1996:

- 40 Mill. Email addresses
- 50 Mill. Fax machines
- 60 Mill. Mobile phones

1999: Western Europe 15 Mill. wireless phones, Germany 5 Mill.

Flexible - no cabling required. Improved transmission quality and security.

Propagation of radio waves inside buildings.

Today, the number and positioning of base stations is estimated by an experienced sales person.

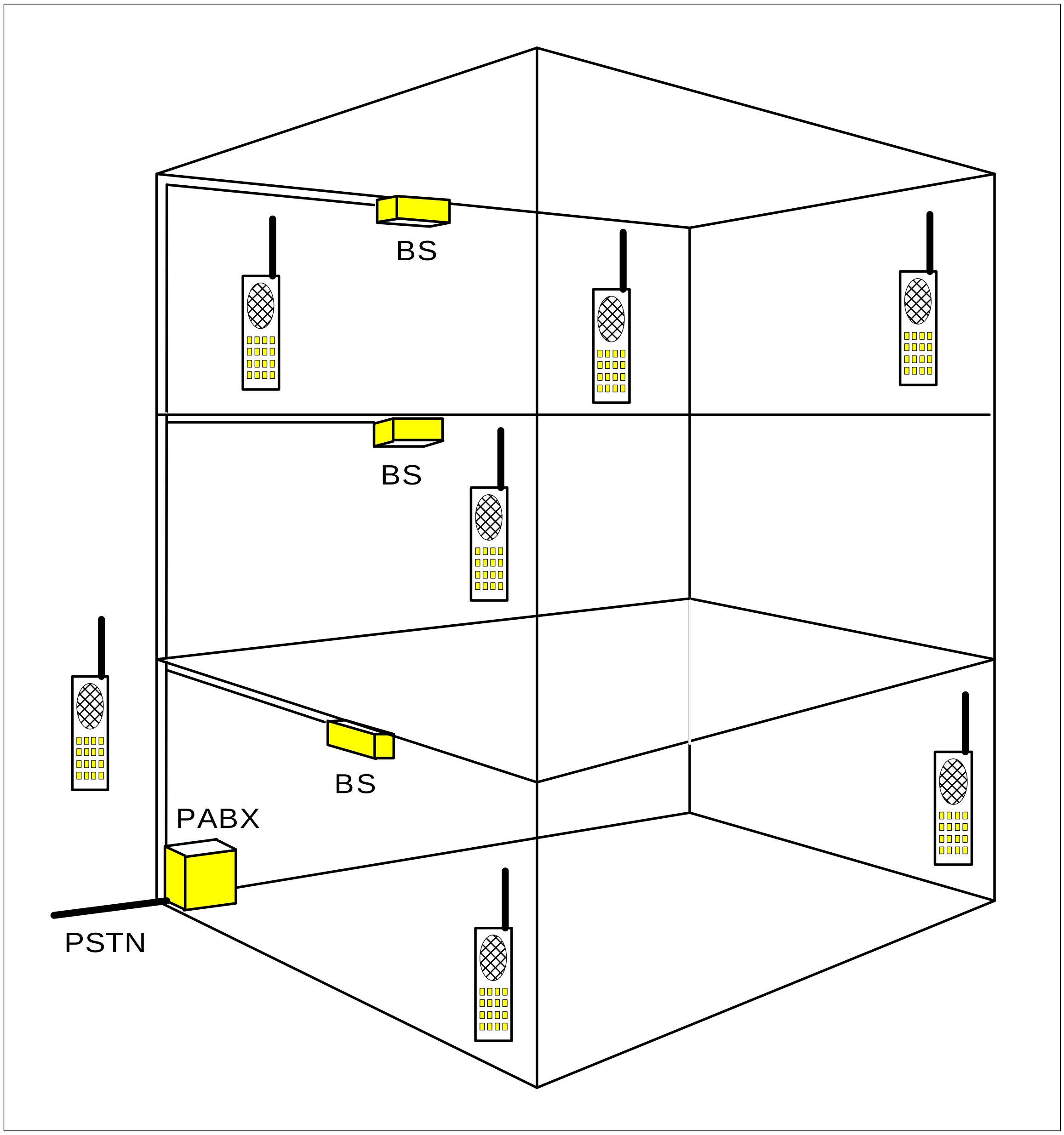
Was Open Problem

- Worldwide first together with AT&T WISE.
- IEEE Expert Magazine, USA: Best Application in Telecommunications 1996.
- Winner Telecom Application Contest of Telecom Italia at CP'98 Conference 1998.

The Challenge

Optimal placement of senders

- Complete coverage of site
- Minimal number of senders



Remarks

Propagation of radio waves inside buildings.

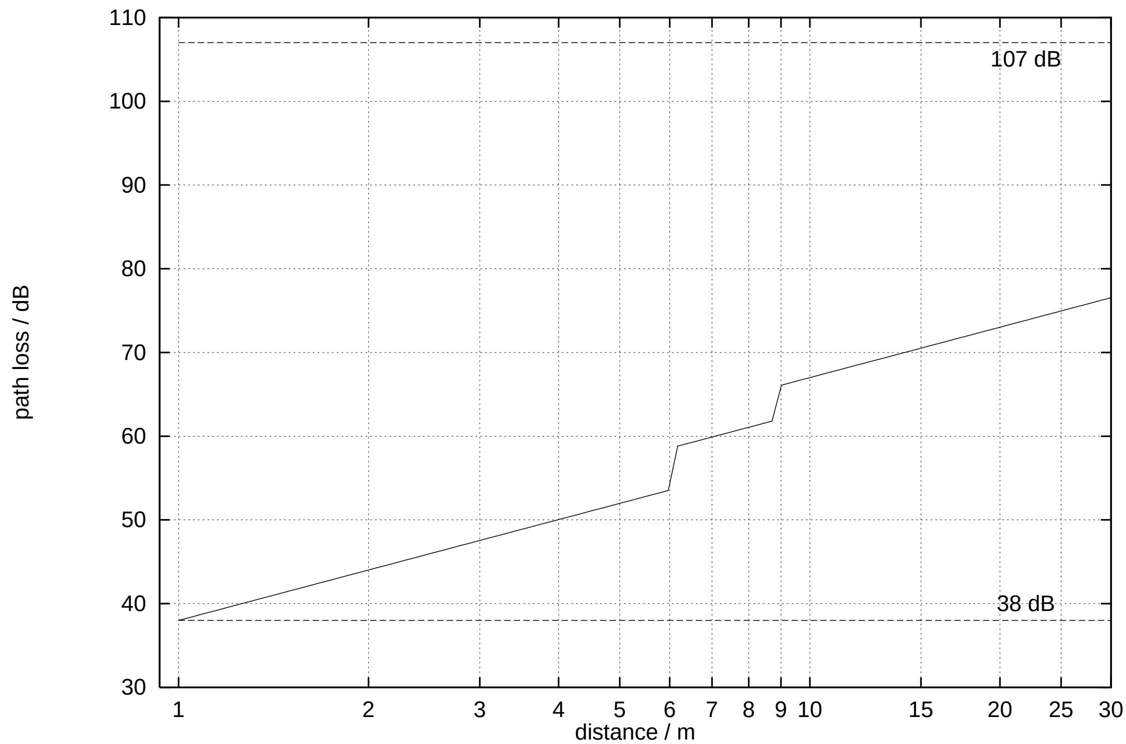
Current systems are cellular in that a base station (sender, transmitter) controls the links to the tranceivers. A (radio) cell is the space that is covered by a single base station. For buildings, multi-cellular systems are required, because walls and floors absorb part of the radio signal.

Radio Wave Propagation

Radio signal suffers from:

- attenuation (weakening) due to distance,
- shadowing (absorption) through obstacles,
- multipath propagation due to reflection.

Path loss, walls at $6m$ and $9m$, log scale



Remarks

The model is based on the power balance of wireless transmission. It combines a distance dependent term with correction factors for extra path loss due to floors and walls of the building in the propagation path.

To take reflection and multipath effects into account, a *fading reserve* (fade margin) is introduced. We also extended the model to take the directional effect of an antenna into account, since antennas do not beam with the same energy in every direction.

The Constraint Approach

- Simulation

- Modelling of site: Walls, Materials

- Propagation of radio waves (ray tracing)

- Optimization

- Constraint solving (intersection of radio cells)

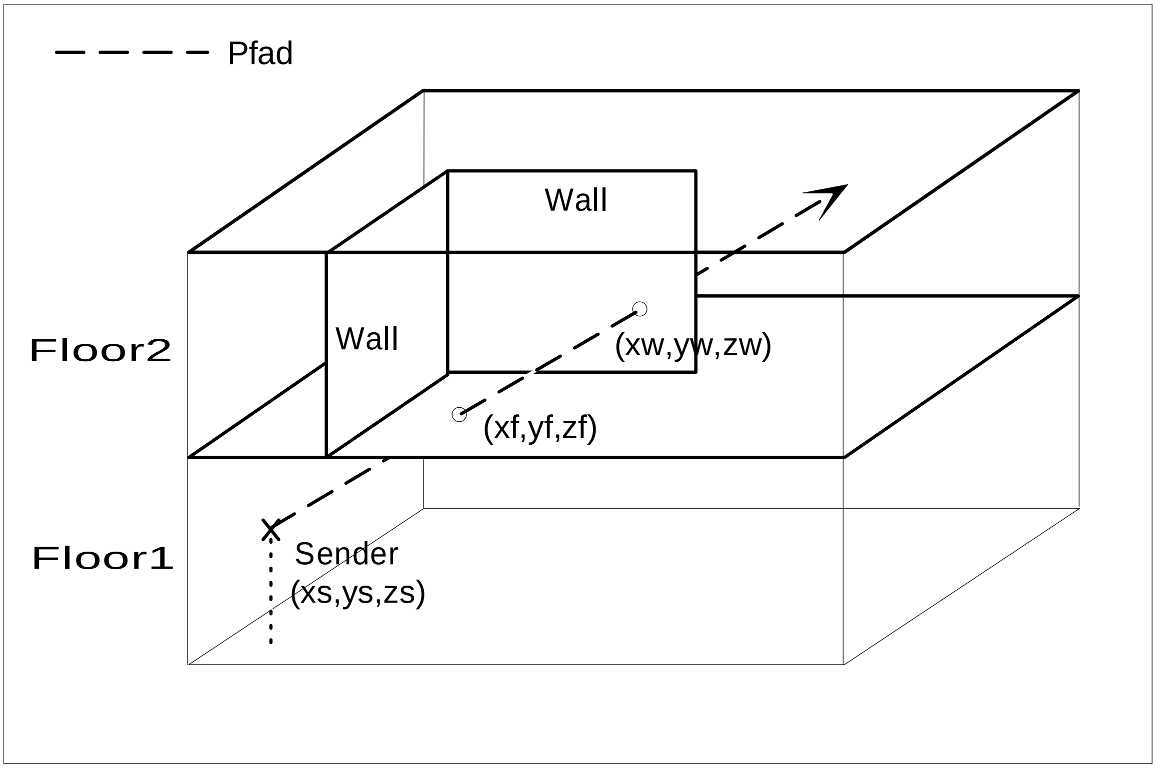
- Search (try equating senders)

- Optimization (branch and bound)

No Remarks

Simulation of Radio Wave Propagation

Ray Tracing



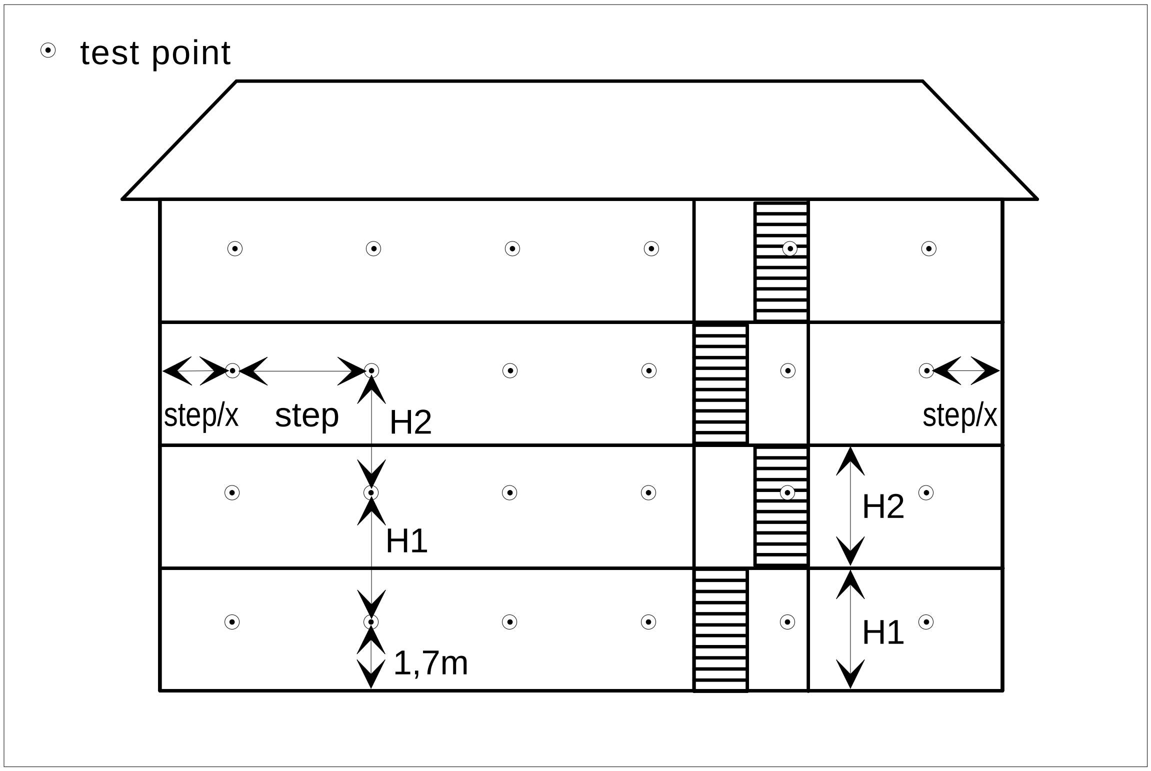
Remarks

Ray tracing simulates the propagation of radio waves through the walls and ceilings of the building. To get to the point of minimal sensitivity (i.e. maximal permissible path loss), each path must be followed through the whole building.

The values of antenna attenuation in the direction of the path, the path loss due to the distance and the insertion losses due to intersections of the path with walls and floors are added up to the maximal permissible path loss.

Test Point Grid

Covers the site



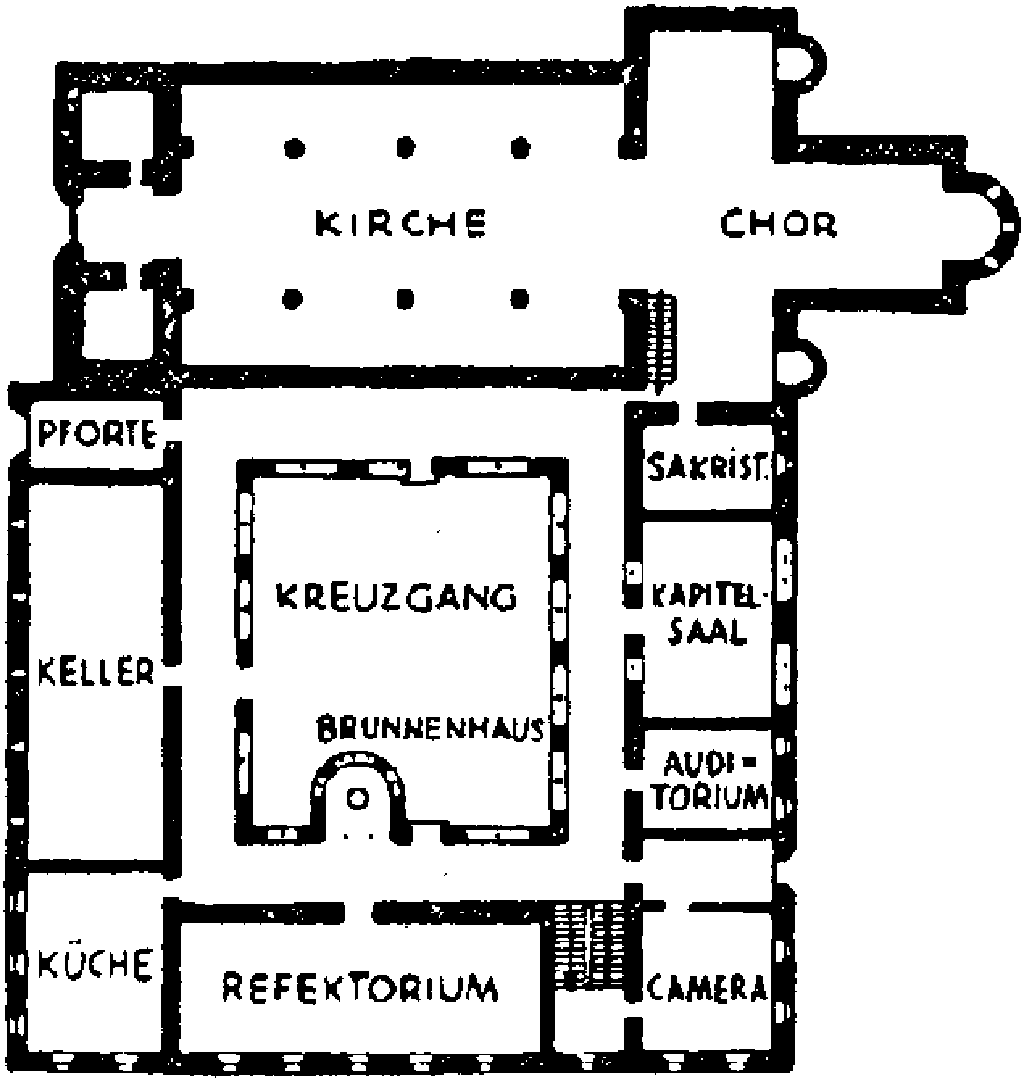
Remarks

In the simulation phase, the characteristics of the building are computed using of test points. Each test point represents a possible receiver position. The test points are placed on a 3-dimensional grid inside the volume that should be covered.

For each test point the space where a base station can be put to cover the test point, the “radio cell”, is calculated. The end points resulting from ray tracing are used to describe the hull of the radio cell. If the test grid is sufficiently small (several per squaremeter), we can expect that if two neighbouring test points are covered, the space inbetween - hence the whole building - can also be covered.

Radio Cells

Modern Monks' Monastery



Remarks

Note that the radio cell will usually be a rather odd-shaped object, since the received power may exhibit discontinuities because of tiny changes in the location - such as a move around the corner.

Constraint Solver

Intersection of radio cells

```
% Sender in rectangle

not_empty @
S in (A,B)#(C,D) ==> A<C, B<D.

intersection @
S in (A1,B1)#(C1,D1), S in (A2,B2)#(C2,D2) <=>
      A = max(A1,A2), B = max(B1,B2),
      C = min(C1,C2), D = min(D1,D2),
      S in (A,B)#(C,D).
```

Remarks

For each of the resulting radio cells a constraint is set up that there must be a location of a base station (geometrically speaking, a point) somewhere in that space. Then, we try to find locations that are in as many cells at the same time as possible. This means that a base station at one of these locations will cover several test points at once. Thus the possible locations are constrained to be in the intersections of the cells covered.

In a first attempt restricted to two dimensions, we approximated a cell by a single rectangle. The 2-D coordinates are of the form `(X,Y)`, rectangles are orthogonal to the coordinate system and are represented by a pair, composed of their left lower and right upper corner coordinates. For each cell, simply a constraint `inside(Sender, Rectangle)` is imposed, where `Sender` refers to a point that must be inside the `Rectangle`.

The first rule (named `not_empty`) says that the constraint `S in (A,B)#(C,D)` is only valid if also the condition `A<C,B<D` is fulfilled, so that the rectangle has a non-empty area. The `intersect` rule says that if a base station location `S` is constrained by two `inside` constraints to be in two rectangles at once, we can replace these two constraints by a single `inside` constraint whose rectangle is computed as the intersection of the two initial rectangles.

```
% Extend to union of geometric objects

empty @ S in nil <=> false.

intersection @ S in L1, S in L2 <=>
     intersect_all(L1, L2, L3), S in L3.

  intersect_all(L1, L2, L3) <=>
     setof(R3,(choose(R1, L1), choose(R2, L2),
               intersect_one(R1,R2,R3)),
           L3).

  choose(X,cons(Y,L)):- (X=Y ; choose(X,L)).

% Prolog Search: labeling - try equating senders

equate_senders(nil):- true.
equate_senders(cons(S,L)):-
     (choose(S,L) ; true),
     equate_senders(L).

% Branch and Bound optimization in Prolog

bb(C,M,L):-
     constraints(C,S), max_sender(S,M),
     equate_senders(S), number_senders(S,N),
     (bb(C,N-1,L) ; L=S).
```

Remarks

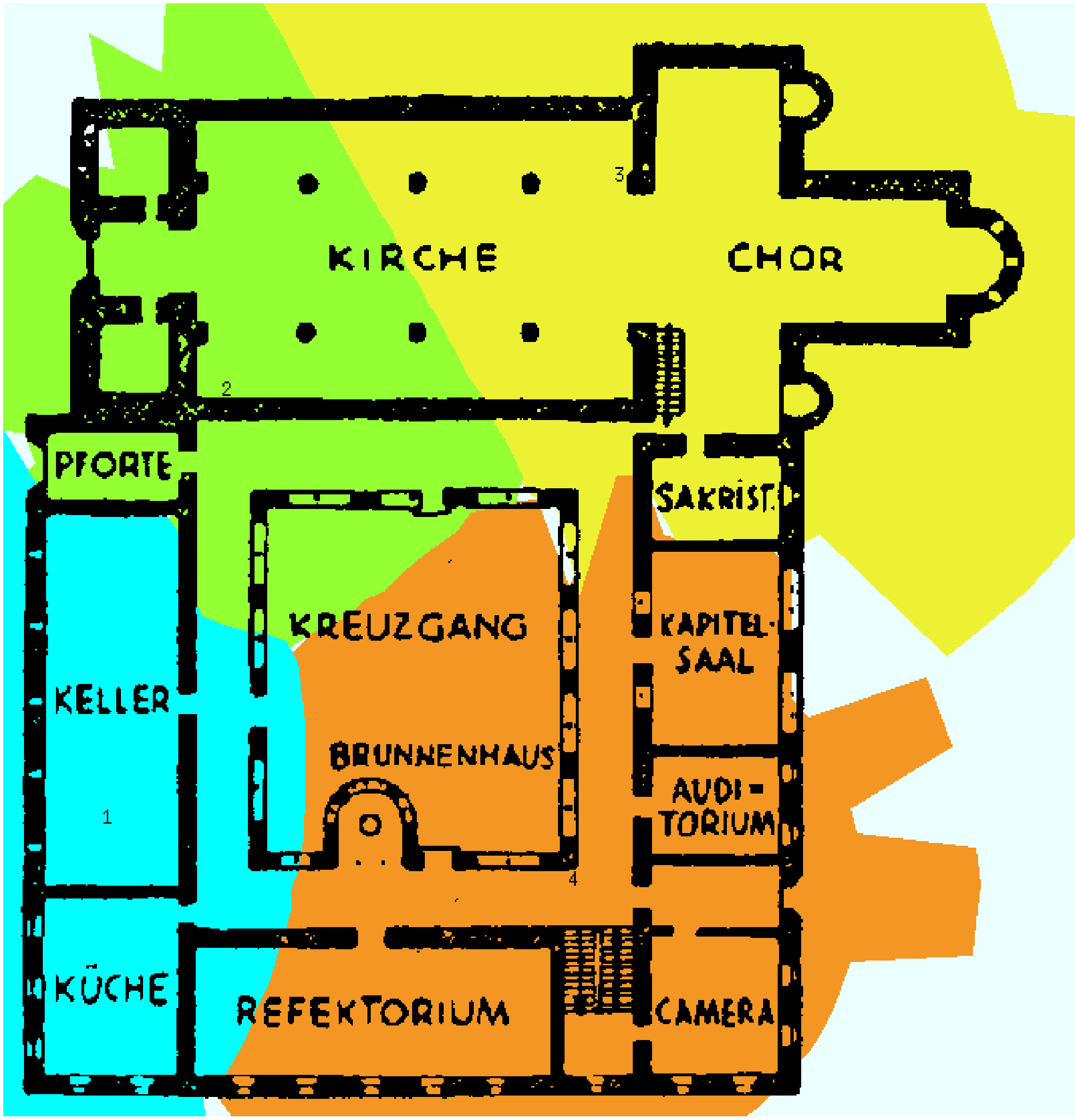
It took just 10 minutes to extend this solver so that it works with union of rectangles, that can describe the cell more accurately - actually to any desired degree of precision. The union corresponds to a disjunctive constraint of the form `inside(S,R1) or inside(S,R2) or ... or inside(S,Rn)` which is more compactly implemented as `inside(S,[R1,R2,...,Rn])`. The subsequent lifting to 3 dimensions just amounted to adding a third coordinate and code analogous to the one for the other dimensions.

To compute a solution, after we have set up all the `in` constraints, we try to equate as many base stations as possible. Equating base stations causes the `intersect` rule to fire with the constraints associated with the base stations.

As a result of this labeling procedure, a base stations location will be constrained more and more and thus the `intersect` rule will be applied again and again until the rectangle becomes very small and finally empty. Then the `not_empty` rule applies, causes failure and so initiates chronological backtracking that will lead to another choice.

A first solution is computed in this way. Next, to minimize the number of base stations, we use a *branch-and-bound method*. It consists in repeatedly searching for a solution with a smaller number of base stations until the minimal number is found.

Complete Coverage of Monastery



Remarks

The result of covering a medieval monastery is shown, where four base stations are needed. If more than one base station covers a region, it is attributed to the base station that provides the strongest signal.

Conclusions

Constraint programming with CHR proved to be

- **rapid:** prototype a few man-months effort.
- **expressive:** everything in CLP - including ray tracing and a graphical user interface.
- **flexible:** from single rectangles to union of rectangles, from 2-D to 3-D within minutes.
- **extensible:** restricting senders to be on walls only - just another constraint on each sender.
- **efficient:** for a typical office building, optimal placement is found within a few minutes.

Remarks

For a typical office building, an optimal placement is found by POPULAR within a few minutes. This is impressive since everything (including ray tracing and a graphical user interface) was implemented in a CLP language. The CLP code is just about 4000 lines with more than half of it for graphics and user interface. The overall quality of the placements produced is comparable to that of a human expert. The precision is influenced by the underlying path loss model with its the fading reserve, the number of rays used in the simulation and the approximation of radio cells by unions of rectangles.

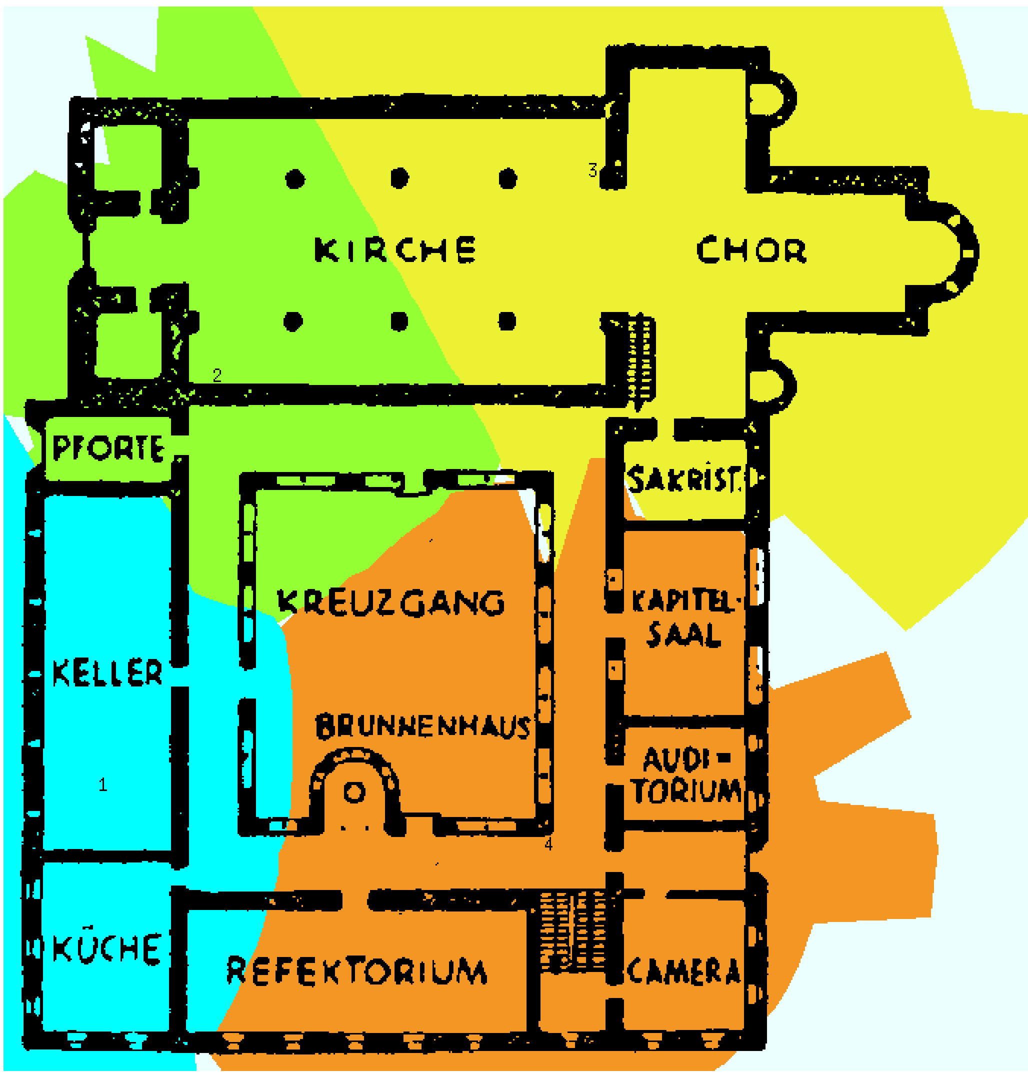
While we worked on POPULAR, without knowing from each other: WiSE uses an adaptation of the Nelder-Mead direct search method that optimizes the percentage of the building covered. About 7500 lines of C++. WiSE has been patented and is in commercial use by Lucent Technologies since 1997 to plan their DEFINITY Wireless Business System - PWT.

Constraint Programming
with Constraint Handling Rules

Optimal Placement of Senders for digital wireless Telecommunication

IEEE Expert Magazine, USA: Best Application in Telecommunications 1996.

Winner Telecom Application Contest of Telecom Italia at CP’98 Conference 1998.



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