ON SELECTING ANTENNA PLACEMENTS IN INDOOR RADIO ENVIRONMENTS

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ABSTRACT

In this work, we introduce an antenna placement algorithm for indoor radio networks. The algorithm aims to minimize the number of antennas required to provide sufficient coverage in an area of interest, minimizing the cost of equipment and installation work. The optimization algorithm exploits a semi-deterministic model for the most dominant radio paths. Each path is in turn determined with the A* path finding algorithm. Both the proposed antenna placement algorithm and the used indoor radio propagation model are evaluated using real measurements, confirming the efficiency of the method.

1. INTRODUCTION

The use of wireless communication for personal and commercial use has grown rapidly over the recent decades. More devices than ever can communicate over radio frequencies and combined with an increasing demand of high quality services, such as streaming high resolution video, a well-planned and optimized network is essential (see, e.g., [1]). However, although substantial efforts have been made to improve outdoor radio networks, it is worth noting that 80% of all mobile usage are within buildings – and the number is expected to reach over 90% in the near future [2]. Radio coverage indoors is usually provided by macro base stations placed outside the buildings. Thus, if the penetration of the radio waves through the building walls is not sufficient, the end user will experience poor services, or, at worst, the use of radio devices will not be feasible. As energy efficient buildings have been introduced to the housing market during recent years, an issue regarding the indoor radio coverage has arisen; good isolation and energy windows have proven to be an efficient damper of radio waves and is a potential threat to indoor coverage. In fact, energy efficient buildings have been found to reject nearly all electromagnetic waves, making it difficult to rely on outdoor antennas to provide good or even descent coverage indoors in such buildings [2–4].

To counter such problems, several indoor network solutions have been developed, such as distributed antenna systems (DAS) and carrier Wi-Fi (see, e.g., [2, 5, 6]). When implementing a Wi-Fi network or a distributed antenna system in large buildings such as shopping malls, apartment buildings, train stations, or office complexes, it is important to plan the network properly to enable good coverage [7–9]. The placement of the antennas are critical in order to optimize the network and therefore an antenna placement algorithm is needed (see e.g. [10–12]). In an existing building, antenna placements are often limited by practical conditions, such as where the wall sockets are located, and by aesthetic considerations. In new buildings, one may instead include antenna placements in the constructions plans, allowing for more freedom in the antenna placements. It may also be noted that a well-planned network will minimize the need for adjustments after it has been set up, further reducing the overall installation costs.

In this work, we present an antenna placement algorithm, such that the expected coverage, given the dominant propagation paths for each antenna to the areas of interest, is above some minimum acceptable level. The network is assumed to be a simulcast DAS or a carrier Wi-Fi network with frequency reuse and automatic channel selection. The proposed algorithm use a greedy search to form the antenna selection, using the length of the propagation path to determine the received signal strength.

2. THE PROPOSED ANTENNA PLACEMENT ALGORITHM

The problem of finding suitable antenna placements is closely related to the sensor selection in a network [13, 14], and may, just as this problem, be formulated as an optimization problem. Let N be the number of target locations and t_j the desired minimum coverage at location $j \in \Omega = \{1, 2, \ldots, N\}$. Furthermore, let M be the number of possible antenna locations. Then, an $M \times N$ prediction matrix may be constructed as

$$\hat{\mathbf{R}} = \begin{pmatrix} \hat{r}_{11} & \hat{r}_{12} & \cdots & \hat{r}_{1N} \\ \hat{r}_{21} & \hat{r}_{22} & \cdots & \hat{r}_{2N} \\ \vdots & \vdots & \ddots & \vdots \\ \hat{r}_{M1} & \hat{r}_{M2} & \cdots & \hat{r}_{MN} \end{pmatrix} \tag{1}$$

where $\hat{r}_{ij}$ denotes the predicted average received signal strength at target location j, given the dominant propagation path from antenna i. Furthermore, let $\mathbf{e}_j$ denote a $N \times 1$ unit vector with all components set to zero, except one at

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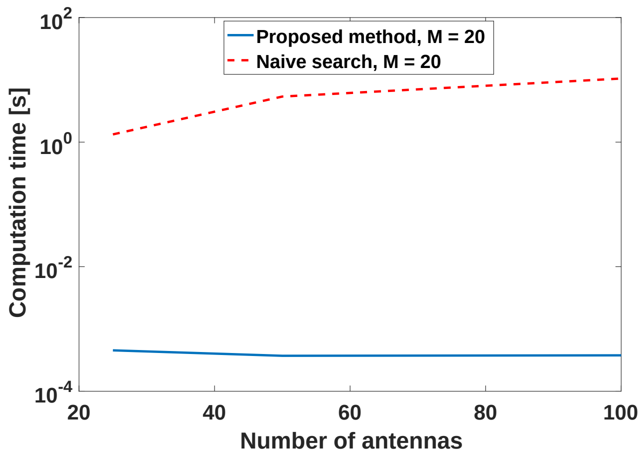


Fig. 1: The run time for the proposed method as compared to a naive search algorithm for different number of antenna positions. Here, the number of target locations is $M = 20$.

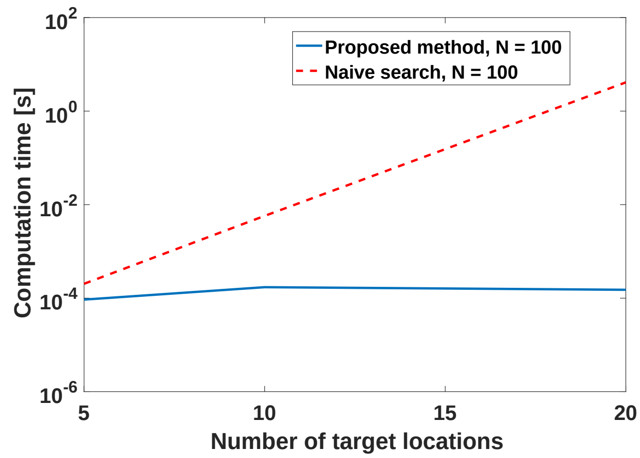


Fig. 2: The run time for the proposed method as compared to a naive search algorithm for different number of target locations. Here, the number of antenna positions is $N = 100$.

place i, which is set to one. Then, $\hat{\mathbf{R}}\mathbf{e}_j$ will be a vector containing all the antenna contributions at target location j. Let $\mathbf{w}$ denote an antenna selection vector with binary components w_j indicating whether an antenna j is selected (1) or not (0). Thus, the optimization problem can be formulated as minimizing the number of active antenna placements, while still retaining a sufficient coverage in all regions of interest, i.e.,

$$\begin{aligned} \mathbf{w}^* = &\arg\min_{\mathbf{w}} ||\mathbf{w}||_0 \\ &\text{s.t.} \quad \|\mathbf{w} \circ \hat{\mathbf{R}}\mathbf{e}_j\|_\infty > t_j \quad \forall j \in \Omega \\ &\mathbf{w} \in \{0,1\}^M \end{aligned} \tag{2}$$

where $\mathbf{a} \circ \mathbf{b}$ denotes a point-wise vector multiplication, here resulting in a vector were the j:th component represents the predicted coverage from antenna j at target i. Furthermore, $\| \cdot \|_\infty$ denotes the infinity norm, defined as the maximum component in the vector, such that

$$||\mathbf{x}||_\infty \triangleq \max(|x_1|, |x_2|, \ldots, |x_n|) \tag{3}$$

for a vector of length n, whereas the ℓ_0-(quasi)norm is defined as the number of non-zero elements in a vector, i.e.,

$$||\mathbf{w}||_0 \triangleq |\{i : w_i \neq 0\}| \tag{4}$$

The minimization thus strives to use as few antennas as possible while ensuring that every target location gets sufficient coverage over the threshold t_j. Note that the formulation above requires the coverage to be expressed in linear scale, as it is necessary that $\hat{r}_{ij} > 0$, for all i and j.

Regrettably, the problem in (2) is combinatorial and involves finding a solution $\mathbf{w}^*$ that fulfills the conditions in (2) out of 2^M possible combinations of $\mathbf{w}$. As a result, the problem becomes infeasible even for a small number of potential antenna placements. However, although there may be many solutions that fulfils the constraints, as we strive to determine only a solution that provides sufficient coverage, it is enough to find a single solution that satisfies the constraints, without this necessarily being the overall best solution. For this reason, we introduce the indicator function $\delta_{t_j}(x)$, such that

$$\delta_{t_j}(x) = \begin{cases} 1, & x \geq t_j \\ 0, & x < t_j \end{cases} \tag{5}$$

This allows the forming of a prediction matrix of the acceptable coverage placements, such that

$$\hat{\mathbf{T}} = \begin{pmatrix} \delta_{t_1}(\hat{r}_{11}) & \delta_{t_2}(\hat{r}_{12}) & \cdots & \delta_{t_N}(\hat{r}_{1N}) \\ \delta_{t_1}(\hat{r}_{21}) & \delta_{t_2}(\hat{r}_{22}) & \cdots & \delta_{t_N}(\hat{r}_{2N}) \\ \vdots & \vdots & \ddots & \vdots \\ \delta_{t_1}(\hat{r}_{M1}) & \delta_{t_2}(\hat{r}_{M2}) & \cdots & \delta_{t_N}(\hat{r}_{MN}) \end{pmatrix} \tag{6}$$

where every element $\hat{\mathbf{T}}_{i,j}$ indicates if a target location j has coverage over the threshold t_j from antenna i. With the transformed matrix, the proposed antenna selection algorithm can be formulated as the minimization problem

$$\begin{aligned} \mathbf{w}^* = &\arg\min_{\mathbf{w}} ||\mathbf{w}||_0 \\ &\text{s.t.} \quad \hat{\mathbf{T}}^T\mathbf{w} \geq \mathbb{1}_N \\ &\mathbf{w} \in \{0,1\}^M \end{aligned} \tag{7}$$

where $\mathbb{1}_N$ is defined as an N length vector of ones. To solve the minimization in (7) only a single feasible solution is required. Here, we therefore propose to solve the problem using

procedure FIND ANTENNA PLACEMENTS
    $i := 1$
    $w := \mathbf{0}_M$
    $V := \emptyset$
    while $\hat{\mathbf{T}}^{(i)} \neq \emptyset$ **do**
        $\mathbf{s} := \mathbb{1}_M^T \hat{\mathbf{T}}^{(i)}$
        if $\mathbf{s}\mathbb{1}_N = 0$ **then return** No solutions exist
        if $s_j = 1$ for any j **then**
            find corresponding row in $\hat{\mathbf{T}}^{(i)}$, denoting it k.
        else
            $\mathbf{p} := \hat{\mathbf{T}}^{(i)} \mathbb{1}_N$
            find largest value in $\mathbf{p}$, denoting its position k.
            if a tie **then**
                select the row in $\hat{\mathbf{R}}^{(i)}$ which maximize a predefined utility function and denote that row k.
        add k to the end of V
        find all targets that antenna k covers and remove them from $\hat{\mathbf{T}}^{(i)}$ and $\hat{\mathbf{R}}^{(i)}$ thus creating $\hat{\mathbf{T}}^{(i+1)}$ and $\hat{\mathbf{R}}^{(i+1)}$.
        i := i +1
    for each $k \in V$ **do**
        $w_k := 1$
    return w

a greedy search algorithm. The resulting algorithm is fast and easy to implement and finds a sufficient solution even if the number of targets and possible antenna location is large. The algorithm starts by summing the columns in $\hat{\mathbf{T}}$ and checks if any of the sums equals to one. This is the equivalent of checking if a target is only covered by a single antenna placement; if that is the case, this placement must be selected. In the opposite case, when all targets can be covered by multiple antennas, the algorithm instead sums the rows in $\hat{\mathbf{T}}$. This is the equivalent of checking how many targets a certain antenna covers. The antenna that covers most targets is selected. If there is a tie, then the antenna that maximizes a predefined utility function is chosen. This function can be adapted to fulfil different requirements. In either case, the selected antenna placement is removed from both the indicator matrix $\hat{\mathbf{T}}$ and the predicted coverage matrix $\hat{\mathbf{R}}$ and the algorithm then starts over again with the new matrices. This continues until all targets are covered. The pseudo code of the algorithm can be found in algorithm 1.

3. EVALUATION

We proceed to evaluate the proposed algorithm using both simulated and measured data. Initially, we compare the proposed method to a naive search algorithm, which searches combinatorially for the smallest set of antennas that fulfils the coverage requirements. It starts with a single antenna and then, gradually, increase the number of used antennas until

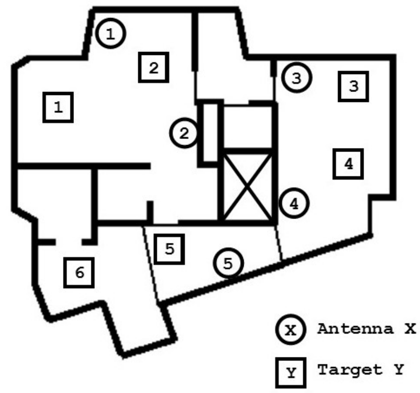


Fig. 3: The test site the antenna selection algorithm was evaluated on. Five possible antenna locations and six locations were good coverage was desired was selected.

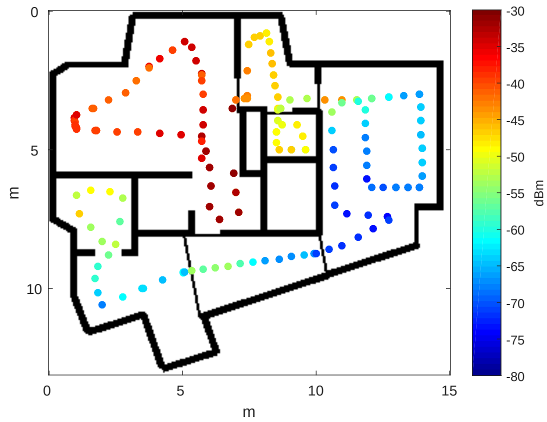
all of the target locations have been covered. This amounts to searching all combinations of antennas at the candidate positions. Figure 1 and 2 show the resulting run time (in logarithmic scale) for the proposed method and the native search algorithm, for different values of number of antenna positions, M, and number of target locations, N. As is clear from the figures the proposed method outperforms the naive search algorithm, especially when N and M increase. It is worth noting that both methods will find a solution, as long as one exists.

To test the antenna selection algorithm on real data, five possible locations to mount antennas and six locations where good coverage is important were selected at a test site, as shown in figure 3. It was decided that the desired coverage on any location would at least exceed -70 dBm for a given Wi-Fi network. To evaluate which antenna combinations that fulfils the desired coverage, one access point was placed at one of the possible antenna locations and measurements were performed. Then, the access point was moved to next location and new measurements were taken. The same procedure was carried out using two access points that were varied over all possible combinations. Three or more access points were never evaluated since several alternatives with two access points were enough to provide coverage. The different antenna alternatives and the antennas they correspond to can be seen in Table 1 along with the measurements collected.

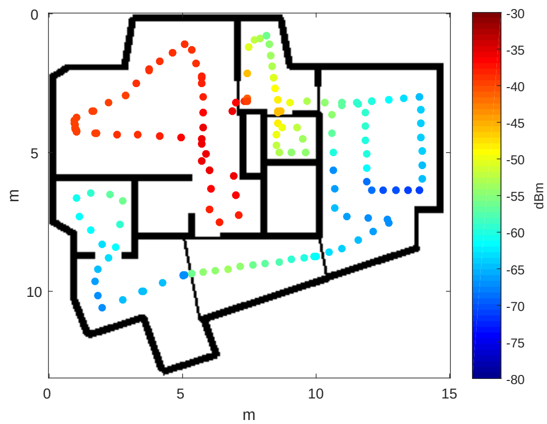
In order to rank the antenna alternatives, the following utility function was used

$$u_i = \prod_{j \in \Omega} \delta_{t_j}(r_j) \sum_{j \in \Omega} (r_j - t_j) \tag{8}$$

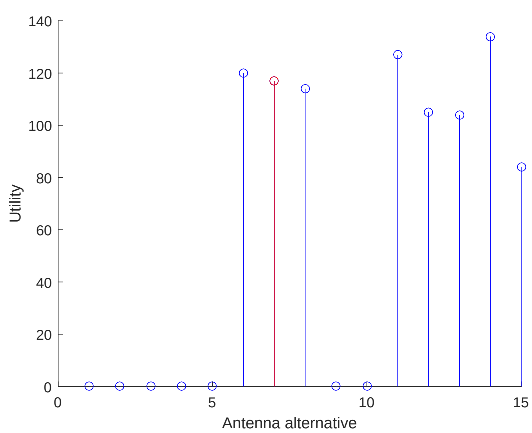
where u_j is the utility of antenna alternative j and N is the number of locations where coverage is important. The utility function sums the excess coverage over the threshold for every target, and if any target does not meet the threshold, the



(a)



(b)



(c)

Fig. 4: The figures in (a) and (b) show the predictions at a test site using the dominant path model with two slopes. One slope for line-of-sight and another for non-line-of-sight propagation. The paths were retrieved using the A* search algorithm. Figure (a) depicts the measurements and (b) the predicted values. The figure in (c) show the utilities for the antenna alternatives in Table 1. The red alternative is the one selected by the greedy search antenna algorithm using the dual-slope dominant path model for predictions.

Index	Antennas	$\mathbf{p}_1$	$\mathbf{p}_2$	$\mathbf{p}_3$	$\mathbf{p}_4$	$\mathbf{p}_5$	$\mathbf{p}_6$
1	1	-44	-40	-66	-73	-70	-62
2	2	-44	-38	-63	-74	-56	-68
3	3	-64	-58	-40	-43	-71	-78
4	4	-74	-69	-45	-42	-67	-78
5	5	-72	-70	-70	-61	-45	-53
6	1 & 5	-45	-43	-60	-60	-40	-52
7	2 & 5	-46	-40	-65	-57	-40	-55
8	3 & 5	-63	-55	-40	-49	-37	-62
9	4 & 5	-77	-74	-43	-40	-40	-57
10	3 & 4	-62	-53	-40	-40	-63	-70
11	2 & 4	-46	-40	-50	-39	-57	-61
12	1 & 4	-49	-41	-47	-47	-65	-66
13	1 & 3	-49	-39	-44	-49	-68	-67
14	2 & 3	-41	-46	-43	-40	-56	-60
15	1 & 2	-43	-38	-57	-69	-65	-64

Table 1: Different antenna alternatives and their corresponding measured received signal strength in six different target locations at the test site. The measurement unit is dBm.

utility is set to zero.

The different alternatives and their corresponding utility are plotted in figure 4c. It can be seen that antenna alternative number 14 is the one that maximizes the utility function. However, the alternatives 6-8, as well as 11-15, are fulfilling the coverage requirement. Predictions were made using the semi-deterministic dominant path model [15] and the dominant paths were retrieved using the A* path finding algorithm [16]. The attenuation of the signal can be influenced in varying degrees depending on if the propagation occurs in line-of-sight (LOS) or in non-line-of-sight (NLOS) [17]. It has been shown that the signal may decay differently in a NLOS scenario as compared to a LOS scenario [18]. To further improve the model, two attenuation slopes were used, which were retrieved by probe measuring the area of interest. The path loss exponents were estimated using the ordinary least square method. Figure 4(a)-(b) illustrate the prediction ability of the used radio path model. As can be seen from the figures, the model is well able to predict the measured gain. The optimization algorithm chooses antenna alternative number 7, marked in red in Figure 4c. This alternative fulfils the desired minimum coverage at -70 dBm on all locations.

4. CONCLUSIONS

In this work, we have introduced a greedy search algorithm for determining antenna placements yielding sufficient coverage in given areas of interest. The algorithm uses the length of the propagation path to determine the expected signal strength. The algorithm is evaluated using simulations, as compared to a naive placement algorithm, as well as using actual measured data.

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