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Published in:
Proceedings of the 8th ACM workshop on Performance monitoring and measurement of heterogeneous wireless and wired networks

DOI (link to publication from Publisher):
10.1145/2512840.2512854

Publication date:
2013

Document Version
Early version, also known as pre-print

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ABSTRACT

In connection with the extension of the Copenhagen Metro system, architects and wireless operators met early in the design phase to plan the radio coverage inside the public areas of the metro transport system. Based on common best practice, an initial design for the antenna installations, and hence radio coverage, was proposed for a distributed antenna system in each of two distinctly different types of underground stations. In this paper, we describe the considerations for the design, and specifically the modelling and analysis of the underground stations by way of a commercial ray-tracing tool. Radio coverage results are given for different designs, including different number and types of antennas, their configuration and placement, as well as the dependency on frequency and construction materials and presence of trains on the station platforms. In a practical case like this, compromises between stakeholders impact to the design and in some cases rule out options with better, more uniform, radio coverage. Also, given the constraints of the problem, common best practice leads to a conservative design. It shows a good margin for uncertainties and unaccounted propagation phenomena by an analytical comparison.

Categories and Subject Descriptors

C.1.3 [**Other Architecture Styles**]: Cellular architecture; C.2.1 [**Network Architecture and Design**]: Wireless Communication

Keywords

metro transport system; underground station; simulcast coverage; distributed antenna system; ray tracing

1. INTRODUCTION

By 2018, the Copenhagen Metro system will have been extended with 17 new stations in what is known as the City Ring [1]. The 17 stations will be part of a fully underground tunnel ring to link the so-called Bridge Quarters of the city with the city centre. Construction work started already in 2009 and has progressed up to the stage where actual construction of the stations has begun. In connection with this, architects and wireless operators met with the client consultant advising on the radio and telecommunications design of the metro to ensure that all necessary installations required for radio coverage were properly accounted for in the construction phase. In the discussion different coverage solutions were discussed as to their technical, architectural, and practical characteristics. From these discussions, an initial design was made by experienced radio frequency engineers in the operators planning department, outlining possible radio coverage solutions. A great deal of impiricism is involved in deriving the solutions, from the trials and errors of experience, as well as specialised knowledge about radio frequency propagation. Taken together, such approach generally establishes a common best practice for design of indoor radio systems, e.g. as outlined in [9].

The radio system design needs to consider both the link budget, to determine maximum path loss (or receive thresholds), and the offered capacity. An example of such design considerations for a CDMA based distributed antenna system is given in [4], and for a specific case study of the Rio de Janeiro metro in [8]. For the City Ring system, the detailed radio system design has not yet been completed as it awaits final capacity predictions and choice of radio technology solutions closer to actual operation. Instead, in this paper our aim is to discuss the modelling and analysis of the initial radio coverage design by way of a commercial ray-tracing tool. The study of propagation conditions and coverage solutions for tunnel environments have been studied in several previous publications, e.g. [6], [11] and [2], whereas not much attention has been given to understand the radio coverage of underground stations. Initially, our investigations were to confirm the operators in their design decisions with respect to radio coverage, however, on a more overall level we want to show how designs based on common best practice compare to analytical investigation using state-of-the-art ray-tracing methods, so as to better understand the former. Common best practice needs to be conservative due to the uncertainties involved, but how much margin is actually included? Another aim is to show that in practice, despite better technical solutions, there are compromises to be made in actual realisations. Since our methodology is to use ray-tracing prediction, it is important to understand how different prediction methods influence to the results,

PM2HW2N'13, November 3–8, 2013, Barcelona, Spain.

http://dx.doi.org/10.1145/2512840.2512854 .

and more importantly, how the model impacts. Generally, one drawback of ray-tracing analysis is the uncertainty on the electromagnetic properties of the complex materials that make up real physical structures, as well as the accuracy of the geometrical model used for analysis [7]. To some extent we are fortunate that the structures here are "simple" compared to other environments, but besides, we have taken great care about the details of the geometrical model as will be shown later.

We will discuss the overall design consideration in the following Section 2 and detail our modelling of the two underground stations that we have analysed in Section 3. In Section 4 we analyse the ray-tracing model applied in the predictions, as well as the influence of different material parameters. Based on this we select a computationally fast ray-tracing model for analysing the different configurations in Section 5, but we also include here a more detailed analysis of the impact from trains on the platforms using a traditional ray-tracing model. Finally, in Section 6 we summarise the overall observations from the study.

2. SYSTEM DESIGN CONSIDERATIONS

The design for the Copenhagen metro targets operation in the 800-900MHz and 1710-2200 MHz frequency range, and potentially even higher to include the LTE band at 2600 MHz. The overall design relies on having all RF equipment maintained in a central facility room, common to all operators serving the metro. The RF signal is distributed from the central location by radio-over-fibre and terminated at the stations in local facility rooms. Back in the analogue electrical domain, the RF signal is distributed passively throughout the station, primarily using a distributed antenna system design based on tappers, splitters and discrete antennas (Chapter 13 in [4]). A parallel connection from the central facility carries the RF signal intended for the underground tunnels, but here the passive distribution is taken care of using leaky feeder cables emanating out from the stations and into the tunnel. This design is intended to minimize, if not avoid altogether, the placement of active RF equipment inside the tunnels where access requires coordination with the metro service and consequently long service delays.

Good coverage for high data rate wireless services would be expected inside the stations, besides the specific need for good and seamless voice service coverage between the stations, tunnels and outdoor wireless systems. Also uniform, or at least sufficient, coverage throughout the station is a requirement, and the best server should be provided by the distributed antenna system inside and not by an outdoor base station. For the City Ring system, the initial assumption has been to serve each station on a single base station sector, or cell, with approximately the same output power level available on each distributed antenna element; a typically applied value of 0 dBm per antenna was used as a design target. Potentially, more cells (carriers) on the same sector can be used to balance capacity according to need. Stations, tunnels and ground level (outdoor) systems will operate on different base station sectors (cells), which requires special attention to handover zones at the concourse level which connects to ground level and the platform level which connects to the tunnel. The platform is particularly troublesome since when metro trains are merely passing through the station all users should ideally stay connected on their respective system - tunnel for train passengers and station for travellers on the platform.

Based on their experience, operators are generally concerned about the impact from construction materials close to the antennas. E.g. for architectural and counter-vandalism reasons it might be convenient to place antennas above dropped ceiling tiles. From experience, however, there is a risk that the space next to the antenna eventually gets cluttered with ventilation ducts, cable traces, piping, etc. due to misunderstandings between project partners in the planning phase, practical restrictions that lead to deviations from installation instructions, or later additions and updates to the station installations. Also, material specifications for the dropped ceiling tiles, and materials in general, can deviate between the planning and actual implementation phase, if altogether characterised for radio frequency properties.

Given all these considerations, several options discussed as part of the initial design, including different number of antennas, antenna positions, antenna directivity and the use of leaky feeders also for station coverage, were analysed with respect to the radio coverage and used to support the operators in fixing the design for the stations.

3. ENVIRONMENT - DESCRIPTION OF THE MODEL

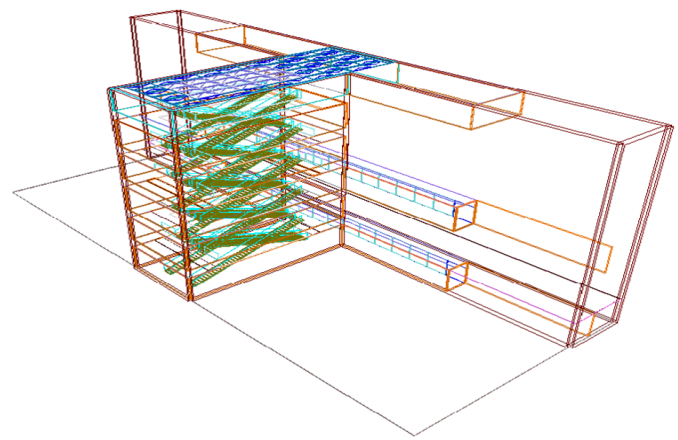

Figure 1: Large underground station vector database. Note that the tunnel sections next to the upper and lower platforms are not shown.

The 17 stations that constitute the new Copenhagen Metro system include two standard types of stations, both with two floors - concourse and platform. Some of them connect the two floors with one escalator section, whereas the others include two escalator sections with an intermediate rest level at middle height. The latter is the case for "Nørrebros Runddel", which was selected for the analysis due to this more challenging coverage situation. Also, the City Ring contains a unique underground station called Marmorkirken. It is placed under Frederik's Church in the centre of Copenhagen, where up to 10.000 passengers are expected during weekdays [1]. Due to concerns of structural damage, the Marmorkirken station is being built as a deep six floor underground station with metro trains passing well below the church. In the following, we will refer to Marmorkirken as

"large station" and "Nørrebros Runddel" as "standard station". The stations are substantially different in layout and therefore give rise to different constraints on the radio coverage. To facilitate the ray-tracing study, the stations were described in a detailed vector database in which we modelled the structure of the outer shell of the underground station, the internal partitions (concrete decks and platforms, glass separations), wall claddings, dropped ceilings and escalator structures. Further, for part of the study, the tunnels were modelled with rectangular tube sections extending out from the station.

3.1 Description of the large underground station

The six levels that characterize this station are the concourse, three intermediate levels and two platforms. Figure 1 shows the vector database used in the simulations (Figure 4 shows the corresponding cross-sectional view). The description of the model is as follows: the concourse connects the outdoor area with the station; going down through the escalators, it is possible to arrive at intermediate levels 1 and 2; the upper platform is placed right after intermediate level 2; finally, through intermediate level 3 we arrive at the lower platform. All levels are connected by escalator sections.

The concourse level is 3 meters high whereas the remaining levels are 4.7 meters high. The area of the central part containing the escalator sections is 240 m^2 and the platform (corridor) next to the trains is 44 by 3.5 m. Both platforms are separated from the trains by sliding doors made of safety glass. Regarding the type of material, the walls are composed of thick reinforced concrete covered with 37 mm brick cladding on standoffs. The ceilings are constructed in a combination of partly aluminium lamellas and slabs, and partly mineral wool plates. The escalators are stainless steel constructions with safety glass used for the balustrades and outer cladding on the sides. We will discuss the materials further in connection with Tables 1, 2 and 3. In Section 5 the lower platform level and the central part of the station are studied in terms of received power. In the central part, different antenna configurations are analysed.

3.2 Description of the standard underground station

In Figure 2, the vector database of the standard station is presented. This underground station consists of two levels connected by two escalator sections with their corresponding rest levels at middle height. Concourse level gives access to the station from outside, and by using the escalators it is possible to arrive at the platform level where trains are leaving in opposite direction from the sides of the platform. The standard station has a very regular shape with overall dimensions of 44 by 7.5 meters.

The composition of materials is much the same as for the large station, however, besides the mineral wool, the ceiling in the central part of the concourse level has a geometrically complex sky roof construction with glass and concrete slabs at an angle to one another. The structure is partly visible in Figure 2. In Section 5, the received power is studied at the concourse level to see the effect from hiding antennas above the mineral wool ceiling.

Also, on the platform level, we investigate the effect from different antenna configurations and the presence of trains on the platforms.

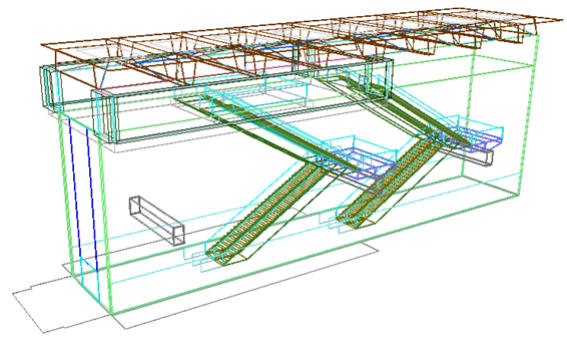

Figure 2: Standard metro station vector database. Note that the tunnel sections on either side of the platform are not shown.

4. PROPAGATION MODELLING

During the last years, different approaches have been studied in order to obtain precise and fast propagation models for predicting indoor radio propagation. Two different propagation models are used in the received power predictions in this paper: Intelligent Ray Tracing (IRT) and Dominant Path Model (DPM). IRT belongs to the ray-optical propagation models where hundred of rays are considered for each receiver location. This usually results in high computation times, but IRT takes advantage of a smart preprocessing of the 3D vector database [7]. To further reduce the computation time, DPM was proposed [10]. As in most of the cases more than 95 percent of the energy arriving at the receiver is provided by only two or three rays, even the dominant ray would be sufficient to obtain a good prediction. The DPM calculates the received power based on empirically determined values for transmission, reflection (waveguiding) and diffraction losses, whereas in the IRT model the use of Fresnel coefficients is recommended [10]. For our investigations we estimated the material parameters from the range of values provided with the ray-tracing tool[1]. The most important empirical parameters used for the DPM model at the investigated frequency of 870 MHz are listed in Table 1 and Table 2, and the corresponding intrinsic parameters in Table 3 for the IRT. The DPM parameters for diffraction loss refer to a specific diffraction model implemented in the tool [5], in which the loss is calculated in dependence of the angle of incidence and the diffracted angle. The total diffraction loss can vary in the range from 6 dB up to "Incident min" + "Diffracted" (Table 2). The parameters will change for the higher frequency of 2140 MHz we also investigated, especially the material conductivity and transmission loss, but most will stay approximately the same. The parameters should generally be considered as characteristic (frequency) average values for the properties of the complex physical materials and structures that make up the metro station. In reality, many materials exhibit a complicated behaviour in dependence of their actual composition, moistore and agent content, thichness, etc., and therefore also considerable variation with frequency. For instance, in [3] the authors investigated different compositions of reinforced concrete. The general observation was that reinforced concrete is reflective to electromagnetic waves below approximately 1 GHz, but

[1]from AWE Communications

shows considerable variation in reflection coefficient above 1 GHz. In the metro station, most concrete walls are covered by brick or glass cladding mounted on standoffs, which will tend to make the walls more "absorptive" due to the added transmission loss of the cladding.

Table 1: Transmission and Reflection Loss. Empirical parameters used in DPM predictions - 870 MHz

Material Name	Transmision Loss(dB)	Reflection Loss(dB)
Stainless Steel	350	0.05
Granite	2	10
Concrete	3.5	9
Aluminium	350	0.05
Glass	1.7	7.53
Brick Cladding	1	10
Mineral wool	0.5	17

Table 2: Diffraction Loss. Empirical parameters used in DPM predictions - 870 MHz

Diffraction Loss			
Material Name	Incident min (dB)	Incident max (dB)	Diffracted (dB)
Stainless Steel	12	36	12
Granite	12	36	12
Concrete	12	36	12
Aluminium	12	36	12
Glass	12	35	11
Brick Cladding	12	36	12
Mineral wool	9	33	15

Table 3: Fresnel parameters used in IRT predictions - 870 MHz

Material Name	Rel.Permittivity	Rel.Permeability	Conductivity(S/m)
Stainless Steel	1	30	5000
Granite	5	1	10^{-4}
Concrete	4.5	1	0.01
Aluminium	1	1	10000
Glass	2.5	1	10^{-4}
Brick Cladd.	4	1	10^{-6}
Mineral wool	2	1	10^{-6}

The most significant impact to the prediction results will come from using either IRT or DPM. To see the difference in prediction, we performed a simulation at the frequency of 2140 MHz in the lower platform corridor next to the tunnel of the large underground station. The prediction layer, at a height of 1.5 meters above the floor, and the omni-directional antennas mounted in the dropped ceiling are visible in Figure 3. In terms of computation time, the DPM simulation takes less than 1 minute, in comparison to 20 minutes for the IRT on a high-end laptop. The results provided by the IRT model show a mean received power of -33.5 dBm, whereas in the case of DPM the mean received power is 7 dB lower at -40.5 dBm. This is generally consistent with the fact that the dominant path carries less energy than the full incoming field. In reference [10] a number of different buildings were studied and compared between DPM, IRT and measurements. Here it was observed that DPM generally predicts lower power levels, and predictions that are in better agreement with measurements - in part because the empirical parameters are easier to calibrate with the effects produced by real complex materials and structures. For our purposes, the more pessimistic and faster prediction provided by the DPM model is preferred over the IRT, except when the detailed ray path information is needed to give representative results.

5. COVERAGE ANALYSIS / RESULTS

The following subsections report the simulated results for the two different underground stations. In the large underground station we compare several antenna configurations with respect to the number and configuration of antennas. In the standard underground station, three types of antenna configurations are the object of study: placing antennas above or below the dropped ceiling at the concourse level, using omni versus directional antennas at the platform level, and using leaky feeders to complement the coverage from the discrete distributed antennas. All the options arose as a result of discussions between the operators, client consultant and architects.

5.1 Antenna configuration analysis in the large underground station

In order to study the optimization of the number of antennas, different lay-outs can be considered. Three different configurations are analysed in the presented vector database model: the full antenna configuration, including in total 22 omni-directional antennas (Kathrein, linear-polarised type 80010249) in the central part of the station; a second configuration containing 16 antennas, where we leave out two antennas in the intermediate level 1, lower and upper platform levels; and finally, a minimal configuration interleaving antennas in-between floors as suggested in [9]. The details about the number of antennas in each level is shown in Table 4. Figure 3 shows the full antenna configuration, including the 22 antennas in the central part mentioned above, and additionally the 3 antennas in each of the platform corridors and the 6 antennas that are in the main concourse area.

In the following results, only the central part of the station is analysed, predicting the received power samples every $1 \times 1\ m^2$ pixel at a height of 1.5 m above the floor of each of the six levels: Counting from above in Figure 4 they are concourse, intermediate level 1, intermediate level 2, upper platform, intermediate level 3 and lower platform. The received power has been predicted at two frequencies, 870 and 2140 MHz, for an output power level of 0 dBm on each distributed antenna element.

Figure 5 shows the sample cumulative distribution function (CDF) of the predictions over the central part at 870 MHz.

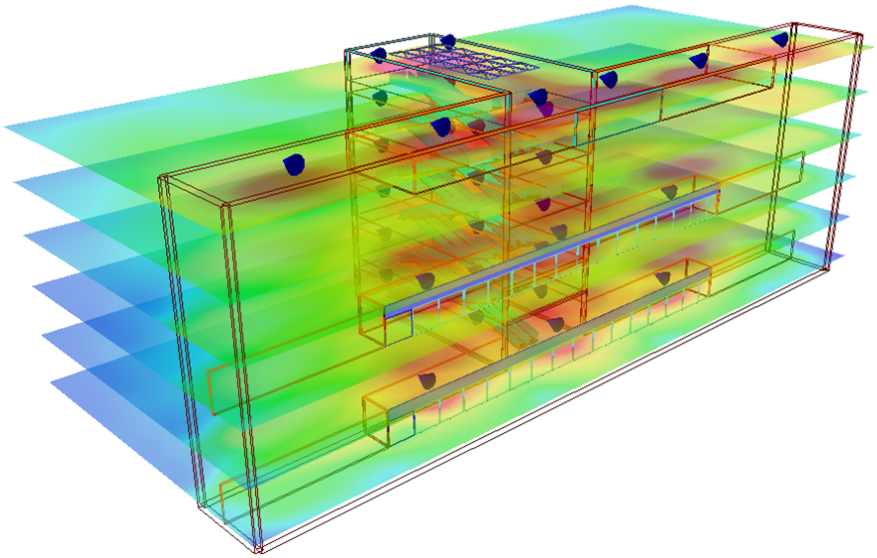

Figure 3: The six prediction layers in the large underground station, 1.5 meters above the corresponding floor.

Table 4: Description of the three antenna configurations

Antenna Config.	Lower Platf.	Intermed. level 3	Upper Platf.	Intermed. level 2	Intermed. level 1	Concourse level
10 Ant.	0	4	0	4	0	2
16 Ant.	2	4	2	4	2	2
22 Ant.	4	4	4	4	4	2

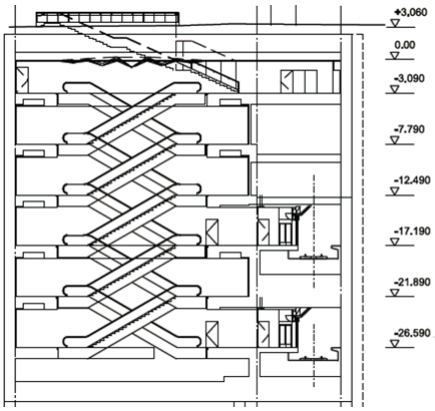

Figure 4: Cross-sectional view of the large station, showing the six levels.

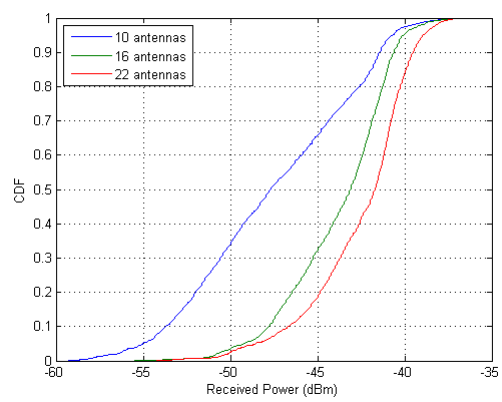

Figure 5: Coverage predictions in the central part of the station for the three different antenna configurations (870 MHz).

There is no big difference in using 16 or 22 antennas, since at the platform level coverage will also be provided by the antennas in the corridors next to the tunnels and we can therefore do with less antennas in the corresponding central part. Reducing the number of antennas even further, to only 10 antennas, leads to much less uniform coverage on the other hand.

Figure 6 shows more detail by collecting the results only for the lower platform and intermediate level 3, respectively; in the former case, the number of antennas change, whereas for the latter there is no change (Table 4). At the platform level, without antennas in the central part the power level drops overall by approximately 10 dB compared to the full 22 antenna configuration. The same change has only but a small, within 3 dB, impact to intermediate level 3.

From Figure 5 and Figure 6 we can conclude that changing from 22 to 16 antennas implies basically just a small reduction of the mean level in the overall distribution of received power, whereas the change to 10 antennas changes the distribution overall; specifically the impact to the minimum level would be of concern.

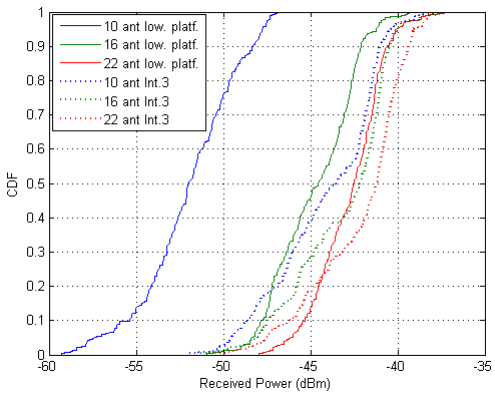

Figure 6: Coverage predictions in the central part: (solid lines) lower platform and (dashed lines) intermediate level 3 (870 MHz).

Tables 5, 6 and 7 summarise the statistics for the two frequencies. The decrease with frequency is about 12 dB in the mean from 870 MHz to 2140 MHz, but the distribution of received power around the mean remains essentially unchanged, with the exception of the minimum value (-75.4 dBm) in Table 6. Whereas the 12 dB decrease is mainly due to the increased free space coupling loss (about 8 dB), the relatively lower minimum level with small number of antennas seems to suggest additional shadowing effects at the higher frequency. This would be of concern going to even higher frecuency, e.g. the 2600 MHz LTE Band.

Table 5: Summary of received power (dBm) in the central part of the station at 870 MHz

Antenna Configurations	Min. Value	Max. Value	Mean Value
10 Ant	-59.3	-36.4	-45.3
16 Ant	-55.5	-36.4	-43
22 Ant	-54.2	-36.3	-41.8

Table 6: Summary of received power (dBm) in the central part of the station at 2140 MHz

Antenna Configurations	Min. Value	Max. Value	Mean Value
10 Ant	-75.4	-46.6	-57.1
16 Ant	-67.2	-46.2	-54.5
22 Ant	-66.2	-45.3	-53

Table 7: Summary of the mean received power (dBm) in the central part of the station at 870 MHz and 2140 MHz

Antenna Configurations	870 MHz	2140 MHz
10 Ant	-45.3	-57.1
16 Ant	-43	-54.5
22 Ant	-41.8	-53

5.2 Use of Leaky Feeders in the standard underground station

Due to the architects concern for installing visible antennas (see Section 5.4), the operators looked into a solution with radiating cables running vertically at each end of the standard station (Figure 2) so as to cover the escalator and the rest levels at middle height. In the following simulations, two leaky feeders (coaxial cables with periodic apertures) were placed at each end with a horizontal separation of 3 m and running vertically from the platform floor and 13 m up to the ceiling. Each leaky feeder was fed with 0 dBm transmit power at one end of the cable. The feeders are characterised by a longitudinal attenuation of 7.3 dB/100 m and a coupling loss of 78 dB, specified at a coupling distance of 2 m, at the frequency of 870 MHz used in the analysis.

Figure 7 shows the received power predicted at a height corresponding to 1.5 m above the resting levels of the escalator sections. We can observe low levels of received power, in the range from -100 to -60 dBm with a mean value of approximately -80 dBm. Due to the coupling loss, the power level is low already close to the feeder, but decreases only in inverse proportion to distance from the cable (cylindrical wave). In the area of interest, the resting levels, the level is around -80 dBm for the center rest level and higher for the one on the right due to the proximity to the wall. The white parts are areas with very low coverage, e.g. the areas occupied by the escalators. The operators' design target for the minimum received mean power is typically in the range from -75 to -80 dBm.This will allow for unaccounted fading effects, e.g. shadowing due to the detailed structure of the station and the presence of people. Since the leaky feeders produce mean levels on that same range, they are of little use. This is because they do not leave implementation margin and generally produce much lower power levels than using discrete antennas (see Section 5.4).

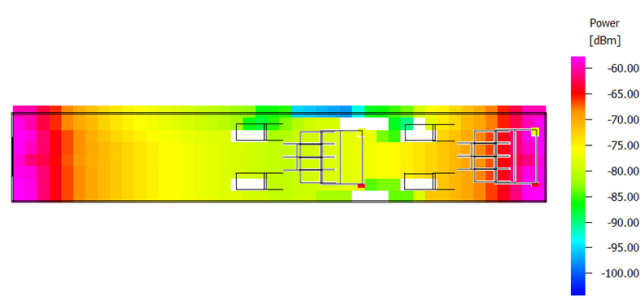

Figure 7: Coverage prediction with leaky feeders (rest level at 870 MHz).

5.3 Visible and hidden antenna placement in the ceiling of the standard underground station

In this section, the impact of hiding the antennas above the suspended ceiling is studied. The design for the standard station uses four omni-directional antennas at the concourse level, placed in the part of the ceiling with mineral wool plates and just next to the escalator sections. This gives the option to place antennas either visible, below the mineral wool, or invisible above in the space containing installations for mains power, ventilation, etc. When placed below, the antennas are in visual sight of one another, whereas when above, they are screened from each other by large concrete beams running across the ceiling. From simulations at the frequency of 870 MHz, using the same settings as before, the predictions at a height of 1.5 m above the floor of the concourse level show that the mean level changes by approximately 7 dB from -41.5 dBm when antennas are visible to -48.5 dBm when antennas are 0.5 m above the dropped ceiling. The main effect however, is that the coverage becomes more uniform when antennas are placed above and the dominance of each antenna improves. In a simulcasting distributed antenna system, the total mean received power is usually taken as the power sum of the contributions produced by the individual elements (the principle applied in our simulations). When the antennas are visible to each other, there are large areas of the concourse level in which the total power level is high, but no single antenna produces a signal that dominates. This may cause artificial fading effects that need to be considered. On the other hand, operators would generally have concerns in placing antennas in the space above the dropped ceiling tiles due to the uncertainty on the exact electromagnetic properties of the ceiling tiles and the potential presence of large metallic structures next to the antennas.

5.4 Comparison between omni and directional antennas in the standard underground station

One of the options that arose in connection with the coverage of the standard station was the use of omni-directional antennas in combination with leaky feeders: Omni-directional antennas mounted underneath the three concrete beams seen in Figure 2 would provide good coverage of the platform and the leaky feeders coverage of the escalator sections. As already shown, the leaky feeder solution was of little use, and the architects had concerns about visible antennas. They much preferred antennas placed behind the ventilation panels above the glass-doors that give access to the trains. In this section, we compare the coverage of the platform between omni antennas (Kathrein, linear-polarised type 80010249) mounted at a height of 4 m and centered underneath the three concrete beams (two of the them supporting the resting levels), and directional antennas (Kathrein, cross-polarised type 80010465) pointing to the center of the platform floor at 2.8 m height and placed in the ventilation panels. Three directional antennas are used: two on one side at opposite ends of the platform, and a third with center position on the other side. All antennas are supplied with 0 dBm transmit power. Figure 8 (solid lines) shows the received power predicted at a height of 1.5 m above the platform floor at a frequency of 870 MHz, with Figure 9 giving an additional interpretation of the result for the directional antennas. The omni-directional antennas give rise to very uniform coverage, but as explained in Section 5.3 also with less dominance from the individual antennas. The mean received power is lower for the omni's by approximately 7 dB relative to the directional antennas, but the mean level of -45.5 dBm still leaves a large margin to cover uncertainties in the predictions. One of the structures that could cause some uncertainty in the predictions is the large stainless steel construction of the escalators. The dashed curves in Figure 8 divides the samples between those in the location of the escalators (red dashed curve to the left) and those in the remaining part of the platform (green dashed curve to the right). Indeed, the predicted samples in the area of the escalators present the critical part of the overall distribution, signifying the impact of the large metallic structure.

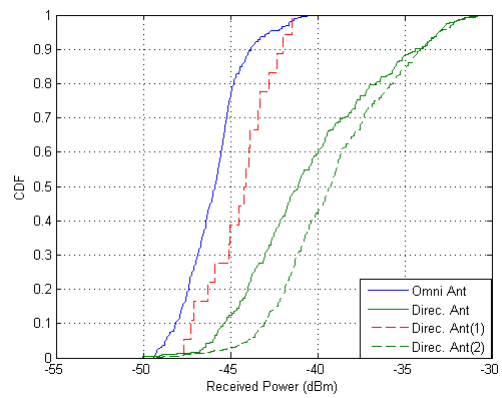

Figure 8: Coverage predictions 1.5 m above the floor of the platform in the standard station (870 MHz); see the text for details about the legends.

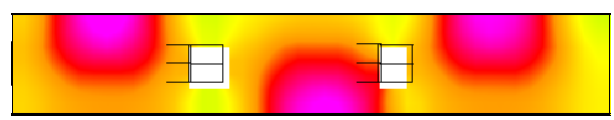

Figure 9: Coverage prediction with directional antennas (platform level at 870 MHz).

While the directional antennas might be preferred due to architectural considerations, the omni's have the advantage of the more uniform coverage and the reduced direct illumination of the tunnel sections. The latter is an issue when trying to define the handover zone between the cells belonging to tunnel and station; the handover zone must be well-defined with a clear distinction between the two adjacent cells [9].

5.5 Coverage analysis with trains on the platform

When trains are present on the station they might have a small impact to the coverage. Also, in relation to the handover zone, it is of interest to see how well the signal from the distributed antenna system on the station is received inside the trains, and the tunnel in general. The following results illustrate the case, using now the more computation-

ally complex IRT model to include the effects from the composite aluminium and glass structure of the metro train and the waveguiding effect in the tunnel.

Figure 10 shows the predictions at a height of 1.5 m in the area of the tunnel normally occupied by the trains. Directional antennas, as discussed in the previous section, are used on the platform at an output power level of 0 dBm and frequency of 870 MHz. Irrespective of the presence of the train there is a high level inside the tunnel section, and only a small reduction when the train is present. In our model of the train we reflected the open (large window) construction that is typical of modern metro trains, and therefore the signal penetration is quite strong, subject to the properties of the glass we have assumed (Section 4).

Due to waveguiding, the signal from the station can propagate well inside the tunnel sections. Considering the first 40 m of the tunnel we can determine a distance dependent path loss exponent of approximately 1.3, thus demonstrating propagation attenuation below free space. This is corroborated by other studies that present an exponent of 1.6 and 1 ([6] and [11], respectively) in tunnels at 900 MHz.

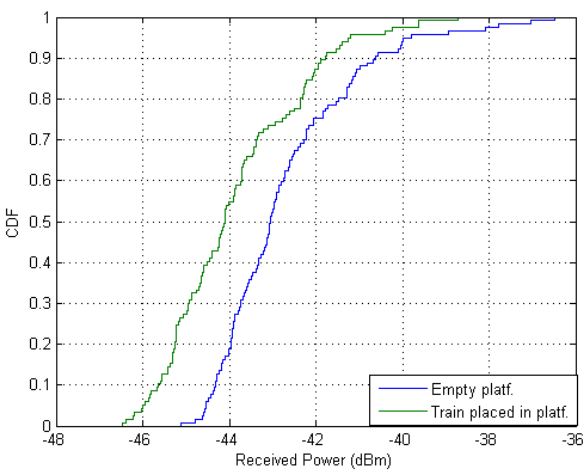

Figure 10: Coverage predictions in the area occupied by the train at a height of 1.5 m above the train floor (870 MHz).

6. CONCLUSIONS

The design of installations for radio coverage in public areas is dominated not only by technical issues, but also a range of other more practical considerations. In this paper we have analysed a design for the radio coverage inside two different stations of the new Copenhagen Metro system, due to commence operation in 2018. Based on a common best practice design, agreed between architects, wireless operators and the client consultant advising on the radio and telecommunications design of the metro, we analysed different antenna configurations and placement of antennas using a commercial ray-tracing tool. Detailed modelling of the two stations was done and the impact of construction materials and ray-tracing models were analysed.

All of the investigated design options, but the leaky feeders, provide very good coverage inside the stations, and most of them leave a good margin of some 10-20 dB for uncertainties in the modelling (geometrical structure and material characteristics) and unaccounted propagation phenomena (fading). The final design will depend on compromises between both technical, practical and architectural considerations, and will not necessarily favor the best technical options. Our analysis has demonstrated some of the possibilities to reduce the required number of antennas and improve the uniformity of coverage. Specifically, good and uniform coverage requires not many, but a certain minimum number of antennas, and preferably of the omni-directional type, hidden above ceiling tiles where possible. We should emphasize that practical and architectural considerations could impact such recommendation. Further, the analysis has demonstrated the need to pay attention to handover zones between the station and tunnel systems, not to cause too many unnecessary handovers between them.

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