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A simple statistical signal loss model for deep underground garage

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Abstract

In this paper we address the channel modeling aspects for a deep-indoor scenario with extreme coverage conditions in terms of signal losses, namely underground garage areas. We provide an in-depth analysis with regard to the path loss (gain) and large-scale signal shadow fading, and propose a simple propagation model which can be used to predict cellular signal levels in similar deep-indoor scenarios. The measurement results indicate that the signal at 800 MHz band penetrates external concrete walls to reach the lower levels, while for 2000 MHz wall openings are required for the signal to propagate. From the study it is also evident that the shadow fading between different levels of an underground garage are highly correlated. The proposed frequency-independent floor attenuation factor (FAF) is shown to be in the range of 5.2 dB per meter deep.

I. Introduction

The telecommunication industry is adopting new radio technologies, moving from 2G/3G to 4G systems, and within next 10 years the first commercial 5G networks are also expected to be available [1], [2], [3]. This technology evolution is heavily driven by the introduction of new services and a steady increase of the number of mobile users. In addition to mobile voice and broadband (MBB) services, new emerging applications based on Machine Type Communications (MTC) will increase significantly both the number of devices connected to the mobile radio network and also the geographical area which requires service coverage [2], [3]. For this reason, Mobile Network Operators (MNOs) are planing their radio networks to provide close to 100 % (probability) service coverage across the different frequency bands, cell types (macro, micro, pico) and technologies (2G, 3G, 4G, WLAN) deployed. To achieve this target, the required radio network planing has become a very complex task in recent years and will remain an important part of the 5G network deployments optimization as well. Further, the network deployment scenarios not sufficiently investigated in past for 2G/3G/4G systems due to their infrequent occurrence in real-life MNO deployments, will need to be analyzed and characterized in terms of radio channel propagation conditions. A typical example for this is the case of growing MTC services where applications rely on the large scale deployment of devices such as, environmental sensors, remote controlled units, industrial actuators, which were not available in the past or were not operating connected to wireless networks. [1].

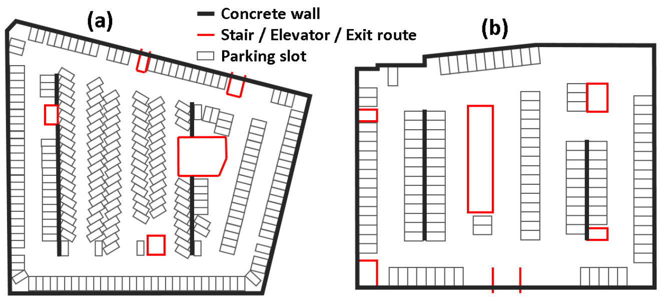

Fig. 1. The layouts of the two deepest underground parking garages in Denmark: (a) Friis, level -3 and (b) Dalgashus, level -1.

In this paper we address the channel modeling aspects for a deep-indoor scenario with extreme coverage conditions in terms of signal losses, namely underground garage areas. Typically today, in these use cases, MNOs provide voice services by means of a combination of cell types (macro and micro, indoor) and/or technologies, tailored for the expected traffic load. Although penetration loss and indoor attenuation models have been studied widely in the literature [4], [5], [6], [7], [8], [9], to the best of our knowledge none of them discusses the rate of attenuation across floor for underground structures.

In this paper, our investigations are based on radio channel measurements of deployed (live) urban 3G and 4G networks, which provide radio coverage outside and inside selected underground garage locations. We provide an in-depth analysis in terms of path loss (gain) and large scale signal shadowing and, propose simple propagation models which can be used to predict cellular signal levels in similar deep-indoor scenarios. Our study also highlights the indoor radio coverage limitations of current network deployments.

The paper is organized as follows: In Section II the scenarios, measurement setup and procedures are discussed. The results are analyzed in Section III, and finally the conclusions are drawn in Section IV.

II. Measurement Campaign

A. Scenarios

The measurement campaign took place at the two deepest underground car parks in Denmark, which belong to Friis and Dalgashus Shopping Center. Located at the heart of Aalborg city, Friis is a modern building complex consisting of a shopping center, hotel, offices, business center and car park. Its parking lot is built over an area of approximately 60 x 70 meters and has 4 levels with the capacity of 850 parking spaces. The first level is around 4 meters underground, while all remaining are approximately 2.5 meters deep each. This makes the garage almost 12 meters below ground. Dalgashus is a shopping center and residential building in the center of Herning city. Its parking lot is also 4 levels deep, but the last level is for its residents only and hence inaccessible during our measurement. Dalgashus car park is smaller than Friis', approximately 50 x 60 meters in size and can accommodate around 480 cars. The average floor height of the garage is 2.2 meters; however its first level is half-submerged with small open windows along one side of the building, near its entrance. Figure 1 shows the layouts of the two garages, which is very similar across levels of each garage. Both garages are constructed with thick concrete walls and floors. Visitors can access the garage via exits / entrance marked in red in the figure.

B. Measurement Setup and Procedures

A Rhode & Schwartz TSMW Universal Radio Network Analyzer is used to record all radio signals from surrounding live Universal Mobile Telecommunications System (UMTS) and Long-Term Evolution (LTE) cells at the frequency bands of interest, i.e. 800 and 2000 MHz. The device is connected to a Global Positioning System (GPS) antenna for marking outdoor locations, and two omni antennas with 0 dBi gain for receiving the signals. The antennas are placed on top of our car, which is traveling at an average speed of 10 km/h. For indoor locations we relied on a set of markers placed at every turn the car made. The radio signal strength is measured differently between LTE and UMTS: The LTE power measurement is extracted from the Secondary Synchronization Signal (S-Sync), which is transmitted every 5 ms on 62 sub-carriers. The sensitivity for the LTE power measurement is -127 dBm. The UMTS power is based on Received Signal Code Power (RSCP) measurement and has sensitivity of -123 dBm. The RSCP measurement is performed every 10 ms on Common Pilot Channel (CPICH).

Being at the heart of the city, next to the pedestrian and shopping streets, gives the two car parks the advantage of having very good cellular coverage. As a result, during the measurement we are able to identify signals from at least 10 macro cells inside both garages. To make it easier for plotting together the different power levels due to non-identical cell location, transmitting power, antenna pattern and technology, the indoor received power is normalized to its maximum value and hereafter is referred to as the *indoor attenuation*. Let $P_{Rx,i}(x,y,z')$ be the received signal power in dBm from the i^{th} macro cell at the indoor location defined by $[x,y,z']$ coordinates:

$$\Gamma_i(x,y,z') = P_{Rx,i}(x,y,z') - P_{Rx,i}(x_r,y_r,z'_r) \quad (1)$$

$$P_{Rx,i}(x_r,y_r,z'_r) = \max\big[P_{Rx,i}(x,y,z')\big] \quad (2)$$

where $\Gamma_i(x,y,z')$ is the indoor attenuation in dB and the *reference point*, $[x_r,y_r,z'_r]$, is the location where the maximum received signal power is observed indoor. It is important to note that such normalization does not change the distribution of the observed power samples, nor the slope of the Least-Square Linear Regression (LR) analysis presented in the next section. To ensure a reasonable deep indoor coverage during the measurement, we discarded all cells whose maximum indoor received signal power was lower than -80 dBm. This guarantees that we have at least around 50 dB of dynamic range for deep underground indoor attenuation measurement. In order to model the rate of attenuation across floors, we also normalize the absolute depths z' to the depth of the reference point z'_r:

$$z = z' - z'_r \quad (3)$$

From this point onwards all reference to depth means the relative depth z, unless otherwise stated.

In general, the total path loss, PL_{total}, between an outdoor cell and a deep underground user equipment (UE) can be expressed as follows:

$$PL_{total} = PL_{out} + W + PL_{in} - z \times L_{FAF} \quad (4)$$

where PL_{out} is the loss up to the external wall, W is the penetration loss due to the external wall(s) and PL_{in} is the additional loss from the outer wall to the indoor location. All these terms are in dB. The term L_{FAF} is the Floor Attenuation Factor (FAF), which is measured in dB/m and represents the additional loss due to the increasing depth z. The main focus of this paper is to derive the L_{FAF} statistically from measurement.

III. Result analysis

A. Propagation into Underground Building Structure

The COST 231 [4] assumes that radio waves penetrate building's external wall that is in direct view of the base station, while in [6] the authors argue that the outdoor-to-indoor paths are possible only through wall openings such as door or windows. In this section, we look into how the signal propagates from outdoor to underground building structure.

Figure 2 shows the received signal power from the LTE cell A at 800 MHz outside Friis Shoping Center. The area highlighted in pink is the Friis' building, and the black triangle marker is the cell's location. The cell points directly towards Friis, illuminating the area between the two black lines. The square and diamond marker denote the two potential entries for the signal into the underground parking lot: The first is the building corner closest to and in direct view of cell A. The latter is the entrance to the underground parking lot. In

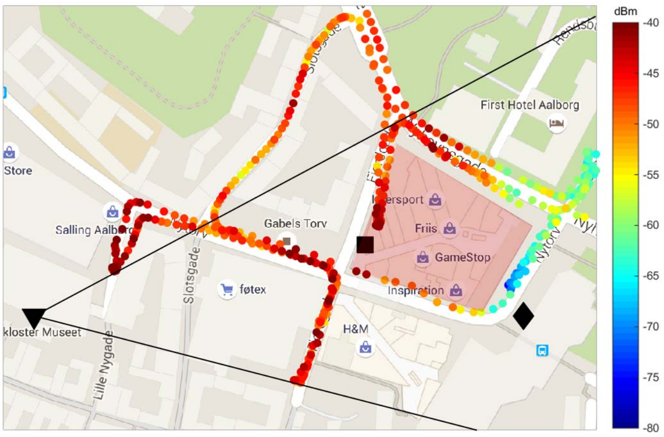

Fig. 2. The received signal power outside Friis from cell A at 800 MHz.

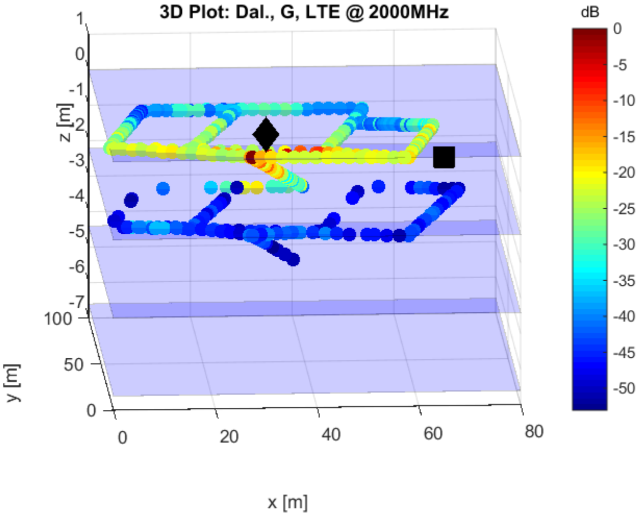

Fig. 5. The measured indoor attenuation in Dalgashus from cell G at 2 GHz.

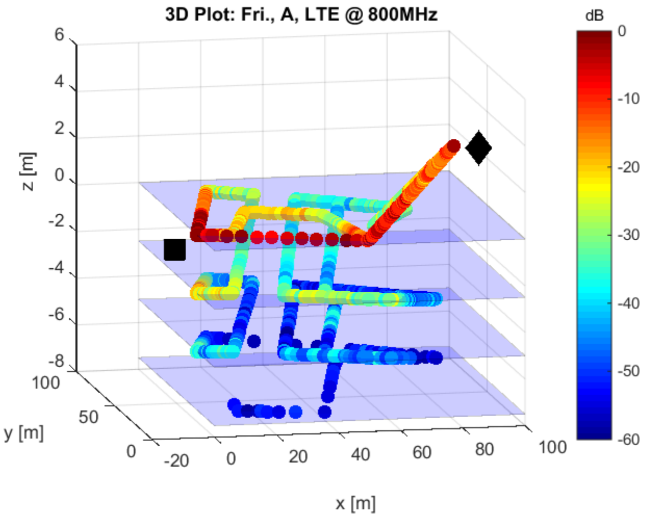

Fig. 3. The measured indoor attenuation in Friis from cell A at 800 MHz.

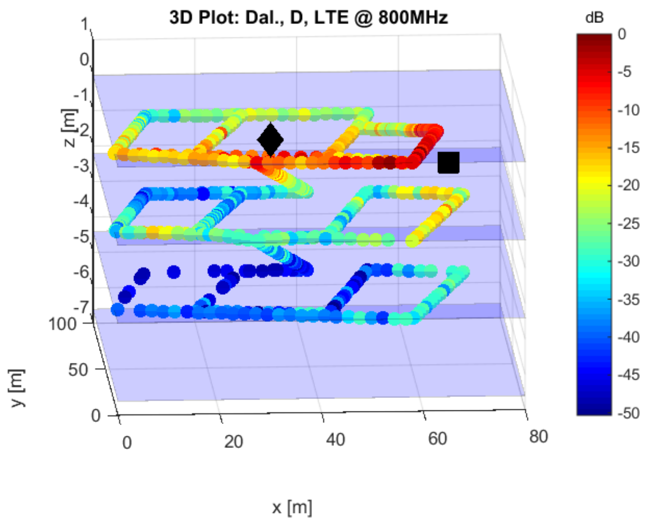

Fig. 4. The measured indoor attenuation in Dalgashus from cell D at 800 MHz.

Figure 3 the indoor attenuation from cell A is plotted in 3D. The diamond and square marker in this figure corresponds to the same markers in Figure 2. Warm colors indicate strong received signal strength, and cold ones mean that the signal is weak. We observe that the signal has penetrated the concrete wall at the square marker, and the received signal strength here is higher than that of the triangle marker. At the square marker, the signal is measured -43 dBm outdoor, and -68 dBm indoor, putting the estimated outdoor-to-indoor penetration loss at 25 dB. Typically, the penetration loss for concrete walls is less than 10 dB at 800 MHz [5], [9], but in this case the signal has to penetrate also 4 meters underground. Similarly, in Dalgashus the main propagation path is through the concrete wall, marked by the black square in Figure 4, which is in direct view with the cell under measurement, and the outdoor-to-indoor penetration loss is approximately 20dB. However, as the frequency increases in Figure 5, the penetration loss of the concrete wall also rapidly increases [5], [9], and the path going through the garage entrance becomes dominant.

Before the measurement campaign, we expected that the stairs and elevator shafts inside the two building complexes could be paths for signal to propagate down to the underground levels. However, there is no clear evidence supporting this assumption from the measurement data. The reason might be that the stairs and elevator shafts are surrounded by concrete or glass walls, and/or they are located too deep inside the complexes, making it difficult for the signal to propagate down to the lower levels via these paths.

From Figure 3 and 4, the shadowing maps seem to be highly correlated over floors. To measure this, we extract data separately from the driving routes on three levels (L-1, L-2 and L-3), matching them point-by-point across levels, and then compute the correlation coefficient between them. The correlation coefficient is between [-1, +1], where +1 indicates a perfect direct correlation, -1 in case of a perfect anti-correlation, and other value showing the degree of linear

TABLE I

CORRELATION BETWEEN LEVELS

Description	Correlation coefficient		
	L-1 vs L-2	**L-2 vs L-3**	**L-1 vs L-3**
Friis: A (LTE)	0.91	0.76	0.73
Dalgashus: D (LTE)	0.66	0.69	0.83

dependence between the variables. The results are presented in Table I, with value ranging from 0.66 to 0.91, confirming the high correlation between floors.

B. Floor Attenuation Factor

In this section we derive the FAF statistically from all valid data sets from our measurement campaign, as shown in Table II. Each row of the table represents data from an unique macro cell, identified by its location (Friis or Dalgashus), cell's pseudonym, frequency band (800 or 2000 MHz) and technology (LTE or UMTS). The "Samples" column indicates how many indoor samples were collected during the measurement, and the "Min. z" is the deepest level relative to the reference point that the signal can still be observed. In order to extract the FAF, the Least-Square LR is applied separately to each data set using the following equations:

$$\beta = \frac{\sum_{i=1}^{N}(\Gamma_i - \bar{\Gamma})(z_i - \bar{z})}{\sum_{i=1}^{N}(\Gamma_i - \bar{\Gamma})^2} \tag{5}$$

$$\alpha = \bar{z} - \beta \times \bar{\Gamma} \tag{6}$$

$$\epsilon = \sqrt{\frac{1}{N}\sum_{i=1}^{N}[\Gamma_i - (\beta \times z_i + \alpha)]^2} \tag{7}$$

where Γ_i is the indoor attenuation value and z_i is the depth of the i^{th} measurement point ($i = 1, 2, ...N$). $\bar{\Gamma} = \frac{1}{N}\sum_{i=1}^{N}\Gamma_i$ and $\bar{z} = \frac{1}{N}\sum_{i=1}^{N} z_i$ is the average indoor attenuation and average depth of the entire data set, respectively. The term β and α are the slope and the intercepting point of the least-square LR fitting curve, respectively. The root mean square error (RMSE), or ϵ, between the measurement data and the LR fitting curve is also computed and shown here, because it serves two purposes: first, it is an indication of how well a model fits with the measurement data, and secondly it represents the fluctuation due to obstacles and other random propagation effects, which can be useful for establishing the shadow fading model for underground garages.

Figure 6 shows the dependency between the indoor attenuation and the depth from cell A, D and G, which has the most number of indoor samples for each pair of location and frequency band. The slopes of the fitting curves indicate the rate at which the loss increases with the decrease of the relative depth, or the FAF. From Table II we observe that the FAF values extracted from different cells are similar if they are measured in the same environment: In Friis the FAF value ranges from 3.8 to 4.3 dB/m, while in Dalgashus it is from 5.5 to 5.8 dB/m at 800 MHz band. The reason for higher FAF in Dalgashus is that its first garage level is not completely underground, and therefore the mean indoor attenuation of that

TABLE II

DEEP UNDERGROUND INDOOR ATTENUATION IN FRIIS AND DALGASHUS

Description	**Samples**	**Min. z**	**Linear Regression**		
Location: Cell (Tech)		**[m]**	β	α	ϵ
800 MHz band					
Friis: A (LTE)	1,037	-7.50	4.3	-24.9	9.4
Friis: B (LTE)	360	-9.58	4.1	-13.7	6.6
Friis: C (UMTS)	222	-8.87	3.8	-19.4	8.6
Friis, combined			**4.1**		**9.4**
Dalgashus: D (LTE)	591	-4.40	5.5	-17.4	7.2
Dalgashus: E (UMTS)	247	-4.40	5.7	-23.4	5.9
Dalgashus: F (UMTS)	231	-4.40	5.8	-24.0	7.2
Dalgashus, combined			**5.7**		**7.2**
2000 MHz band					
Dalgashus: G (LTE)	382	-3.99	6.3	-28.4	8.6
Dalgashus: H (LTE)	374	-3.81	5.8	-29.9	8.1
Dalgashus, combined			**6.1**		**8.6**

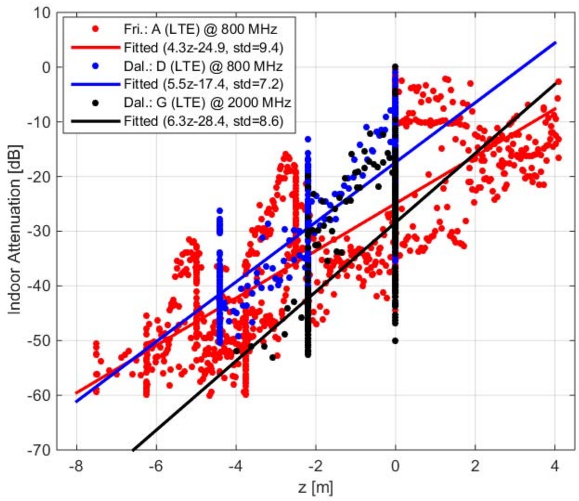

Fig. 6. Example of measurement data and linear regression fitting curves.

floor is lower than those of the other floors. This affects the slope of the fitting curve. Another interesting observation is that the 2 GHz measurement in Dalgashus shows similar FAF values as those measured at 800 MHz, indicating that the FAF does not seem to change significantly with the increase of frequency. This is somewhat coherent with the findings in [8], where the in-building attenuation rate in horizontal plane is also frequency-independent and measured at 0.6 dB/m for frequencies ranging from 800 MHz to 18 GHz.

By averaging all slopes from the data sets measured in Friis at 800 MHz, we obtained a FAF of 4.1 dB/m for this scenario. Similarly, FAF values of 5.7 and 6.1 dB/m are derived for Dalgashus at 800 and 2000 MHz, respectively. Combining all cases, regardless of different scenario and frequency band, gives an average FAF of 5.2 dB/m. The attenuation rate in the z dimension therefore is much higher than the 0.6 dB/m in-building attenuation in the x and y dimension, and also the 0.6 dB/m height gain [8]. The RMSE is 9.4 dB for Friis and 7.2 dB for Dalgashus, which is in agreement with the WINNER II model C4 NLOS outdoor to indoor macro cell with shadow fading's standard deviation of 10 dB [10].

IV. Conclusions

A measurement campaign was carried out at two deepest underground garages in Denmark to investigate the feasibility of using outdoor cellular network to serve deep underground devices, such as in the future MTC. Our study shows that the signal at 800 MHz band is able to penetrate the external concrete wall to reach the lower levels, while at 2000 MHz band it would require wall openings such as door or windows for the signal to enter the lower levels. There is evidence that the shadowing at different levels are highly correlated. We propose a simple signal loss prediction formula that is derived based on the measurement results. The proposed Floor Attenuation Factor (FAF) is shown to depend mainly on building structure, not frequency. The average FAF is approximately 5.2 dB per meter deep, which is much higher than the horizontal indoor attenuation or the height gain, which are approximately 0.6 dB/m as measured in the literature. In the worst scenario, more than 60 dB of additional loss was observed at 12 meters deep, which indicates that outdoor-to-underground coverage can be challenging at such depth.

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