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Evaluation of Indoor Radio Deployment Options in High-Rise Building

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Abstract

In this paper we set out to analyze the indoor capacity under a realistic high-rise building scenario. The study takes into consideration the number of indoor cells deployed per floor, different inter-site distances (ISDs), transmit power settings and outdoor macro interference levels. The outcome shows large variation in performance gain just by optimizing indoor cell locations, highlighting the need for thorough indoor radio planning. Investing into more indoor cells helps to increase capacity, and also to cope better with outdoor interference, but the gain tends to be diminishing due to the increase of inter-cell interference (ICI). Increasing transmit power brings largest gain when the density of indoor cell is low, and the noise and/or outdoor interference is the dominant source of performance degradation. When analyzing performance gain of an ideal receiver-side Interference Cancellation (IC) algorithm, the study also shows that, if the Dominant Interferer Removal (DIR) rate is below 50%, doubling the number of indoor cells would bring better capacity gain than investing into such an IC receiver.

I. Introduction

Mobile data traffic volumes keep increasing year after year, forcing mobile network operators to increase the capacity of their networks to avoid congestion and poor user quality of experience. As the majority of the traffic is originating from indoor activities, indoor solutions are an attractive option among the different network upgrade possibilities. Especially considering that penetration losses tend to increase with modern building, due to the use of energy efficient 2 or even 3 layer windows, it is getting increasingly hard to cover the indoor location from outside. Densification of the indoor small cell layer was found to be considerably more energy and cost efficient than the densification of outdoor macro and micro layers in a suburban scenario [1] .

However, indoor solutions suffer from floor- and wall-penetration losses, and thus the requirements on inter-site distance (ISD) are typically much higher than on outdoor solutions. This leads to a higher interference among indoor sites. Another issue is the interference coming from the outdoor network deployed at the same frequency, which an operator can be forced to due to the lack of spectrum.

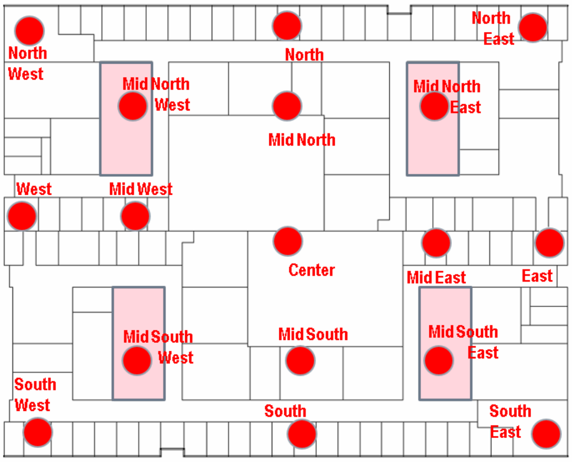

Fig. 1. Indoor scenario and micro cell deployment options.

In this paper we look at different indoor deployment options, varying the number of Long-Term Evolution (LTE) indoor cells per floor, and varying the amount of interference from the outdoor network, representing either different outdoor-to-indoor penetration losses or different ISD for the outdoor network. Additionally, we look at the impact of the transmit power of the indoor cells, and the gain of having interference mitigation solutions implemented in the user equipments (UEs). The outcomes of the paper are key development strategies for mobile network operators to provide the best mobile broadband indoor user experience.

The paper is organized as follows: In Section II the indoor scenario and the choice of propagation model is discussed. The capacities of various indoor deployment options are analyzed in Section III, and finally the conclusions are drawn in Section IV.

II. Indoor Scenario and Propagation Model

A. Scenario

In this paper a typical high-rise office building is used to investigate the capacity of different indoor deployment options. For our analysis we assume that the layout of all floors is identical, and it is illustrated in Fig. 1. The layout has a dimension of 60 m x 75 m x 3.5 m, and consists of corridors, multiple small rooms separated by light walls (i.e

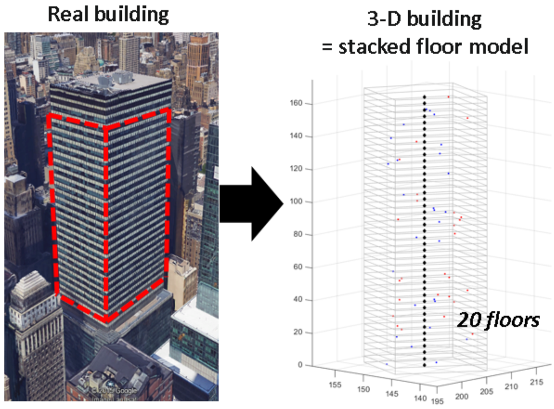

Fig. 2. 3D building: A stacked floor model.

plasterboard wall), and 4 large elevator shafts / emergency stairs surrounded by heavy walls, i.e. load-bearing wall made of thick concrete, marked by pink color in the figure. The floors and outer walls are also made of thick concrete. We assume that there are 17 potential locations for deploying indoor cell's antennas within the building: One in the center, and eight in the middle, hereafter referred to as "tier-1", and the other eight close to the building's outer wall ("tier-2"). They are named after their relative positions and marked by red dots in Fig. 1. The building is assumed to have 20 floors, as shown in Fig. 2.

B. COST231 Multi-Wall Model

The indoor path loss model considered in this paper is the COST231 Multi-Wall [2], hereafter referred to as COST231. It has been widely used in literature, and also for initial Wireless Local Area Network (WLAN) planning for indoor environments [3]. The path loss in dB is given by:

$$L_{COST231}(d) = L_{FS}(d) + k_f^{\left[\frac{k_f+2}{k_f+1}-b\right]} L_f + \sum_{i=1}^{W} k_{wi} L_{wi} \quad (1)$$

where $L_{FS}(d)$ is the free-space path loss in dB between transmitter (Tx) and receiver (Rx), with separation distance d in meter. The parameter k_f and L_f denotes the number of floors and loss between adjacent floors, respectively. The empirical factor b is introduced to take into account the fact that the total floor loss is a non-linear function of the number of penetrated floors. The k_{wi} and L_{wi} is the number and loss for walls of i^{th} type, respectively. W indicates number of wall types. [2] provides the recommended values for these parameters for certain environments, and the set recommended for the dense environment is used throughout our study (see Table I). On top of the mean path loss yielded from Eq. 1, a long-term fading following log-normal distribution with standard deviation of 4 dB, is included to represent additional obstacles in the building that has not been modeled in the 3D building map.

TABLE I
COST231 Multi-Wall Parameters

Parameter	Value
Light wall loss (L_{w1})	3.4 dB
Heavy wall loss (L_{w2})	6.9 dB
Floor penetration loss (L_f)	18.3 dB
Empirical factor (b)	0.46

C. Outdoor Macro Interference Model

Since radio spectrum is becoming a scarce and precious resource, indoor solutions, provided by a network operator, will most probably be allocated a portion of spectrum that is shared with the operator's outdoor network. An important factor affecting indoor performance, therefore, is the level of outdoor interference leaking into the building. In this paper we assume the building is located in a dense urban area, where it is surrounded by a number of outdoor macro cells. The outdoor interferences come from four outdoor macros located at four sides of the building, assuming the same output power and distance to the building. The macro signals are attenuated at rate of 0.6 dB/m, when propagating deeper indoor, and additionally affected by the log-normal long-term shadow fading with 4 dB standard deviation. The macro signals are summed pixel-by-pixel throughout the building's layout, and the maximum interference level is a parameter in our simulator. We model three degrees of outdoor interference: high, medium and low, which correspond to the maximum interference level of -60, -80 and -100 dBm, respectively. Note that the maximum level is measured indoor, i.e. the effect of outer wall penetration loss, if any, is already included. A low degree of outdoor interference could be due to one or a combination of these factors: (a) the interfering macro cell is far away, (b) the building under study is being shadowed by other buildings, (c) the outdoor to indoor penetration loss is very high due to the outer wall's material and thickness. The -60 dBm interference can be generated, for example, by a macro located 200 m away, sending out 43 dBm over a directional antenna of 17 dBi, which is pointing towards the building of interest. Based on the 3GPP's Urban Macro (UMa) path loss model [4], the received signal outside the building is approximately -40 dBm. Subtracting the outdoor-to-indoor penetration loss of 20 dB, we have an indoor interference level of -60 dBm.

III. Capacity Analysis

A. Simulation Assumptions

When there is only one indoor cell per floor (1x), given that the floor plan is symmetrical, it is logical to place the cell at the center of the building layout to maximizing its coverage. If more cells are deployed per floor, a number of possible combinations might exist. Table II shows a list of deployment options considered in this paper, varying with the number of indoor cells, and also their antenna locations in the building. In each configuration the antennas are placed symmetrically, either at tier-1 (i.e. in the middle of the building) or tier-2

TABLE II
INDOOR DEPLOYMENT OPTIONS

Deployment Option	Location(s)
1 cell per floor (1x)	
1AP	Center
2 cells per floor (2x)	
2APSNT1	Mid-South and Mid-North
2APEWT1	Mid-East and Mid-West
2APMIXT1	2APSNT1 (odd floor) 2APEWT1 (even floor)
2APSNT2	South and North
2APEWT2	East and West
2APMIXT2	2APSNT2 (odd floor) 2APEWT2 (even floor)
4 cells per floor (4x)	
4APMIDT1	Mid-South, Mid-North, Mid-East and Mid-West
4APCORNERT1	Mid-SouthWest, Mid-NorthWest, Mid-SouthEast and Mid-NorthEast
4APMIXT1	4APMIDT1 (odd floor) 4APCORNERT1 (even floor)
4APMIDT2	South, North, East and West
4APCORNERT2	SouthWest, NorthWest, SouthEast and NorthEast
4APMIXT2	4APMIDT2 (odd floor) 4APCORNERT2 (even floor)
8 cells per floor (8x)	
8APT1	All 8 tier-1 locations
8APT2	All 8 tier-2 locations

TABLE III
SIMULATION PARAMETERS

Parameter	Value
Center frequency	2 GHz
Bandwidth	20 MHz
Transmit power	17 or 23 dBm
Transmit antenna	4dBi omni-directional
Receive antenna	0 dBi omni-directional
Shadowing standard deviation	4 dB
Mininum throughput requirement	10 Mbps
Outdoor macro interference	-100, -80 and -60 dBm
UEs distribution	Uniform across layout and floor

locations (closer to the outer wall). This is to ensure that a relatively regular network layout existed inside the building, and there is no area with exceptionally-low coverage.

Key simulation parameters are mentioned in Table III. All indoor cells are equipped with a 4 dBi omni-directional antenna, which is mounted on the ceiling at the height of 3.5 m. The transmitting power is either 17 dBm or 23 dBm. The carrier frequency for indoor cells is 2 GHz, and the allocated bandwidth is 20 MHz. The 2 GHz band is chosen to avoid excessive outdoor-to-indoor interference or vice versa, due to the fact that this frequency does not penetrate building walls as well as the 800 MHz [5]. Based on the transmit power and instantaneous path loss, the simulator derives the Signal to Interference plus Noise Ratio (SINR) for all indoor UEs, and then it computes their throughputs from the SINR based on the LTE mapping curve given in [6].

The UEs are assumed to be uniformly distributed inside the building, with 0 dBi omni-directional antenna. Each UE has a probability of starting a data transfer session at a simulation time slot that is controlled by an independent Poisson arrival process. Each session is modeled as a File Transfer Protocol (FTP) transfer, with fixed down-link payload of 2 MB, and the inter-arrival times between the sessions are varied to create different network load points.

In this paper we use the down-link network capacity as the Key Performance Indicator (KPI). We define network capacity as the maximum load (Mbps/floor) that the network can support while fulfilling a minimum data rate requirement of 10 Mbps for at least 95% of the users. We find that averaging over 20 floors is enough to remove the influence of the first and the top floors, where lower level of ICI is experienced. The result, therefore, can be generalized for building with higher number of floors.

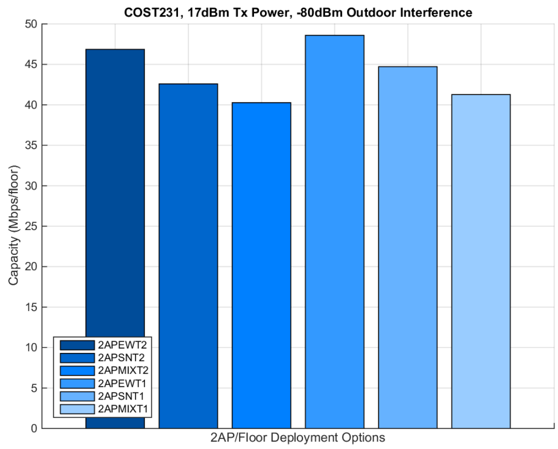

Fig. 3. Capacity for different 2x deployment options.

B. Result Analysis

First, we compare the performance of different deployment options having the same number of indoor cells per floor to pinpoint the most optimum one for futher investigation. Fig. 3 illustrates the capacity from all available 2x deployment options, assuming that the Tx power is 17 dBm and the maximum total outdoor interference is -80 dBm. The deployment achieving the best capacity is the 2APEWT1, where antennas are placed at the Mid-East and Mid-West positions on the tier-1 ring in the middle of the building. The runner-up is the 2APEWT2, in which antennas are also located in East-West, but on the tier-2 ring, which is closer to the building outer wall. These are the options that offered the best average SINR, probably because they have a good balance between ISD (to minimize the ICI) and distance to all UEs in the cell (to maximize received power). The difference between the best and the worst option (i.e. 2APMIXT2) is approximately 8 Mbps/floor, or equivalently 20% capacity gain.

The capacity for all 4x deployment options are shown in Fig. 4. In this case, the 4APMIDT2 is the best, followed by the 4APMIDT1. Because antenna placement in the 4APMIDT1 is relatively closer than the 4APMIDT2, it generates slightly more interference. The 4APMIXT2 turns out to be the worst option: By alternating the antenna positions on the odd and

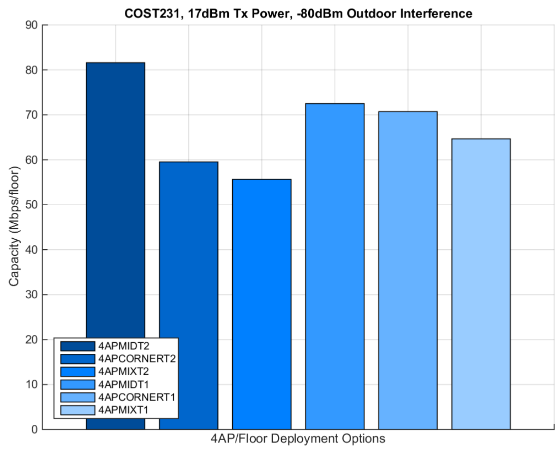

Fig. 4. Capacity for different 4x deployment options.

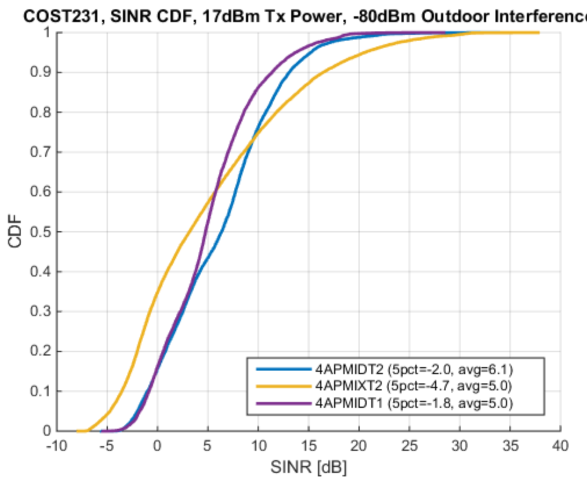

Fig. 5. Full-load SINR from three 4x deployment options at 17 dBm Tx power, evaluated at outdoor interference level of -80 dBm.

even floor, the SINR for cell-center UEs get improved at the expense of the cell-edge ones. This leads to the lowest cell-edge SINR among the options, which limits the achievable capacity. For illustration, the cumulative distribution functions (CDFs) of the full-load SINR for three above-mentioned deployment options, under the outdoor interference level of -80 dBm, are plotted in Fig. 5. The gap between the best and the worst configuration for 4x deployment options is even greater than the 2x case: it is up to 25.9 Mbps/floor or 46% capacity gain. This number highlights the need for carefully planning indoor deployment to achieve the best performance. By performing similar analysis, the best option for deploying 8 cells per floor is identified as the 8APT2, i.e. antennas are located at the outer wall to reduce the average ISD.

Secondly, Fig. 6 shows the network capacity varying with the number of deployed cells at 17 dBm Tx power. The first group of bars are for low outdoor interference level (-100 dBm), whereas the second and third ones are for medium

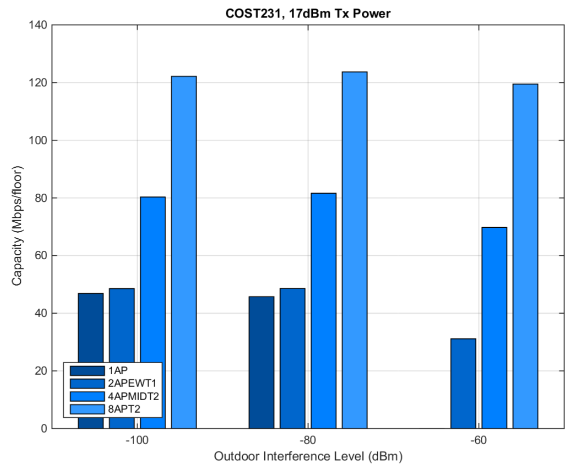

Fig. 6. Capacity for the best deployment options at 17dBm transmitting power.

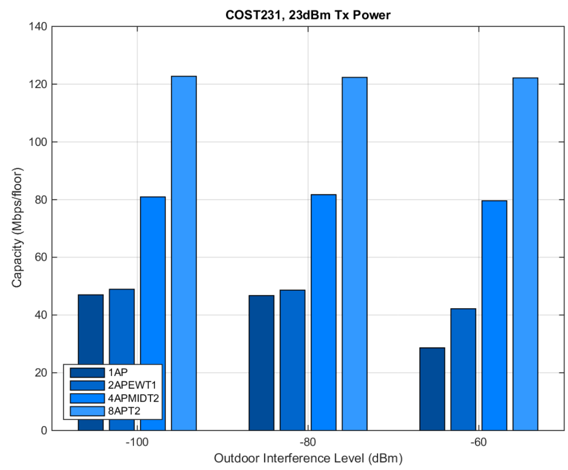

Fig. 7. Capacity for the best deployment options at 23dBm transmitting power.

and high interference level (-80 and -60 dBm, respectively). When the interference level is high, one indoor cell per floor is no longer able to provide sufficient throughput to 95% of its UEs, and therefore its capacity for that point is not available. Looking into the outdoor interference level of -80 dBm for example, we observe that the per-floor capacity increases with investing additional resources into the building: In comparison to one cell per floor, the 2x, 4x and 8x options would bring approximately 6, 79 and 171% gain, respectively. The small gain of 6% hints that network operators should probably skip x2 and go directly to x4 or x8 option. It is also important to note that adding cells will bring diminishing return due to the increasing interference: If we divide the capacity for the number of indoor cells, then the resulted average capacity per floor per cell are 45.7, 24.3, 20.4 and 15.5 Mbps for the 1AP, 2APEWT1, 4APMIDT2 and 8APT2 option, respectively. This trend does not change with different levels of the outdoor

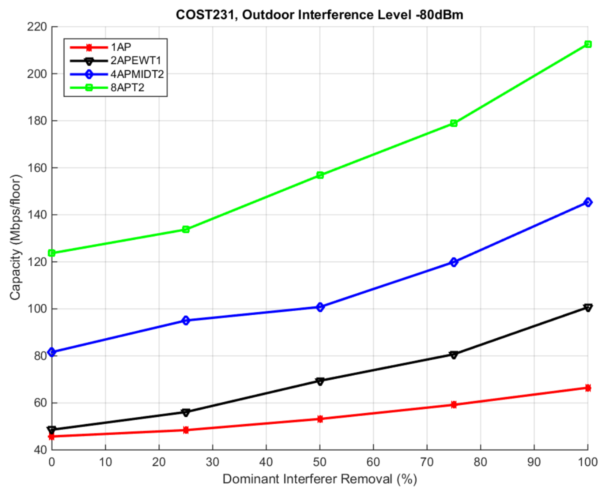

Fig. 8. Capacity gain vs interference cancellation efficiency at 17 dBm Tx power, evaluated at outdoor interference level of -80 dBm.

interference.

All indoor deployment options are able to cope well with low and medium level of macro interference, performance degradation is observed only for high outdoor interference scenario. In the case of the 2APEWT1, the capacity drops from 48.6 Mbps/floor (for low outdoor interference scenario) to 31.1 Mbps/floor (high outdoor interference scenario), or equivalently 35%. However, the capacity degradation is only 2.2% for the 8APT2, suggesting that a denser indoor deployment might be required when the building is heavily-interfered by outdoor macros.

Thirdly, Fig. 7 illustrates how network capacity changed when increasing the Tx power to 23 dBm indoor. No gain is observed for low and medium outdoor interference levels, as network is already interference-limited, and the main source of interference is from adjacent indoor cells. Increasing Tx power only helps when the outdoor interference becomes significant factor affecting the indoor performance. The largest gain can be seen with the 1AP case: From not being able to provide sufficient capacity (with 17 dBm Tx power) to being able to provide 95% UEs with the minimum throughput requirement, and achieve the capacity of 28.6 Mbps/floor, very close to the 2APEWT1 deployment option at 17 dBm Tx power.

Finally, we investigate the capacity gain in relation to the efficiency of a receiver-side Interference Cancellation (IC) algorithm. Network operators often have to consider investing in more indoor cells, or in IC-supporting feature to achieve similar performance gain. We model the effect of an ideal Interference Cancellation (IC) scheme as being able to remove certain percentage of the dominant interferer. All UEs are assumed to be IC capable. In Fig. 8, the Dominant Interferer Removal (DIR) ratio of 100% means that the strongest interference is completely rejected, while 0% indicates that no interference cancellation is applied. Our study shows that if the DIR is below 50%, the capacity gain by the IC algorithm is often less than doubling the number of indoor cells. For example, the capacity of 4APMIDT2 deployment option increases from approximately 80 to 100 Mbps/floor, when an IC scheme with DIR of 50% is applied. In comparison, by upgrading from 4APMIDT2 to 8APT2, the capacity will reach around 120 Mbps/floor.

IV. Conclusions

It is predicted that mobile network operators will have to gradually resort to indoor solutions to cope with the ever increasing demand for indoor wireless traffic. In this paper we investigate the indoor capacity for a real-world high-rise building scenario. Assuming the COST231 Multi-Wall model and a realistic outdoor to indoor interference model, we look at different indoor deployment options, varying the number of indoor cells per floor, and the amount of interference from outdoor network, representing either different building penetration losses or different ISDs of the outdoor macro network. We also analyze the impact of Tx power of the indoor cells and the gain of having interference mitigation solutions implemented at the UE-side. The outcome shows a large variation in the performance gain, up to 46% in certain scenario, just by optimizing the indoor cell locations, which highlights the need for thorough indoor radio planning. Investing into more indoor cells helps to increase capacity, and also to cope better with outdoor interference, but the gain is diminishing because the interference between indoor cells also increases. Increasing transmit power from 17 to 23 dBm is a lucrative option when the density of indoor cells is low and the noise, and/or outdoor interference is the dominant source of performance degradation, as it could bring significant gain in such cases. The analysis onto the ideal receiver-side IC scheme shows that, doubling the number of indoor cells would bring higher capacity gain than investing into the IC receiver, if it can only cancel up to 50% of the strongest interference.

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