On the Performance of Indoor Ultra-Dense Networks for Millimetre-Wave Cellular Systems

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Abstract. The combination of Ultra-Dense Networks (UDN) and millimetre Waves (mmW) communications has recently been recognized by the industry and research community as a promising solution to cope with the evolving requirements of the fifth generation (5G) of cellular networks. Indeed, the problem of capacity provisioning has drawn the attention to mmW due to the spectrum scarcity at lower frequency bands. Additionally, the densification process has already started with the introduction of the well-known Heterogeneous Networks (HetNets).Thus the use of UDN is another natural approach for increasing the overall network capacity, especially in such indoor environments where high data rates and service demand are expected. In this paper, the combination of the previous paradigms is analysed by means of comprehensive system-level simulations. Unfortunately, the particularities of indoor deployments make radio propagation difficult to predict and limit the macro-cell coverage, hence these simulations have been evaluated using advanced Ray Tracing (RT) techniques. Results confirm the superior system performance of the mmW and UDN tandem with respect to current operating bands.

Keywords: Millimetre waves · mmW · Ultra-dense networks · UDN · Energy efficiency · System-level simulations · 5G · Indoor planning

1 Introduction

During the last decade, cellular networks have witnessed the rapid penetration of smart-devices. This tendency has recently been fuelled by the evolution of these devices into the so-called *smarter* smart-phones and the irruption of a new wide range of wireless devices, including tablets, wearable sensors, and smart-watches [1]. Our society can be referred as the *Networked Society* [2]; in fact, we will be more *networked* than ever in coming years since it is expected that the total number of mobile subscriptions keeps exponentially growing year-by-year, and the amount of wirelessly connected devices will increase by 40 % at the beginning of 2020 [3,4]. As a result of this unprecedented revolution, the fifth generation (5G) of cellular systems will target significantly increased network

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capacity and better spectral efficiency to answer the rapidly increasing cellular traffic demand [5]. For instance, it is expected that 5G networks will need to support peak data rates of 10 Gbps for downlink, 1000 times higher mobile data volume per area, and up to 100 times higher number of mobile devices [6]. Moreover, operators will also have to face the challenge that a significant portion of this traffic will be generated in indoor locations, accounting for up to 90 % of the total network load [7].

Given this, both the industry and standardization bodies have joined efforts to make current networks meet future user's requirements; however, these are not likely to suffice. It is obvious that radio spectrum is scarce at current operation bands due to the growing service demand, and that liberating bandwidths up to 100 MHz in the existing licensed bands would be at a considerable expense in both economic and technological aspects [8]. Moreover, according to the International Telecommunication Union (ITU), the estimated spectrum bandwidth requirements will be between 1340 MHz and 1960 MHz by 2020 [9]. To that end, millimetre Waves (mmW) communications have emerged as the key enabler of such networks due to the vast amounts of contiguous available spectrum within this frequency range [10].

Without any doubt, mmW communications will boost network capacity by increasing the available spectrum. Nevertheless, due to the propagation characteristics at these frequencies, and particularly, in indoor environments, they also bring the possibility of further exploiting network densification in order to provide better coverage. Precisely, Ultra-Dense Networks (UDN) are also considered a key paradigm for future 5G scenarios since they aim at improving the overall network areal spectral efficiency by increasing the total number of access points [11].

It is this combination, the tandem constituted by mmW and UDN, the one that has been envisioned as a promising solution in order to solve the challenge of indoor service provisioning in the next generation of cellular systems [12,13]. Existing network planning methods have mainly been conceived to ensure outdoor coverage; however, due to the strong outdoor-to-indoor penetration loss, indoor areas suffer from poor Signal-to-Interference-plus-Noise Ratio (SINR), and hence, the indoor service demand becomes very expensive in terms of resources for the already congested macro-cells [14]. Thus, there is an urge to investigate the impact both paradigms in the context of 5G networks. Previous studies on the mmW side have mainly been focused on their propagation characteristics [15–18]. In [19,20], coverage and capacity provisioning of mmW have been studied in the context of outdoor communications. Likewise in [21], coverage probability and cell throughput have been compared for microwave networks.

Similarly, on the UDN side, a mathematical model and performance characterization of dense heterogeneous networks have been proposed in [22]. Energy Efficiency (EE) is another *hot topic* in this field, and examples can be found in [23,24]. However, the research focused on mmW and UDN for indoor cellular deployments is still in its infancy, and therefore, few publications can be found

Table 1. Summary of related work.

Ref.	mmW	Test case	Method	Main aspect
[27]	×	Indoor	Measurements	Channel modeling
[28]	×	Outdoor	Simulations	Interference manag
[17]	✓	Outdoor	Simulations	Channel modeling
[18]	✓	Outdoor	Analytical	Downlink coverage
[29]	✓	Outdoor	Measurements	Network capacity
[14]	✓	Indoor	Measurements	Outdoor-indoor cov
[16]	✓	Indoor	Measurements	Channel modeling
[30]	✓	Outdoor	Simulations	Network Capacity
[31]	×	Outdoor	Simulations	Scheduling

that investigate it. Table 1 provides a comparative perspective of several related contributions in both areas.

To the best of the authors' knowledge, only very recent publications [25] have contributed with system-level performance evaluations of UDN and mmW, although realistic scenarios were not considered. In our previous work [26], we presented a novel framework for cellular indoor planning and deployment optimization of indoor UDN operating at mmW based on Multiobjective Optimization (MO) and Ray Tracing (RT) techniques. By means of the statistical method presented therein, it was shown that effective network planning and topology/layout adaptation [32] provide significant improvements in terms of system capacity, cell-edge performance, and energy efficiency. In this paper, we continue the research in that line and further analyze the proposed framework by means of system-level simulations. Thus, the contribution of this paper is a detailed performance assessment and a comparative analysis of different ultra-dense topologies at both low and high frequencies. The results show that, besides the clear gain associated to the allocation of more bandwidth operating at mmW, several other benefits including better energy efficiency and cell-edge performance exist.

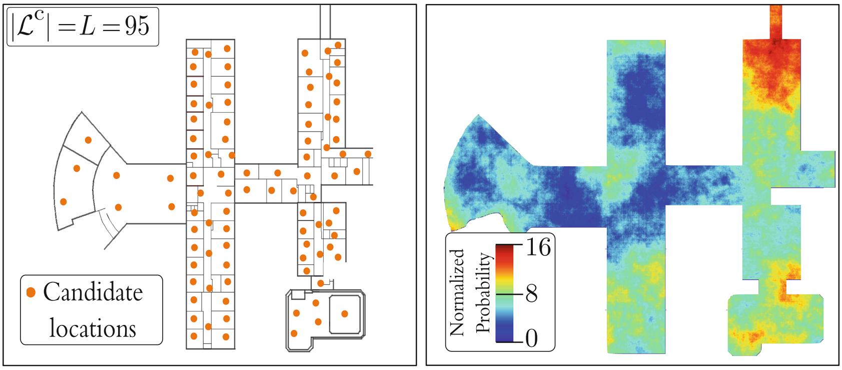
The rest of the document is organized as follows: First, the system model and performance metrics are described in the next section. Section 3 describes the evaluation settings and the analysis of the results. Finally, conclusions are drawn in Sect. 4.

2 Methodology

This section is divided in three parts that provide a detailed description of the experiments and the adopted methodology.

2.1 Simulation Scenario

The simulated scenario is a realistic indoor dense deployment covering a specific area of the School of Electrical Engineering of Aalto University as Fig. 1a illustrates.



(a) Nodes possible locations (b) Irregular spatial density

Fig. 1. Simulation environment

As mentioned, mmW propagation models are still immature [33]. Indeed, results show that the accuracy of these models are highly dependent on the environment and simulation characteristics. Thus, in order to have a precise radio characterization of the indoor environment, the propagation has been simulated by means of RT techniques [34]. RT is a deterministic propagation model that allows for accurate radio propagation prediction in indoor layouts at different frequency ranges [35].

The evaluation area corresponds to an indoor sub-area of the building of 92×84 m^2 with a pixel resolution of $1/7\times1/7\,\text{m}^2$. In order to create a highly densified environment, an average Inter-Site Distance (ISD) of 3–4 m was set between each access point. The possible locations of all possible nodes are also shown in Fig. 1a. Antennas were placed on the ceiling (at a distance of 2.4 m from the floor) and the height of the users was set to 1.5 m, according to [36]. For evaluation purposes, 140 users are distributed within the area of interest following a given traffic distribution. In this work, only an irregular service demand is considered (see Fig. 1b).

2.2 System Model

This study focuses on the system level evaluation within the LTE-Advanced framework [36], an extended statistical analysis of the proposed system model can be found in [26]. The downlink of an Orthogonal Frequency Division Multiple Access (OFDMA) cellular network is considered herein. A frequency reuse factor of one (full reuse scheme) has been selected among all active access points. In terms of resource allocation, a Round Robin (RR) scheduler is considered and all available resources in a cell are assigned at a given time. That is

$$m_i = \frac{m_\text{C}}{m_\text{U}}, \tag{1}$$

where m_i is the number of Physical Resource Blocks (PRBs) assigned to the user i, m_C is the total number of PRBs assigned to each cell, and m_U is the total number of users attached to the node. We note that, as the focus is on

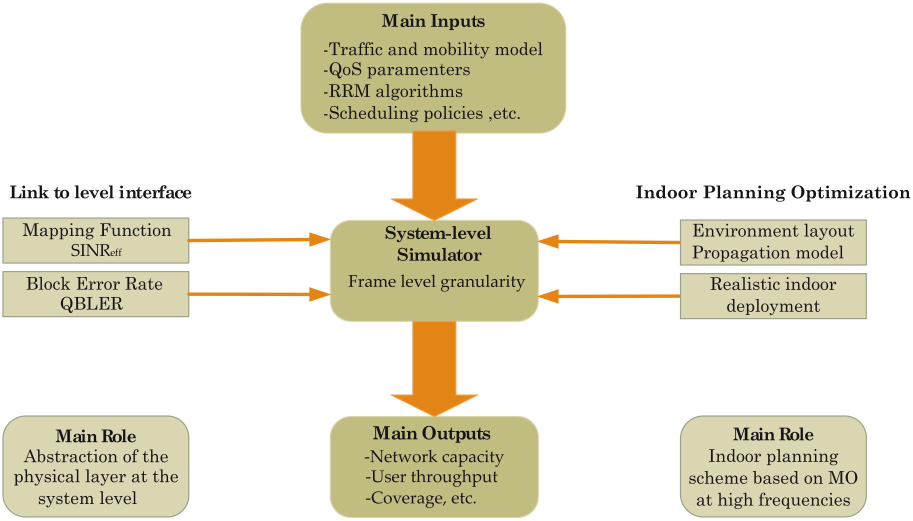


Fig. 2. System-level simulations framework

the comparison among network topologies and operating bands, the selection of an arbitrary scheduling discipline does not affect the conclusions. The same applies to the size of the operating band size.

The implementation of the semi-static system-level simulations have been developed in a MATLAB environment, and based on Monte Carlo experiments (a schematic of the simulator is illustrated in Fig. 2). The SINR to link throughput mapping has been carried out by the guidelines provided in [37]. In total, results compiled statistics taken from 3000 independent experiments or user drops. Table 2 summarizes the simulation parameters based on 3GPP specifications [38]. Precisely, the system considers a 20 MHz of bandwidth ($B_{\text{eff}} = 18$ MHz) thus the total number PRBs available for users is 100, each simulated drop corresponds to a Transmission Time Interval (TTI), that is 1 ms.

2.3 Performance Metrics

Performance metrics were selected according to 3GPP recommendations [39]. For instance, to evaluate and illustrate the network performance, Cumulative Distribution Functions (CDFs) of user's throughput were computed. Additionally, numeric results were documented for the 50$^{\text{th}}$-tile and 5$^{\text{th}}$-tile representing the in-cell and cell-edge users, respectively. Finally, three additional aspects have been investigated: the network energy efficiency as defined in [26], the impact of user density on the end-to-end performance, and the system fairness by means of the Jain's index (Υ) defined as follows:

$$\Upsilon(T_1, T_2, \cdots, T_m) = \frac{\left(\sum_{i=1}^{m} T_i\right)^2}{m \cdot \sum_{i=1}^{m} T_i^2}, \tag{2}$$

Table 2. Simulation parameters

Parameter	Value	Parameter	Value
System parameters			
Nodes	$L \in [10, 95]$	Inter-site distance	3-4 m
Pixels resolution	$1/7 \times 1/7\,\mathrm{m}^2$	Number of pixels	391510
Sys. bandwidth (B)	18 MHz	Number of PRBs	100
Sub-carriers power	-17.8 dBm	Interference margin	4.0 dB
Shadowing STD	7.0 dB	Rx. noise figure	7.0 dB
Thermal noise	-174 dBm/Hz	Receiver height	1.5 m
Min. SINR	-10.0 dB	Sensitivity ($P_{\min}$)	-126 dBm
Carrier Frequencies: 2.6 GHz and 28 GHz			
Antenna Sectorization: No			
Power Allocation: Homogeneous			
Propagation Model: Ray Tracing / Deterministic			
Highest MSC: 64-QAM, R = 9/10			
Scheduler: Round Robin			
Simulation Type: Monte Carlo			
User Drops: 3000			
Min. UEs per drop: 140			
Coverage outage threshold (κ_{COV}): 97.5%			
Transmitter parameters			
Antenna height	2.4 m	Power (P_T)	13 dBm
Antenna pattern: omnidirectional			
Antenna gains: 3 dBi @2.6 GHz and 12 dBi @28 GHz			

where T_i is the throughput of the i^{th} user. The ideal fairness case is achieved when the index Υ is equal to 1.

3 Simulation Results and Discussion

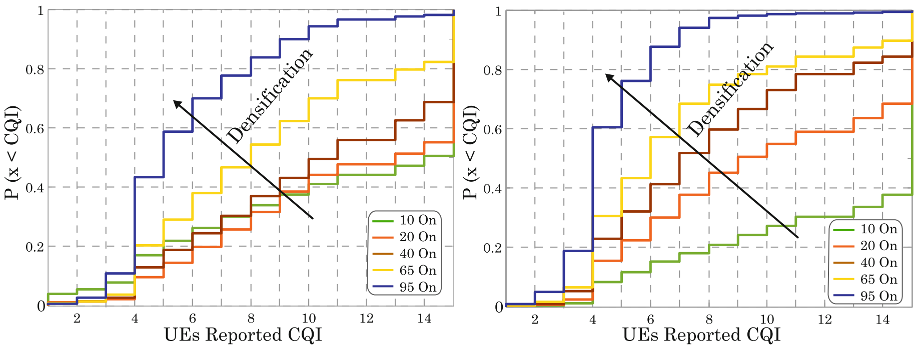
This section is divided into two main parts. The first part explains the evaluation scenarios. The second part presents the results obtained for the experiments previously described in each of the considered scenario.

3.1 Simulation Setup

In this study, two different frequencies (see Table 2) were considered. The particular topologies ($L \in \{10, 20, 40, 65, 95\}$) were the obtained from the statistical optimization process presented in [26]. For completeness, our baseline scenario, where node locations are not optimal, has been also included in the evaluation. Specifically performance metrics were evaluated in 10 independent scenarios.

3.2 Impact on Signal Quality

This section evaluates the degradation of the signal quality (in terms of the downlink SINR) when selected topologies move from sparse to denser ones. In LTE



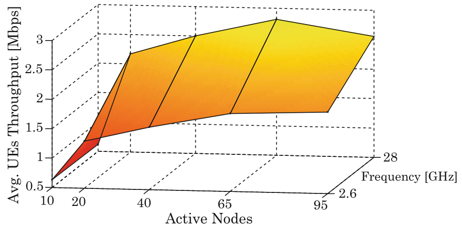
(a) 28 GHz UEs CQI (b) 2.6 GHz UEs CQI

Fig. 3. Reported UEs CQI

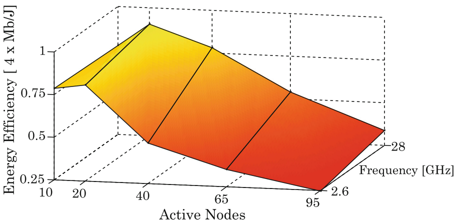
systems, users report the status of their radio channel using the Channel Quality Indicator (CQI); as the reported CQI gets better, a higher modulation scheme is selected [37]. Figure 3 depicts the results at frequencies previously described. From the figure, it is clear that the degradation ratio is more critical at lower frequencies where Inter-Cell Interference (ICI) increases together with network densification. At higher frequencies, ICI effects are reduced as a result of the natural and better isolation of the indoor cells. Thus, the high penetration loss of mmW can be exploited constructively in indoor environments. For instance, the network densification can be increased by a factor of 4 and still user's reported CQI distribution is comparable with sparse scenarios (see Fig. 3b).

3.3 Impact on User Throughput and Energy Efficiency

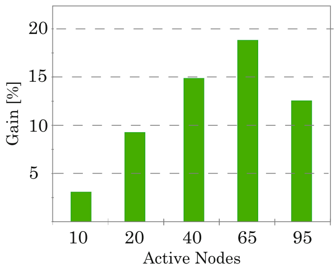
In the following, the average user's throughput, network EE, and cell-edge performance are analysed at the proposed scenarios. Due to the amount of independent experiments, previous metrics are represented by means of surface plots which indicate average values (see Fig. 4). Looking at Fig. 4a, results confirm the observed behaviour in [26]: 1) an indoor-planning aware network will provide substantial gains in terms of user's throughput at both frequencies, and 2) if we compare the performance of both frequencies, we can observe that mmW communications will provide considerable gains (up to 54 %) with respect to the operation at 2.6 GHz. Regarding the EE, defined as the sum-rate to energy consumption ratio, Fig. 4b shows the EE for each simulation. In this manner, the conclusions and observations drawn from our previous work, have also been verified through a more realistic, yet highly complicated, system-level simulations, where the effect of many network functionalities such as Channel State Information (CSI) feedback, realistic link adaptation, and scheduling cannot be captured without losing mathematical tractability. In addition, mmW will also improve the EE providing gains of 39 % over the 2.6 GHz band. Similar results can be observed in Fig. 4c where 5^{th}-tile gains can increase up to 18 % operating at higher frequencies.



(a) User throughput



(b) Energy efficiency



5th-tile UEs Throughput [kbps]

Active Nodes	2.6 GHz	28 GHz
10	1.9	3
20	87	96
40	202	223
65	304	340
95	145	165

(c) 5^{th}-tile gains

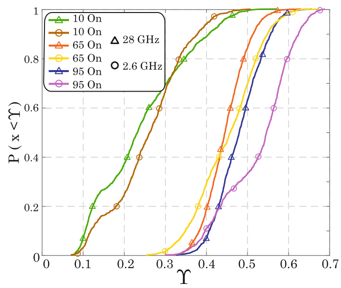
Fig. 4. Results on user's throughput, EE, and cell-edge

3.4 Impact on System Fairness

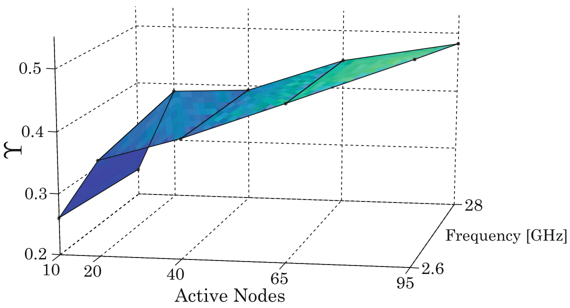
Figure 5 depicts the results corresponding to the evaluation of the system fairness at two different frequency values for the proposed network topologies. Particularly, Fig. 5a represents the CDF of Jain's fairness index of the users in the whole system for a selected number of topologies. Looking comparatively at both frequencies, results show that similar fairness improvements are noticed at 28 GHz and at 2.6 GHz. In fact, it is clear that the sparsest topology, with 10 active nodes, may even result in a deterioration of the system fairness. On the other hand, the greater the value of active nodes, the better fairness performance can be achieved (up to 37.5 % gains). For the sake of clarity, system fairness of all topologies has also been represented in Fig. 5b by means of surface plots. From the figure, it can be seen that previous behaviour is confirmed, and even expected, since activating more nodes in a given area will increase the number of available resources per user. However, one common aspect at both frequencies is that, for a given network densification value, system fairness does not change significantly.

3.5 Impact of Service Demand Volume

It is also interesting to consider the effect of changing user density at both frequencies and at different network topologies. To that end, the initial number of users ($\nu = 140$) has initially been doubled, and finally, increased by a factor of 4. Figure 6 presents the system performance of two separate network deployments



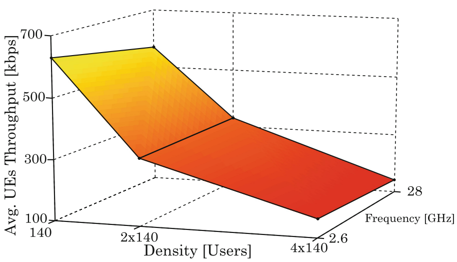
(a) CDF of the Υ



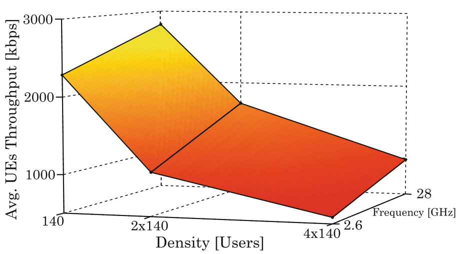
(b) Fairness (Υ)

Fig. 5. System fairness for different scenarios

with 10 and 65 active nodes, respectively. From the figure, it can be observed how the increment of the total amount of users present on the network can rapidly deteriorate the performance in terms of end-to-end throughput. However, results clearly show how dense networks operating at higher frequencies can mitigate this degradation, outperforming those cases where 2.6 GHz and sparse topologies are considered (see Fig. 6b), which makes sense because more nodes can be activated to support the user density increment without noticing the negative impact of the ICI.



(a) 10 nodes



(b) 65 nodes

Fig. 6. UEs volume densification

4 Conclusions and Future Work

Ultra-dense networks based on millimeter-wave communications have been identified as part of the key enablers of future 5G cellular systems. Consequently, the main objective of the work presented in this document was to investigate the feasibility and effectiveness of the novel network planning framework for indoor cellular environments proposed in [26]. Indeed, by means of system-level simulations, this study has verified the compatibility of the analysis, the statistical optimization process, and the obtained outputs presented in our previous work. The main conclusions can be summarized as follows:

– First, the performance of dense environments operating at 28 GHz have been evaluated in terms of user throughput, cell-edge performance, and network energy efficiency. The results clearly validate the already investigated advantages of such environments, including the possibility of having more energy efficient topologies, that at the same time, provide more capacity (compared with lower carrier frequencies) and better cell-edge performance.
– Second, Radio Resource Management (RRM) challenges related to resource allocation and scheduling were analyzed. It was shown that throughput fairness can by significantly increased in network topologies much denser than the existing ones.
– Third, an additional aspect has been investigated: the impact of the volume of users within the selected topologies. Results have shown that vast volume of users mitigate the overall network performance, although its effect is less harmful when both mmW and UDN are considered.

The natural continuation of this work relies on the evaluation of the proposed framework considering additional RRM functions, load balancing techniques, and the further extension of the simulator to compute traffic-aware system-level simulations. Additionally, future work includes the analysis of RRM mechanisms and indoor networks in the context of Machine-to-Machine (M2M) communications focusing on traffic profiling methods.

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