Performance Analysis of Repeater-Aided Millimeter Wave Urban Mobile Communication Networks

Armand Nabavi, Stefan Schwarz
Christian Doppler Laboratory for Dependable Wireless Connectivity for the Society in Motion
TU Wien, Institute of Telecommunications
Gusshausstrasse 25/389, A-1040 Vienna, Austria
Email: armand.nabavi@tuwien.ac.at
Email: sschwarz@nt.tuwien.ac.at

***Abstract*—In this paper we investigate how replacing base stations with repeaters in a millimeter-wave fifth generation (5G) mobile communications system deployed in an urban environment affects user coverage and throughput in the downlink. Provided the system performance remains adequate, such a step can lead to substantial cost reductions for mobile operators. For this analysis, the much discussed 28 GHz band is considered and the communications system is simulated using the Vienna 5G System Level Simulator.**

***Index Terms*—mmWave, repeaters, coverage, system level simulations**

I. Introduction

The analysis of millimeter-wave mobile communications networks has become more and more relevant with the deployment of 5G technology in urban environments. Service providers need to decide where to place how many base stations in order to fulfill performance requirements at a reasonable cost. Since base stations are expensive to deploy, operate and maintain, it is worth investigating whether some of them can be replaced by much cheaper devices such as repeaters while still ensuring sufficient system performance. Those can be used to extend the range of base stations, which is beneficial for poorly covered areas. In this paper, we consider a cellular system operating at a carrier frequency of 28 GHz, which lies in a band requested by several large operators [1]. Additionally, pathloss models suitable for such systems deployed in Manhattan grid like environments have been developed and validated in [2]–[4]. While previous works such as [5] discuss performance in terms of achievable rate, there exists, to the authors' knowledge, no previous publication on simulation-based system level throughput analysis of such systems.

This paper is divided into two main sections. At first, the system model including the simulated scenarios, the network elements and the pathloss model is presented. Then, the simulation results obtained with the Vienna 5G System Level Simulator [6] are shown and discussed.

II. System Model

A. Scenarios

In this paper, we are using a Manhattan type layout representing a square city block. Base station sites are placed on all street intersections along a main diagonal of the region of interest to make sure every part of each street lies in LOS of at least one base station. Users are randomly placed on the streets using a 2D Poisson Process with a fixed density.

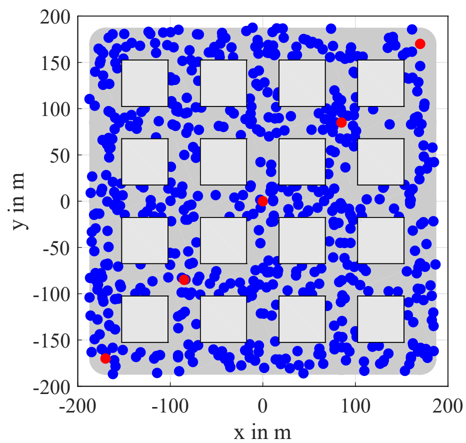
In order to analyze the performance of our system, three scenarios have been selected. In the first one, all sites are equipped with a base station. This configuration is referred to as **full setup** (Fig. 1a), it is the most expensive to deploy but is also expected to yield the best system performance. The second scenario, which is called **reduced setup** (Fig. 1b), omits two of the base stations compared to the full setup, thereby creating areas with poor coverage. Lastly, the **repeaters** scenario (Fig. 1c) is based on the second one, but it uses two repeaters each to compensate for the two missing base stations. The repeater placement ensures that each user is in LOS and in the direction of a service antenna beam of a repeater or in LOS of a base station. To replace the two additional base stations of Fig. 1a (which each serve two streets) with repeaters, we require a total of four repeaters, since we assume that each repeater must be in LOS to its serving base station. It is expected that the repeaters setup will lie between the two other scenarios in terms of performance.

B. Network Elements

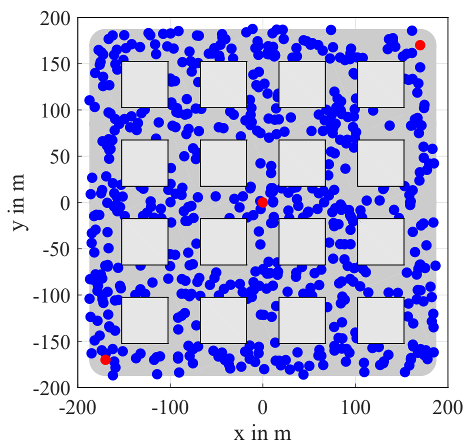
The base stations are assumed to have an antenna array that has equal gains along both horizontal and vertical streets. The antenna power used in the simulations is to be understood as an EIRP. The repeaters are Amplify and Forward devices. It is assumed that they have one donor antenna array directed at the closest base station in LOS and a service antenna that has equally strong beams in both perpendicular directions. The repeater gain is determined by a fixed value constrained by a power limit. It is assumed that the repeater operates in full-duplex mode. The users are assumed to have a single, isotropic antenna.

C. Pathloss Model

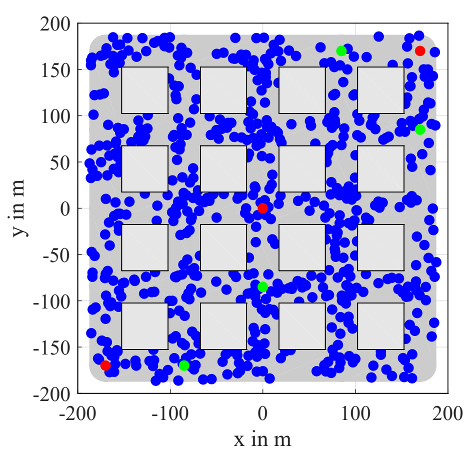
The pathloss model used in these simulations is taken from [2]. Each link is divided into up to three segments depending on the network elements' relative positions. For devices located on the same street, the link consists of one LOS segment. If they are located on perpendicular/parallel streets,



(a) full setup



(b) reduced setup



(c) repeater setup

Fig. 1. Simulated scenarios with users (blue), base stations (red) and repeaters (green).

there are one/two additional NLOS segments to consider, respectively. The model specifies the pathloss as

$$PL = 10\alpha_{LOS}\log_{10}(d_{LOS}) + 10\alpha_{NLOS}\sum_{i=1}^{M}(\log_{10}(d_{NLOS,i})) + \beta + ML_c \quad (1)$$

with the number of NLOS paths $M \in \{0, 1, 2\}$ where L_c denotes the corner loss. The parameters α and β are chosen in accordance with the UMi Street Canyon pathloss model from 3GPP TR38.901 V15 [7]. This model has been specifically designed for Manhattan grid scenarios and millimeter wave communication systems and has been validated by measurements in [3]. It has to be noted, however, that aspects such as the street width and the presence of street lamps/signs, furniture and foliage (trees, bushes) in the streets can have significant effects on the pathloss behaviour [4]. These effects have not been considered in this generic scenario.

TABLE I
SIMULATION PARAMETERS

Parameter	Value	Unit
carrier frequency	28	GHz
bandwidth	100	MHz
channel model	PedA	
base station EIRP	40	W
scheduler	round robin	
α_{LOS}	2.1	
α_{NLOS}	3.53	
β	$32.4 + 20\log_{10}(28)$	dB
L_c	8	dB
number of slots	50	
simulation runs	50	
max repeater gain	60	dBi
max repeater tx power	20	W
repeater donor antenna gain	40	dB
repeater service antenna gain	45	dB
user density	$\{0.001, 0.01, 0.05\}$	m^{-2}

It can be seen from the pathloss model (1) that NLOS links exhibit a much higher pathloss than LOS one due to the additional NLOS term and the corner loss. It is therefore assumed that each repeater only amplifies the signals from base stations that are in LOS and along the main lobe of its donor antenna array. With the configuration shown in Fig. 1c, this means that each repeater can be considered to serve only one base station, which reduces the computational complexity of the simulation model.

III. SIMULATION RESULTS

At first, we are calculating the distribution of the macroscopic SINR for each configuration as shown in Fig. 2.

As expected, there are areas with poor coverage in the reduced setup scenario, which affects about 40 % of the users on average. Using repeaters to compensate improves coverage significantly, yielding even higher coverage values than the full setup. The latter's slightly lower performance is attributed to the fact that it uses more base stations than the other configurations, thus generating more interference.

A more important performance metric is throughput at the user side, which also takes into account fast fading, the

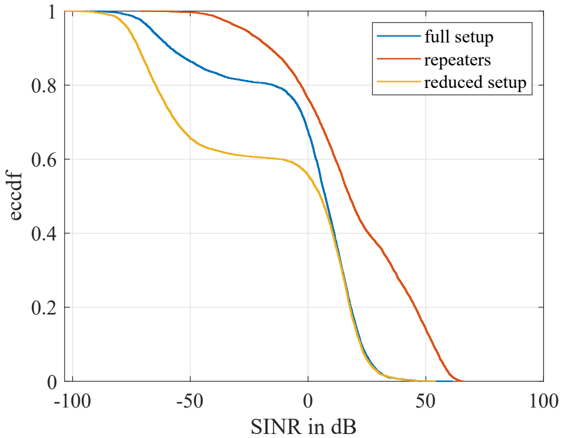


Fig. 2. Macroscopic SINR.

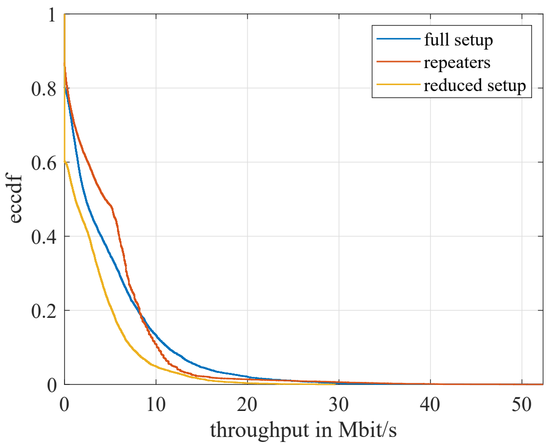


Fig. 3. User throughput averaged over slots, user density $0.001\,\mathrm{m}^{-2}$

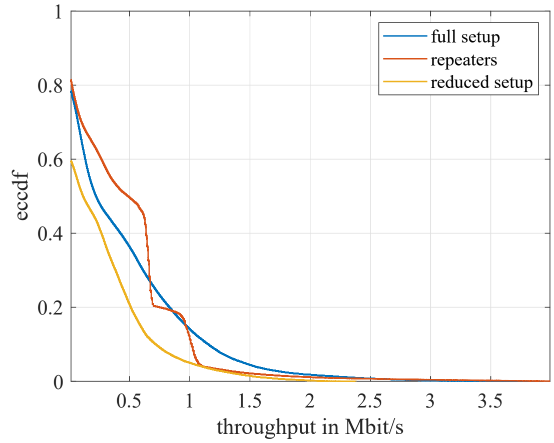


Fig. 4. User throughput averaged over slots, user density $0.01\,\mathrm{m}^{-2}$

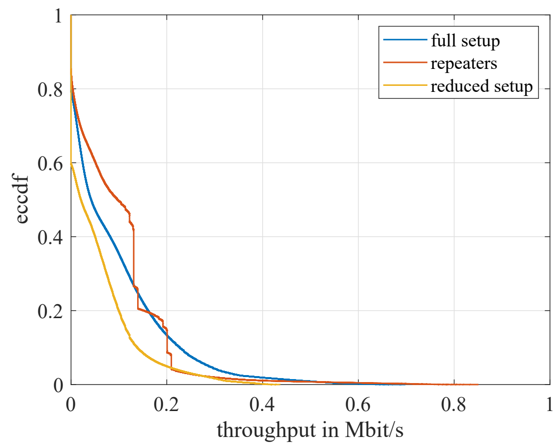


Fig. 5. User throughput averaged over slots, user density $0.05\,\mathrm{m}^{-2}$

available transmission ressources as well as the scheduling and feedback algorithms. These results are displayed in Fig. 3.

While both the full setup and the repeater setup yield similar coverage values, their throughput distributions are different from each other. With the full setup, we observe a larger number of users with high throughput values whereas using repeaters leads to more users having lower throughput. This is explained by the fact that there are more transmit ressources available in the full setup, which are distributed among a slightly smaller number of users per base station.

The lowest performance is obtained for the reduced setup scenario, which is expected given the pathloss distribution and the number of available base stations.

In order to substantiate this set of observations, we are looking at the throughput results for simulations with higher user densities. It is expected that the amount of available transmission ressources will become a limiting factor for the repeaters scenario's performance if the user density is sufficiently increased. In that case, there should be a noticeable performance gap compared to the full setup (which has more ressources available), showing that replacing base station with repeaters does limit performance in crowded scenarios. The results are shown in Fig. 4 and Fig. 5.

These new simulations show that the previous observations regarding the performance differences between the three different setups are still valid for higher user densities. In order to see whether the amount of transmission ressources is already starting to become a limiting factor for the repeaters scenario's performance, we are analysing the throughput per user and per slot (instead of the average over all slots as done before). These results are displayed in Fig. 6 and Fig. 7.

If we are looking at the number of user slots used for transmission, we see that in both cases, fewer slots are used in the reduced setup case than in the repeaters scenario, although the same amount of transmission ressources are available. This is due to the fact that in the former case, poor coverage (as shown in the SINR plot Fig. 2) is the limiting factor. When comparing the full setup and the repeaters scenario, the results are different depending on the user density. While the full setup uses fewer user slots in the lower density

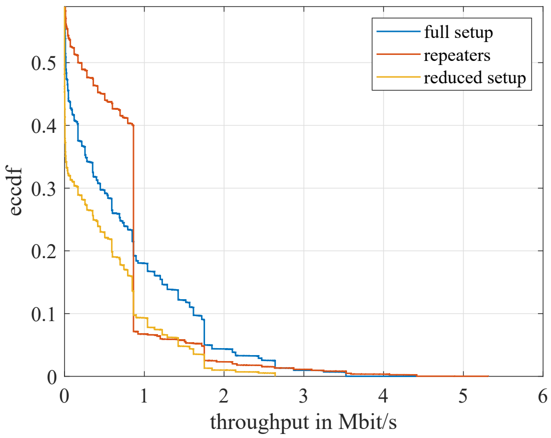


Fig. 6. User throughput per slot, user density $0.01\,\mathrm{m}^{-2}$

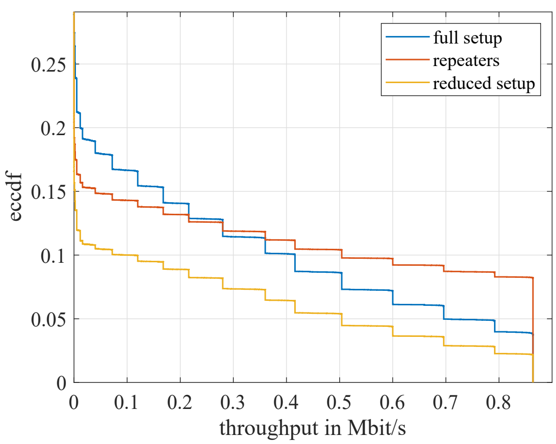


Fig. 7. User throughput per slot, user density $0.05\,\mathrm{m}^{-2}$

case, it manages to use more than the repeaters scenario in case of higher densities. This shows that when increasing the user density, after a certain point (that lies between the two simulated densities), the amount of transmission ressources becomes a limiting factor for the repeaters scenario. The reason that this is not visible in the average throughput results in Fig. 5 is that due to higher overall SINR values (see Fig. 2), higher CQI values are picked on average in the repeaters scenario, compensating for the smaller amount of available slots.

If we increase the user density even further, we expect the full setup to also exhibit higher average throughput values than the repeaters scenario.

Unfortunately, we were not able to simulate even higher user densities due to hardware constraints.

IV. Conclusions

In this paper, we have shown that coverage in mmWave mobile communications networks deployed in urban environments can be significantly improved by using repeaters without having to deploy much more expensive base stations. This is particularly effective for areas with low user densities. For higher user densities, we have demonstrated that using repeaters instead of base stations is only advisable to a certain extent, depending on the targeted user throughput values.

Acknowledgment

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