

Research Article

Performance Evaluation of 5G Millimeter-Wave Cellular Access Networks Using a Capacity-Based Network Deployment Tool

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The next fifth generation (5G) of wireless communication networks comes with a set of new features to satisfy the demand of data-intensive applications: millimeter-wave frequencies, massive antenna arrays, beamforming, dense cells, and so forth. In this paper, we investigate the use of beamforming techniques through various architectures and evaluate the performance of 5G wireless access networks, using a capacity-based network deployment tool. This tool is proposed and applied to a realistic area in Ghent, Belgium, to simulate realistic 5G networks that respond to the instantaneous bit rate required by the active users. The results show that, with beamforming, 5G networks require almost 15% more base stations and 4 times less power to provide more capacity to the users and the same coverage performances, in comparison with the 4G reference network. Moreover, they are 3 times more energy efficient than the 4G network and the hybrid beamforming architecture appears to be a suitable architecture for beamforming to be considered when designing a 5G cellular network.

1. Introduction

The increasing demand of applications in terms of throughput and latency explains the evolution of telecommunication standards. The next generation of telecommunication standards such as the 5th-generation (5G) wireless communication networks are expected to considerably accommodate larger number of wireless connections to better support existing and evolving applications including social media, high definition video streaming, full-featured web browsing, and real-time gaming. This can be made possible thanks to new features utilized in 5G wireless access networks as presented in [1, 2]: massive MIMO (Multiple Input Multiple Output), beamforming, small dense networks, millimeter-wave frequency, and movable base stations. However, the fast growing data traffic volume and dramatic expansion of network infrastructure will inevitably trigger tremendous escalation of energy consumption in wireless networks. This will directly result in the increase of green house gas emission and pose ever increasing urgency on the environmental protection [3].

In this study, a capacity-based network deployment tool is proposed to meet the requirement of designing energy

efficient 5G wireless networks, while providing at the same time the higher throughput required by the users. A similar method was used in [4] but was limited to the design of an energy efficient LTE-advanced network at 2.6 GHz, with its three main features: carrier aggregation, heterogeneous networks, and MIMO technology. Here, beamforming is implemented and investigated in order to assess its potential by means of system level simulations, thanks to the use of multiple antennas at the base station. Beamforming increases the base station antenna gain and help focusing antennas' energy in a desired direction, while preventing interference from others [1, 2]. The assessment will consist in examining the influence of the use of beamforming technology on the overall network power consumption, network coverage, and network capacity. A realistic suburban case in Ghent, Belgium, is considered for this study.

The rest of this paper is organized as follows: Section 2 discusses the new features of the 5G wireless access networks, the power consumption models of its base station, and the energy efficiency metrics. In Section 3, the network deployment tool is described and finally Section 4 presents the results obtained with the deployment tool with respect

to the beamforming technology. We then provide the final conclusions in Section 5.

2. 5G Wireless Access Networks

Research on next-generation 5G wireless systems, which aims to resolve several unprecedented technical requirements and challenges, has attracted growing interests from both academia and industry in the past few years. More than 5 billion devices demand wireless connections that run voice, data, and other applications in today's wireless networks [5].

The need for more capacity is just one key driver for mobile networks to evolve towards 5G. For the data-intensive applications to be working smoothly, the industries and academia agree on the following technical requirements for the 5G wireless network, which is not standardized yet [6]:

- (i) *Coverage and Data Rate.* 5G should maintain connectivity anytime and anywhere with a minimum user experience data rate of 1 Gbps [7].
- (ii) *Latency.* The latency requirement is usually more difficult to achieve compared to that of the data rate as it demands that the data be delivered to the destination within a given period of time. For the 5G wireless network, the end-to-end latency requirement is expected to be in the order of 1–5 ms [8, 9].
- (iii) *Connected Devices.* The future 5G network will have the ability to incorporate huge number of connected devices, allowing them to reach up to 100 times the data rate of the 4G wireless network.
- (iv) *Multiple Radio Access Technologies.* The 5G network is not meant to replace the current wireless networks. It will be built upon the existing wireless technologies: the Global System for Mobile Communications (GSM), third generation of mobile communications (3G), high-speed packet access (HSPA), long term evolution (LTE), long term evolution advanced (LTE-A), and wireless fidelity (WiFi) [8, 9].
- (v) *Energy and Cost Efficiency.* 5G wireless networks have to be designed to meet the requirements of data-consuming applications but at a lower cost and higher energy efficiency, compared to the existing wireless networks [8].

Given the above requirements, the following new technologies will have to be enabled to make 5G wireless networks reality [1]:

- (i) *Millimeter-Wave Frequency.* As the frequency spectrum under 6 GHz is highly utilized, it appears that millimeter wave is the best candidate to respond to the huge requirements in terms of network capacity and from Gigabit broadband applications [10].
- (ii) *Massive MIMO.* This is the extension of the MIMO technology used in 4G technology to a large number of antennas. Massive antenna arrays are put together to provide the ability to exploit the maximum possible degrees of freedom available in the spatial domain.

Therefore, it becomes possible to focus these energies towards a desired direction, while preventing propagation in the nondesired direction (beamforming). This can easily be achieved at millimeter-wave frequency since this high carrier frequency requires antenna elements to be very small, allowing the use of many antennas at both the base station (BS) and the mobile station (MS) [11]. There are mainly three types of beamforming architectures that are widely investigated: the digital beamforming (DBF), the analog or radio frequency beamforming (ABF), and the hybrid beamforming architecture (HBF) [12]:

- (1) Digital beamforming: this is the type of beamforming architecture whereby it is assumed that a transceiver is behind every antenna. So, the entire array processing is performed at the baseband side.
 - (2) Analog beamforming: this is the type of beamforming whereby the control of MIMO and beamforming is performed at radio frequency (RF) level. Here, a transceiver is assumed to drive the antenna array and the transmit and receive array processing is performed with RF components having phase shifting and potentially gain adjustment capabilities as well.
 - (3) Hybrid beamforming: the control of MIMO and beamforming is split between RF and baseband. Each set of antenna elements is driven by a transceiver. A hybrid architecture can use two to eight transceivers to drive the antenna array.
- (iii) *Small Cells.* To satisfy the increasing traffic demands due to the growing number of users, densification of the infrastructure whereby 5G small cells are introduced in the 4G macrocell network is set to be a priority aspect in 5G communications [1].

This paper emphasizes the use of beamforming technology in the millimeter-wave frequency bands and investigates its influence on the behavior of the 5G wireless communications networks. The densification will serve as another study in the future work.

3. Capacity-Based Network Deployment Tool

3.1. Design of the Network Deployment Tool. The network deployment tool is designed and proposed to meet the requirements of 5G wireless network. The choice for the design of such a tool is motivated by the fact that it simulates a realistic network that responds to the instantaneous bit rate (voice or data) required by the active users, in the considered area. This tool is used to simulate the different scenarios of 5G wireless communication networks, based on our assumptions, and the results are discussed and compared with the reference scenario. The following lines discuss the different steps of the simulation tool/algorithm.

3.1.1. Creation of the Traffic. The different steps leading to the creation of traffic files are indicated in Figure 1. First, a

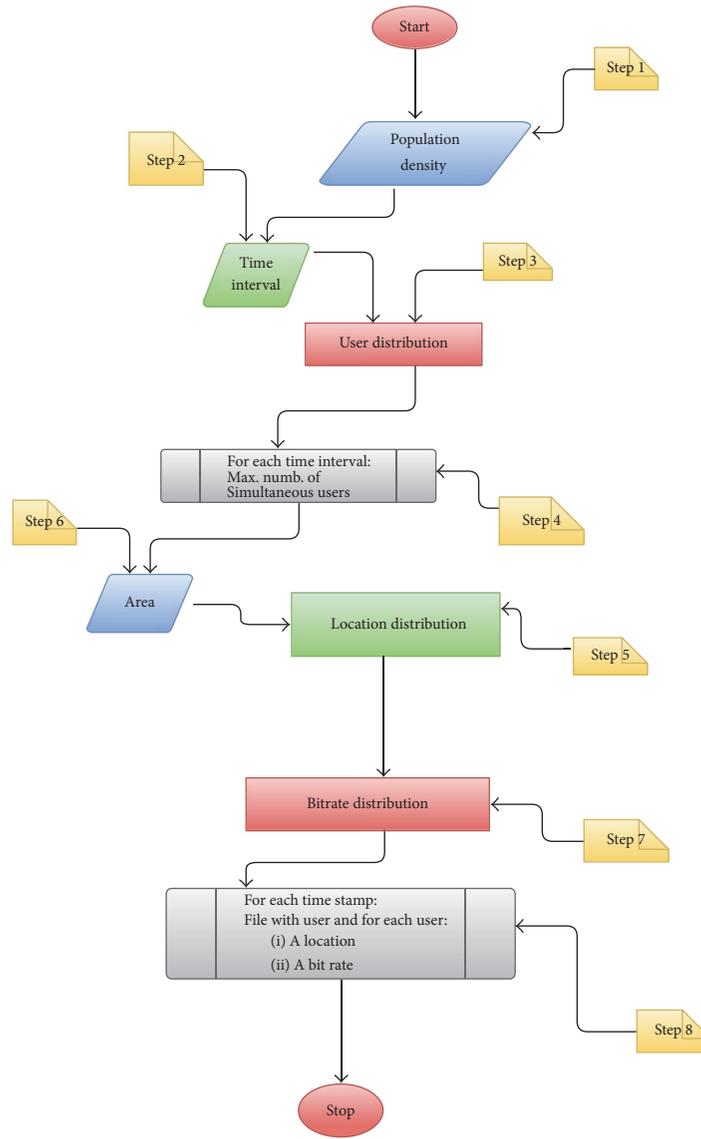


FIGURE 1: Flowchart of the creation of traffic.

traffic file is generated, containing, for each time interval, the maximum number of simultaneous active users. The location of the users in the considered area and the required bit rate are determined. All this information is gathered in a single file for each time interval; there are as many traffic files as the number of simulations. Various distribution functions are put together to produce these traffic files:

- (i) User distribution (Figure 1, step 3): for a requested bit rate (voice and data), this distribution returns the maximum number of simultaneous active users. A distribution based on the confidential data retrieved from a Belgian mobile operator in Ghent has been used, which depends on the population density of the selected area [4].
- (ii) Location distribution (Figure 1, step 6): the location of each user within the selected area of simulation is here defined. A uniform distribution is considered,

meaning that each location in the area has the same chance to be chosen as a user location [4].

- (iii) Bit rate distribution (Figure 1, step 7): based on the confidential data from the mobile operator, this distribution returns the bit rate that the individual user demands for its service. It is assumed that some users making voice calls at 64 kbps and those requesting data transfer need 1 Mbps [4].

Other higher bit rate distribution might be used for the future 5G services. It would require the use of massive MIMO technology to achieve these performances. Here, we have based our analysis on the constraints and data provided by a Belgian operator: the same area of interest, the same environment, the same base station, and user bit rate distributions. This will lead to a fair and realistic comparison between the two technologies.

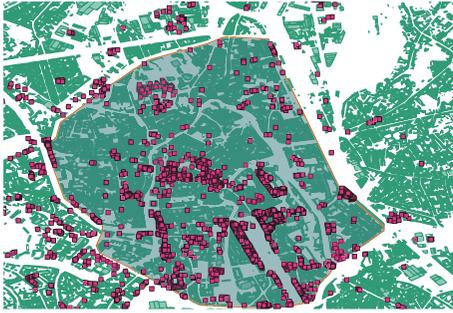


FIGURE 2: Selected area in Ghent, Belgium, and the possible location of the base stations.

3.1.2. *Urban Environment.* In this study, a suburban area of 6.85 km^2 in Ghent, Belgium, has been used for the simulations (Figure 2). The following reference scenarios have been considered:

- (i) Scenario I (reference): 4G network at 2.6 GHz, with 20 MHz bandwidth without MIMO.
- (ii) Scenario II: 5G network at 60 GHz. The bandwidth will be set at 500 MHz.
 - (1) Scenario II.a: 5G network without beamforming.
 - (2) Scenario II.b: 5G network with beamforming implemented at the base station only. The number of antennas will be varied from 8, 16, 32, 64, and then 256.
 - (3) Scenario II.c: 5G network with beamforming implemented at both the base station and the mobile station. The number of BS antenna elements will be changing from 8, 16, 32, 64, and then 256, while on the MS side, the number of antenna elements will be set to 4.

We would like to emphasize that these scenarios will focus on beamforming only, based on the above assumptions. The scenarios whereby the 5G services require high data rates are not examined, since it will require the combination of multiuser massive MIMO technology with beamforming in our analysis. Massive MIMO is a key enabling technology of 5G meant to increase the spectral efficiency by allowing parallel transmissions of user data to match with data-intensive applications [11]. This concept falls out of the scope of this study and will be examined in our further research on 5G.

The scenarios are summarized in Table 1. To ensure at least 96% of 5G users are served, we extended the set of the possible locations of the base stations belonging to an existing Belgian mobile operator. They are indicated with red squares in Figure 2. For a better comparison with the 4G reference network, we assume the distributions described in Section 3.1.1. It is worth mentioning that the simulations have been carried out with the most simultaneous users present, which corresponds to the worst-case scenario. So, a time interval of 36 minutes has been used to allow the

processing of 40 simulations within the 24-hour period (1440 minutes), resulting in the creation of 40 realistic networks. These 40 networks are needed for this time interval to obtain a good estimation of the different parameters. For analysis purposes, the mean value (A_v) and the 95th percentile ($95p$) of the investigated parameters will be considered. This applies to the number of required BSs, the total network power consumption, the capacity, and the coverage provided by the network.

3.1.3. *Generation of the Network.* The algorithm shown in Figure 3 is used to generate many 5G networks in such a way that energy efficiency is guaranteed. The 5G network will be created, for each time interval, based on the traffic file above (Figure 3, steps 1 and 2). Additional input files are needed here: a file containing the extended set of possible locations of the base stations in the considered area, a shape file describing the buildings (location, height, etc.) in the considered environment, a file defining all the link budget parameters for 5G, and, finally, a file consisting of all the typical power consumption values for the different components of the base station. The objective of the algorithm is to provide coverage for each user in the selected area, while optimizing the power consumption of the network. For each time interval of 1 hour, 40 simulations are processed whereby 40 networks are created. In total, for the 24 h time interval, 960 networks will be generated (Figure 3, step 2). The algorithm evaluates the distance between the new user (Figure 3, step 3) in the considered area and the already enabled base station. Based on this distance, the path loss experienced from that enabled base station is calculated and checked whether it is lower than the maximum allowable path loss (MAPL). The latter is the maximum path loss that a transmitted signal can be exposed to while still having sufficient strength at the receiver side to offer the bit rate requested by the user [4]. Of course, depending on the environment, a line-of-sight (LOS) or non-line-of-sight (NLOS) path loss model needs to be used as buildings may block the line of sight between the user and the base station (Figure 2). If the obtained path loss is lower than the MAPL, the new user will be connected on the existing active base station (Figure 3, step 4). Otherwise, if it is not possible to connect to an active one, a new base station will be switched on such that the path loss the user experiences is the lowest one among all the disabled base stations (Figure 3, step 5). At the same time, it should be lower than the MAPL for the user to benefit from the bit rate he requested for his services.

Furthermore, in Figure 3, step 6, the algorithm will check whether users already connected to other base stations can be migrated to this newly enabled base station, since they may experience a lower path loss from this base station. If this is the case, then there is a possibility to reduce the input power of the base station the user is removed from. If no base station can be enabled or all base stations are already active, the user cannot be served. This operation is repeated for all the users defined in the traffic file for a given time interval.

3.2. *Calculation of the Path Loss at Millimeter Waves.* The calculation of both the path loss and the MAPL is based on

TABLE 1: Simulation scenarios.

Scenarios	Beamforming support	Bandwidth [MHz]	Frequency [GHz]	Number of antennas at BS [-]	Number of antennas at MS [-]
4G ref. scenario I	No	500	2.6	1	1
5G scenario II.a	No	500	60	1	1
5G scenario II.b	At BS side only	500	60	8, 16, 32, 64, and 256	1
5G scenario II.c	At both BS and MS	500	60	8, 16, 32, 64, and 256	4

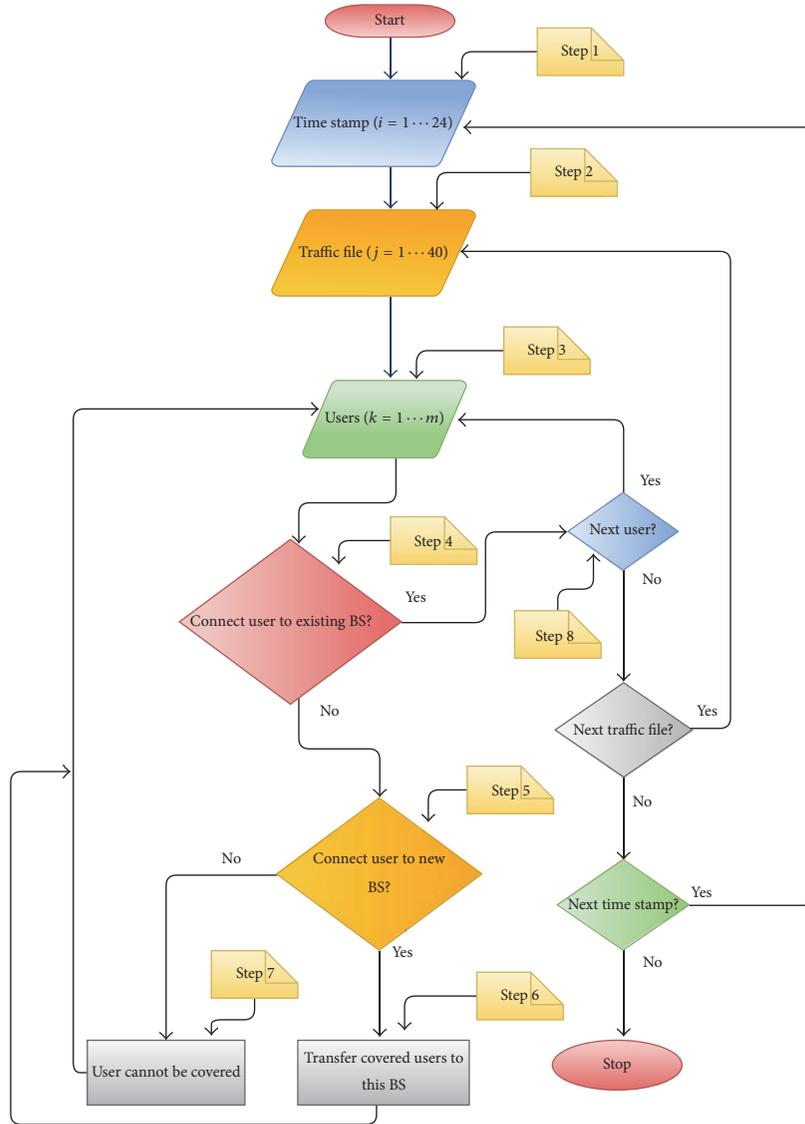


FIGURE 3: Network generation flowchart.

the main link budget parameters for 5G listed in Table 2 [13–18]:

- (i) The beamforming (BF) gain reflects the effect of the use of the multiple antennas at both the base station and the mobile station side. It is defined similarly as $10 \times \log_{10}(N)$ [19], where N is the number of antenna elements at the side where BF is applied. In other words, if BF is applied at the BS side, then N is the number of antennas used at the BS side, and if the MS

is concerned, N is the number of antennas at the MS side. Then, the total antenna array gain is calculated as the sum of the aforementioned beamforming gain and the singular antenna element gain [19].

- (ii) Millimeter-wave atmospheric loss: this parameter accounts for the level of millimeter electromagnetic energy absorbed by gases like oxygen or attenuated by rain or foliage. In this study, we assume a constant value of 3.2 dB for the atmospheric loss at 60 GHz

TABLE 2: 5G link budget parameters.

Parameters	Values
Carrier frequency	60 GHz
Channel bandwidth	500 MHz
Transmit antenna element gain	10 dBi
Transmit array antenna feed loss	3 dB
TX power per base station antenna	10 dBm
Number of receive antenna array elements	4
Receive antenna element gain	6 dBi
SNR	(7.39, 15.4, 17.5) dB ¹
Path loss exponent	3.5
mmWave penetration loss	2 dB
mmWave atmospheric loss	3.2 dB
Implementation loss	3 dB
RX noise figure	7 dB
Other losses (shadow, fading)	20 dB

¹Values of signal-to-noise ratio corresponding to [1/2 BPSK, 1/2 QPSK, and 1/2 16-QAM] [20].

[20]. This parameter introduces an additional attenuation at millimeter waves that must be accounted for since it increases the path loss and therefore reduces the range of the cell.

- (iii) The path loss model: various path loss models related to the millimeter-wave frequency bands are proposed in the literature: the close-in reference distance path loss model [21], the floating-intercept path loss model [21], the alpha-beta-gamma path loss models [22], the Stanford University Intermediate (SUI) path loss models [23], and so forth. In this study, we assume the close-in reference distance path loss model since it is not an empirical model and it offers a substantial simplicity and a reasonable accuracy across many environments and frequency bands [24]. It is applicable to any type of terrain (urban, suburban, or rural) and the propagation coefficient, be it line-of-sight (LOS) or non-line-of-sight (NLOS), expressed through the path loss exponent. The latter takes into account the separation distance between the transmitter and the receiver and the heights of their respective antennas. Equation (1) determines the path loss $PL(d)$ (in dB) at a distance d :

$$PL(d) = PL(d_0) + 10n \log_{10} \left(\frac{d}{d_0} \right) + X_{\sigma}, \quad (1)$$

where n is the path loss exponent for a particular frequency band and environment. It is dimensionless and has been assumed to be equal to 3.5 for the NLOS case [21]; X_{σ} is a zero mean Gaussian random variable with standard deviation σ (in dB) taking into account the fluctuations of the signal resulting from the shadowing and $PL(d_0)$ (in dB). The free space path loss is considered at reference distance d_0 (in m) and defined as follows:

$$PL(d_0) = 10 \log_{10} \left(\frac{4\pi d_0}{\lambda} \right)^2, \quad (2)$$

where λ is the wavelength (in m).

TABLE 3: Power model parameters.

Parameters	Description	Values
P_{trans}	Power RF transceiver per antenna branch	1.5 W
η	Power amplifier efficiency	50%
P_{bhl}	Power backhaul	10 W
P_{cool}	Power cooling system	200 W
P_{rect}	Power rectifier	50 W
P_{dsp}	Power signal processing per antenna branch	1 W

At the millimeter-wave frequency bands, σ is assumed to be equal to 10 dB, d_0 equals 1 m, and $PL(d_0) = 68$ dB [24].

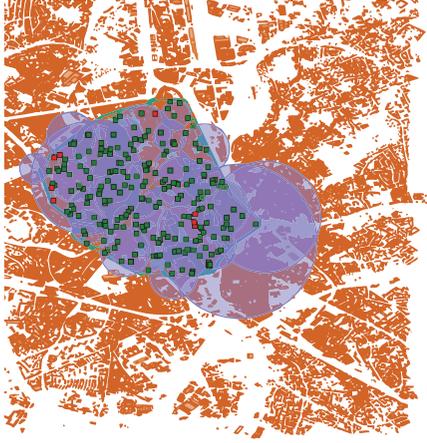
The values of the parameters summarized in Table 2 have been derived according to realistic values found in the literature [2, 5, 13–20]. Based on these 5G parameters, a link budget for the 5G macrocell is designed in order to characterize the expected performance of the considered system. It considers all the gains and the losses at the transmitter and the receiver and in the propagation medium through the receiver.

3.3. Power Consumption Models. Based on the surveys on energy consumption of cellular networks conducted in [25], the base stations appeared to be the most energy-consuming component of the cellular network, with 80% of energy required in the network, compared to the mobile stations and the core network. The main objective of the power consumption model used in this study is to determine realistic input parameters in order to have a clear idea of the power consumption of the 5G wireless networks. Since the simulations focus on the energy efficiency, we implement this model in the deployment tool to assess the power consumption of the network. In Table 3, the power model parameters are summarized.

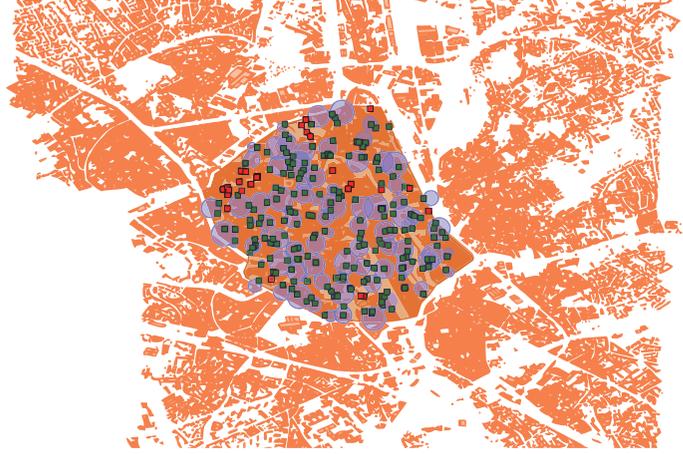
For the 5G base station, we assume the power consumption model defined in [26] whereby the macrocell BS consists of six main power consuming components:

- (i) Digital signal processing (DSP): used for the digitization of the analog signals and their processing.
- (ii) Power amplifier: responsible for the conversion of the DC input power into a significant RF signal.
- (iii) Air conditioning: maintains an acceptable temperature for the base station equipment to work smoothly.
- (iv) Backhaul link: responsible for communicating the backhaul network with the base station. It can be either a microwave link or a fiber one.
- (v) RF transceiver: used for the transmission and reception of the signal at the base station.
- (vi) Rectifier: responsible for the AC to DC conversion needed by the BS equipment.

The power consumption parameters related to these 5G base station components are indicated in Table 3. The air conditioning and backhaul power have constant values, while the



(a) 4G scenario coverage: covered users in green and uncovered users in red



(b) 5G scenario coverage at 500 MHz: covered users in green and uncovered users in red

FIGURE 4: Example of the 4G and 5G network for the reference scenario.

power consumption of the equipment of the base station (the DSP, the power amplifier, and the RF transceiver) scale with the number of antenna elements. To estimate the total power consumed by these last components, we need to multiply their respective power by the number of antennas. The values in Table 3 are assumed for the 5G BS equipment [27]. For the power consumption of the amplifier, the efficiency η (%) of the power amplifier is used instead. It is defined as the ratio of the RF output power to the electrical input power:

$$\eta = \frac{P_{tx}}{P_{amp}} \quad (3)$$

with P_{tx} being the RF output power of the amplifier unit (in W) and P_{amp} being the electrical input power of the amplifier unit (in W). The total power consumption of the base station is given by the equations, depending on the type of beamforming architecture considered:

$$\begin{aligned} P_{DBF} &= N_{ant} \cdot (P_{trans} + P_{dsp} + \eta \cdot P_{amp}) + P_{rect} + P_{cool} \\ &\quad + P_{bhl}, \\ P_{ABF} &= N_{ant} \cdot (\eta \cdot P_{amp}) + P_{trans} + P_{rect} + P_{cool} + P_{bhl}, \\ P_{HBF} &= N_{ant} \cdot (\eta \cdot P_{amp}) + M_{trans} \cdot P_{trans} + P_{dsp} + P_{rect} \\ &\quad + P_{cool} + P_{bhl}, \end{aligned} \quad (4)$$

with DBF, ABF, and HBF standing for digital beamforming, analog beamforming and hybrid beamforming, respectively; N_{ant} is the number of BS antenna elements, M_{trans} is the number of RF transceivers used, P_{trans} is the power consumption of the RF transceiver unit (in W), P_{dsp} is the power consumption of the DSP unit (in W), η is the amplifier unit efficiency, P_{amp} is the electrical input power of the amplifier unit (in W), P_{rect} is the power consumption of the rectifier unit (in W), P_{cool} is the power consumption of the air conditioning (in W), and P_{bhl} is the power consumption of the backhaul link (in W).

3.4. Energy Efficiency Metrics. Deciding which base station provides the better energy efficiency is not simple since various parameters are taken into account (bandwidth, capacity, covered users, etc.). For a better comparison, we will make use of an energy efficiency (EE) metric that takes into account multiple network performance parameters such as the bandwidth, the bit rate, the coverage, and the capacity. The energy efficiency (EE) metric in this study is defined by the following equation [4]:

$$EE = \frac{A \cdot B \cdot U}{P_{el}}, \quad (5)$$

where A is the area covered by the BS (in km^2), U is the number of served users, B is the bit rate based on the base station (in Mbps), and P_{el} is the power consumption of the base station. The higher the EE value, the more energy efficient the network.

4. Results

4.1. Network Performance Comparison without Beamforming. In this section, we evaluate the network performance obtained with the 4G reference scenario and the 5G scenario II.a in Table 1, whereby beamforming is not used at all (neither on BS nor on MS side). For a good comparison of these scenarios, the location of the base stations in the considered area is chosen such that the compared networks serve more than 96% of the users. Figure 4 shows an example of a 4G and 5G network.

Figure 5 shows that the 5G scenario requires more BSs than the 4G reference network (92 BS versus 33 BS). This is explained by the fact that the range of the cell in 5G is 39.6% smaller than the 4G ones based on the assumptions of this study (Figure 4).

However, 5G base stations are less power consuming than 4G ones. There is a reduction of almost 50% in power consumption, despite the higher number of base stations in the 5G networks. In fact, the 5G scenario II.a consumes

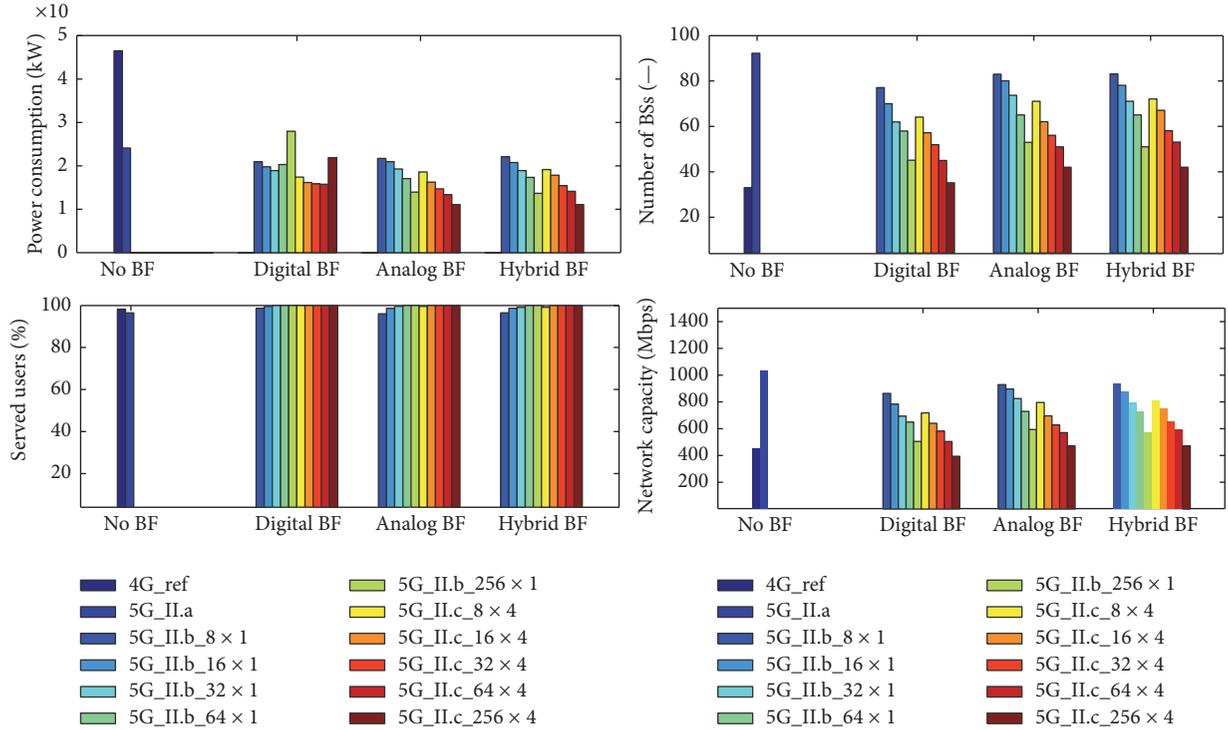


FIGURE 5: Comparison of different parameters when beamforming is used: number of base stations, percentage of served users, power consumption, and capacity offered by the network.

24.1 kW (Figure 5) compared to the 46.5 kW consumed by the 4G reference network. This can be attributed to the new technologies developed by the manufacturers to build low-cost and power efficient RF front-end components [28]. Table 3 shows that, in 5G, the rectifier, the RF transceiver unit, the backhaul link, and the DSP consume 50%, 87%, 87.5%, and 92% less power, respectively, compared to the power consumption of the 4G RF components assumed in [4].

For the entire network capacity (based on the BS), the considered 5G scenario offers higher capacity than the 4G network, 1032.6 Mbps for 5G scenario II.a, while the 4G offers 449.5 Mbps, as shown in Figure 5. This is because the 5G networks use more base stations compared to the 4G ones, as explained above (Figure 5).

Based on the energy efficiency metric defined in Section 3.3, whereby all the above parameters are combined, the 4G reference network is less energy efficient since it does have a smaller EE value compared to the considered 5G scenario (14.6 [km²·Mbps/W] for 4G and 30.6 [km²·Mbps/W] for 5G scenarios II.a). This better performance in terms of EE is sustained by the power consumption of the 5G network, that is, 50% lower than the 4G reference network (Figure 6).

4.2. Influence of the Use of Beamforming. Here, we examine the behavior of the 5G scenarios II.b and II.c described in Section 3.3, whereby beamforming is utilized (Table 4). The results of the simulations are presented in Figure 5.

Based on the digital beamforming architecture, where a transceiver is behind each antenna element, the results show that the more the antenna elements are used, the better the

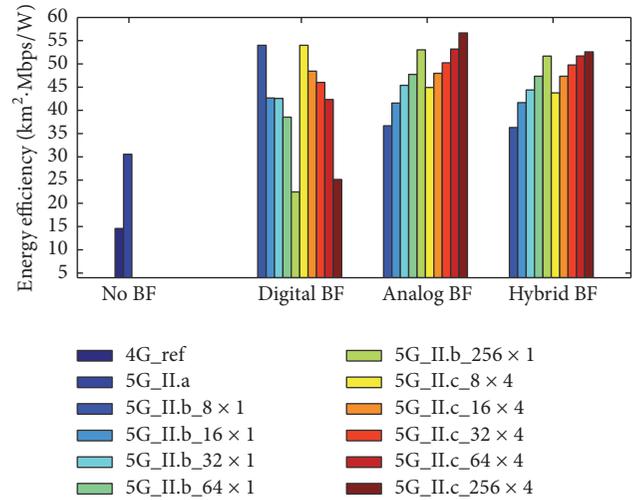


FIGURE 6: Energy efficiency parameter for different beamforming architectures.

coverage provided by the network is. Figure 5 shows that the 5G networks require more base stations than the ones obtained with the 4G reference scenario: +75.4% for scenario II.b 64x1, +36.4% for scenario II.b 256x1, +36.1% for scenario II.c 64x4, and +6.2% for scenario II.c 256x4. The multiple antennas provide additional gains and make it possible to overcome the millimeter waves propagation constraints. This results into a higher MAPL that gives rise to a higher value of the cell range (e.g., when using 256x4, the range increases by

TABLE 4: Simulation results (95 percentile).

Beamforming	Scenario	PC [kW]	# BS [-]	Served users [%]	Area coverage [%]	Network capacity [Mbps]	Energy efficiency [km ² ·Mbps/W]
No beamforming	4G_ref	46.5	33	98.8	98.2	449.5	14.6
	5G_II.a	24.1	92	96.5	45.9	1032.6	30.6
Digital beamforming	5G_II.b_8x1	20.9	77	98.7	65.6	863.5	53.9
	5G_II.b_16x1	19.7	70	99.6	70.4	784	42.6
	5G_II.b_32x1	18.9	62	100	75.5	694.4	42.6
	5G_II.b_64x1	20.3	58	100	78.5	649.6	38.5
	5G_II.b_256x1	27.9	45	100	80.9	505.1	22.5
	5G_II.c_8x4	17.4	64	100	85.2	717.9	53.9
	5G_II.c_16x4	16.2	57	100	79.6	640.6	48.4
	5G_II.c_32x4	15.8	52	100	81.6	582.4	46
	5G_II.c_64x4	15.7	45	100	86.2	504	42.3
	5G_II.c_256x4	21.9	35	100	91.4	394.2	25.1
Analog beamforming	5G_II.b_8x1	21.7	83	96	58.1	929.6	36.7
	5G_II.b_16x1	20.9	80	98.7	64.1	897.1	41.6
	5G_II.b_32x1	19.3	74	99.6	69.4	825.4	45.4
	5G_II.b_64x1	17.1	65	100	72.8	729.1	47.7
	5G_II.b_256x1	13.9	53	100	81.2	593.6	53
	5G_II.c_8x4	18.6	71	99.6	68.6	796.3	44.9
	5G_II.c_16x4	16.2	62	100	73.0	695.5	47.9
	5G_II.c_32x4	14.7	56	100	76.5	628.3	50.2
	5G_II.c_64x4	13.4	51	100	81.1	571.2	53.2
	5G_II.c_256x4	11.1	42	100	81.9	470.4	56.6
Hybrid beamforming	5G_II.b_8x1	22.1	83	96.5	58.2	930.7	36.3
	5G_II.b_16x1	20.7	78	98.7	65.3	874.7	41.6
	5G_II.b_32x1	18.9	71	99.1	69.2	796.3	44.4
	5G_II.b_64x1	17.3	65	100	73.3	729.1	47.3
	5G_II.b_256x1	13.6	51	100	80.4	571.2	51.7
	5G_II.c_8x4	19.1	72	99.1	68.2	807.5	43.8
	5G_II.c_16x4	17.8	67	100	73.2	751.5	47.3
	5G_II.c_32x4	15.4	58	100	76.9	650.7	49.8
	5G_II.c_64x4	14.1	53	100	80	594.7	51.7
	5G_II.c_256x4	11.1	38	100	80.6	470.4	52.6

15.17%). So, when beamforming is applied at both sides, the number of base stations of 5G networks is approaching the 4G ones, specifically when the number of antenna elements is increasing.

Beamforming improves the coverage of the 5G network, in terms of both the area and the served users thanks to the additional gains provided by the multiple antenna elements used. The performance approaches the 4G ones (99%) in terms of served users: 99.6% of the users are covered in scenario II.b (16x1) and 100% in scenario II.c (256x4). In terms of coverage, beamforming improves the coverage of the 5G network by 99% (DBF scenario II.b 256x4), in comparison with the 5G scenario II.a, whereby beamforming is not used.

However, 4G networks still provide better performance: 98% of the considered area is covered while 5G covers 91.4% of the considered area.

In terms of power consumption (Figure 5), when multiple antennas are used on the BS side, the 5G networks consume almost 25% less power (HBF scenario II.b 256x4) than the 4G reference network. This is realized by the technology scaling that allows the manufacturing of very low-power RF front-ends components used in the RF circuits (transceiver, ADC, DAC, mixers, etc.).

When considering a RF beamforming architecture, we obtain similar results (compared to digital beamforming) in terms of number of base stations, served users, and coverage

area. Digital beamforming performances are better than the RF beamforming one: 91.4% of the considered area is covered and 100% of the users are served (scenario II.c 256x4). These performances are achieved since the beamforming function is implemented in the baseband stage where high-speed digital signal processors (DSP) compute complex algorithms that determine the required phase and amplitude of the transmitted signal. This makes the DBF more flexible as it is easy to reprogram the algorithms. However, there is a price to pay, in terms of the power consumption and the cost of implementation, that limits the scalability of the architecture. In fact, the digital beamforming consumes 2 times more power to achieve its performance (Figure 5), compared to RF beamforming. The increase in power consumption is mainly due to the excessive number of RF transceivers and the Analog to Digital Converters (ADC) and Digital to Analog Converters (DAC) required, while the analog beamforming uses only one RF chain to drive the antenna arrays. In addition, the analog beamforming which presents attractive power consumption results has some drawbacks: the phase shifters used in the RF domain have nonideal characteristics that lead to the noise and losses, preventing this architecture from providing similar performances as digital one.

It then becomes obvious to consider a trade-off between the achievement of better performances while meeting the power consumption requirements. For this purpose, a hybrid architecture is proposed [12, 29]. With this architecture, the MIMO precoding and beamforming are performed on the baseband and RF sides, respectively, to allow reasonable number of RF chains required by using 2 to 8 transceivers [30]. In this study, we consider a hybrid architecture with two transceivers. Figure 5 shows that the results are similar (compared to digital beamforming) in terms of number base stations, coverage area, and served users. The requirement of power consumption is also met in hybrid beamforming architecture. It is 2 times less power consuming than the digital beamforming (scenarios II.b 256x1 and II.c 256x4).

(Figure 6) shows that the scenarios II.b and II.c are presenting higher energy efficiency, irrespective of the beamforming architecture used, compared to the 4G reference network: 14.6 [km²·Mbps/W] for 4G, 22.5 [km²·Mbps/W] for 5G scenario II.b 256x1, and 25.1 [km²·Mbps/W] for 5G scenario II.b 256x4. However, the RF and hybrid beamforming architectures are more energy efficient than the digital beamforming: 56.6 [km²·Mbps/W] for ABF 256x4, 52.6 [km²·Mbps/W] for HBF 256x4, and 25.1 [km²·Mbps/W] for DBF 256x4. For the same user coverage (100%), the DBF is performing better in terms of number of base stations; it requires 17% less BS than ABF and HBF, respectively, for scenarios II.c 256x4. Though the RF beamforming architecture is the most energy efficient architecture, based on the considered EE parameter, it does not appear to be the best candidate since it does not cover the considered area as good as the DBF (82% of area covered for ABF 256x4 and 91% of area covered for DBF 256x4). This worse performance in terms of area of coverage may lead to outages during the mobility of the users within the considered area. So, a trade-off needs to be considered between the two architectures. The hybrid beamforming architecture would be recommended

instead since it achieves acceptable performances at low-power consumption, without embarking too many RF front-ends components.

5. Conclusions

In this study, we evaluate the performance of the 5G cellular network using a capacity-based deployment tool. The tool has been proposed to simulate a realistic network that responds to the instantaneous bit rate required by the users, in the considered area of Ghent, Belgium. Various 5G scenarios have been considered for the simulations, whereby suitable link budget parameters, millimeter-wave path loss models, power consumption models, and energy efficiency metric have been used. Based on the results of the simulations, we show that the 5G scenario whereby beamforming is not implemented requires much more BSs than the 4G reference scenario. It is 50% less power consuming and provides 2 times more capacity than 4G. However, it is not a good candidate for network planning because of the poor coverage (46%) of the considered area.

We further extended the analysis to consider multiple antennas and the use of beamforming at both the BS and the MS. The results show that 5G networks supporting beamforming are 3 times more energy efficient than 4G networks, based on the defined energy efficiency parameter. The same 4G network coverage performances are achieved with 4 times less power consumption (scenarios ABF and HBF 256x4). However, among the beamforming architectures considered, the digital beamforming presents better performance than the other two architectures but it does not meet the power consumption requirements. We showed that a trade-off was needed to provide better performances at lower power consumption. This can be achieved with the hybrid beamforming architecture which provides similar results in terms of coverage area, served users, and number of base stations as digital beamforming, while consuming two times less power. So, the hybrid beamforming architecture is a better alternative to digital beamforming to design and deploy 5G networks.

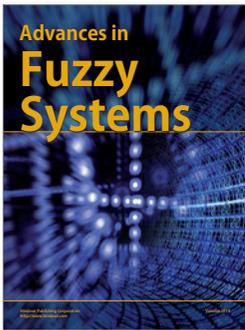
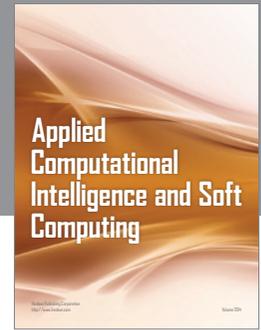
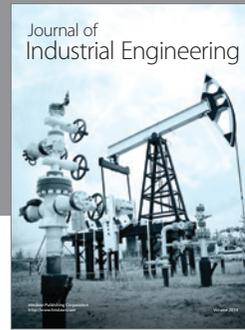
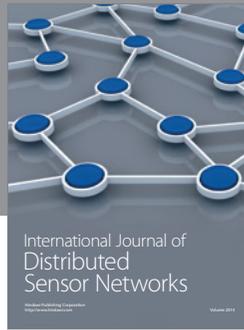
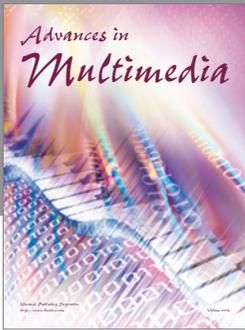
Competing Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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