Simulations of beamforming performance and energy efficiency for 5G mm-wave cellular networks

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***Abstract*— Beamforming is one of the key features enabled in the fifth generation (5G) of wireless communications networks to accommodate the higher throughput demanded by the users for their data-intensive applications. This paper simulates energy-efficient 5G networks with beamforming capabilities deployed on a realistic area in Ghent, Belgium to respond to the instantaneous bit rate needed by the users. Various beamforming architectures have been investigated and the results are compared with the 4G reference network. When beamforming is enabled, the results of the simulations show that under the same coverage performance, 5G networks require 15% more base stations to provide more capacity to the users and are 3 times more energy-efficient than the 4G reference network. Moreover, the hybrid beamforming architecture provides good trade-off between the higher capacity and the low-power consumption requirements and needs to be considered when designing 5G cellular networks.**

***Index Terms*—5G, millimeter wave, beamforming, coverage, power consumption, energy efficiency, network simulation.**

I. Introduction

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. The following new features are enabled in 5G wireless access networks to make it possible, as presented in [1] and [2]: massive MIMO (Multiple Input Multiple Output), beamforming, small dense networks, millimeter wave frequency bands and movable base stations (BS). However, the fast growing data traffic volume and dramatic expansion of network infrastructure will inevitably increase the energy consumption in wireless networks.

In this study, we present how these two technical requirements can be tackled in cellular environments thanks to the system level simulations method. We propose a capacity-based network deployment tool that optimize the positions of BSs within the area of study so as to design energy-efficient 5G wireless networks, while providing at the same time the higher throughput requested by the users. A similar method was used in [3] but was limited to the design of an energy-efficient long term evolution (LTE) network at 2.6 GHz. Here, we implement the beamforming technology with large-scale antennas arrays and the proposed power consumption model for 5G. Moreover, three types of beamforming architectures are investigated: the digital beamforming (DBF), the analog beamforming (ABF) and the hybrid beamforming (HBF). The assessment consists in examining the influence of the use of beamforming technology on the overall network power consumption, network coverage and network capacity. However, massive MIMO and spatial multiplexing features are not investigated since they are out of the scope of this study. Some related works [4]–[6] have discussed the beamforming architectures and investigated the design of the hybrid beamforming with large-scale antennas arrays to meet the same performance of optimal fully digital beamforming in terms of spectral efficiency. The authors showed that hybrid beamforming can achieve same performance of any fully digital beamforming scheme with much fewer number of radio frequency (RF) chains; the required number of RF chains only needs to be twice the number of data streams. To the best of our knowledge, none of these works included the cellular environments within a realistic suburban area.

The rest of this paper is organized as follows: the system model and the assumptions of the study are presented in Section II, followed by Section III which describes the method leading to the design of 5G networks by optimizing the positions of the BSs. Section IV presents the results obtained with the deployment tool with respect to the beamforming technology. We then provide the final conclusions in Section V.

II. System model description

A realistic suburban area of 6.85 km^2 in Ghent, Belgium, has been used for the simulations (Fig. 1). In this area of interest, multiple BSs are deployed, equipped with a large number of antennas, M, operating phase coherently. The BS serves many users and each user is associated to only one BS.

The design of the 5G network is based on a fundamental planning principle whereby at least 95% users are served within the area of interest. Since the dimensioning of a network is done for the traffic at peak hours, the network should be able to handle 224 simultaneous active users in the suburban area. It is assumed that some users are making voice calls at 64 kbps and those requesting data transfer need 1 Mbps. Other higher bit rate distribution might be used for the future 5G services. It would require the use of massive MIMO technology with spatial multiplexing to achieve these performances. Here, we have based our analysis on the realistic constraints and data

Figure 1. Selected area in Ghent, Belgium and the possible location of the BSs

provided by a Belgian operator: same area of interest, same environment, same BS and user bit rate distributions. This will lead to a fair and realistic comparison between the two technologies (4G and 5G).

The users are uniformly distributed within the considered area, meaning that each location in the area has the same chance to be chosen as a user location.

III. METHOD

The method pursued in this analysis proceeds with system level simulations based on the different scenarios defined in Section III.A, by means of the capacity network deployment tool. This latter simulates realistic energy-efficient 5G networks whose number of BSs is optimized to comply with the overall network low-power consumption requirement.

A. Deployment scenarios

The following scenarios have been investigated:

- Scenario I (reference): the 4G network of the Belgian operator operating at 2.6 GHz, with 20 MHz bandwidth (without MIMO) in [3] will serve as baseline for our study. We could have considered a 4G network with MIMO as baseline. However, the confidential data we receive from the Belgian operator did not include any MIMO set up.
- 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 BS only. The number of antennas will be varied from 8, 16, 32, 64 then 256.
  3) Scenario II.c: 5G network with beamforming implemented at both the BS and the mobile station. The number of BS antenna elements will be changing from 8, 16, 32, 64 then 256, while on the mobile station (MS) side, the number of antenna elements will be set to 4.

B. Network optimization algorithm

We propose the algorithm in Fig. 2 in order to optimize the placement of the BSs within the suburban area and generate many 5G networks in such a way that energy efficiency is guaranteed. First, a traffic file containing traffic informations with regards to the number of simultaneous active users at peak hours is generated (Fig. 2, step 2). Additional input files are needed: a file with the set of possible locations of the BSs, two geographic information system (GIS) shapefiles of the investigated area of Ghent (depicting the environment with the buildings'locations and heights), a file with the link budget parameters and finally a file with the power consumption values of the different BS components (Fig. 2, step 3). Based on these informations, the algorithm evaluates the distance between the new user in the considered area and the already enabled BS. Then, the path loss the new user experienced from that enabled BS is calculated and compared to the maximum allowable path loss (MAPL). If the obtained path loss and the requested bit rate are lower than the MAPL and the effective capacity of the BS, respectively, the new user will be connected on the existing active BS (Fig. 2, step 4). Otherwise, a new BS will be switched on provided that the path loss the user experiences is the lowest one among all the disabled BSs (Fig. 2, step 5 and step 6). If no BS can be enabled or all BSs are already active, the user cannot be served (Fig. 2, step 7).

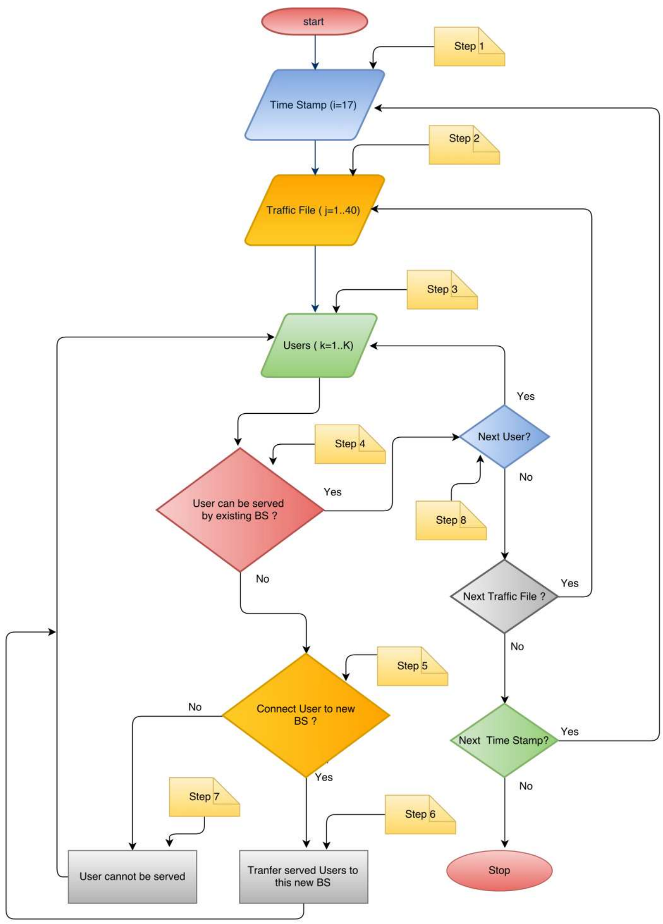

Figure 2. Network optimization algorithm

C. Path loss model

Many path loss models dealing with the millimeter-wave frequency bands are proposed in the literature: the close-in (CI) reference distance path loss model [7], the floating-intercept (FI) path loss model [7], the alpha-beta-gamma path loss models [8], the Stanford University Intermediate (SUI) path loss models [9], probabilistic model, ray-tracing models etc. However, most of these path loss models are empirical and not applicable to many environments as they are specific to the terrains where measurements were conducted. In this analysis, we consider the CI reference distance path loss model as it is not an empirical model and it offers a substantial simplicity and a reasonable accuracy across many environments and frequency bands [10]. The main link budget parameters for 5G listed in Table I have been assumed and used to estimate the path loss experienced by the users.

The CI reference distance path loss model is defined as follows:

$$PL(d) = PL(d_0) + 10nlog_{10}(\frac{d}{d_0}) + X_\sigma \tag{1}$$

Where n is the path loss exponent for a particular frequency band and a given environment. It is dimensionless and has been assumed to be equal to 2 and 3.5 for the line-of-sight (LOS) and non line-of-sight (NLOS) cases, respectively [7]; 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:

$$PL(d_0) = 10log_{10}(\frac{4\pi d_0}{\lambda})^2 \tag{2}$$

Where λ is the wavelength (in m).

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

D. Power consumption models

In cellular environments, the BSs appear to be the most energy-consuming components by the fact that it consumes almost 80% of the total energy required in the network, compared to the mobile stations and the core network [18]. The aim of the proposed power consumption model is to determine realistic input parameters in order to have a precise idea on the power consumption of the 5G wireless networks, based on the beamforming architecture considered. The main BSs' components and their corresponding power consumption values are presented in Tables II and III for the 4G and 5G technology, respectively. 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:

$$\eta = \frac{P_{tx}}{P_{amp}} \tag{3}$$

with P_{tx} the RF output power of the amplifier unit (in W) and P_{amp} the electrical input power of the amplifier unit (in W).

The total power consumption of the BS is modeled by the below equations, depending on the type of beamforming architecture:

$$\begin{aligned} P_{DBF} = N_{ant} \cdot (P_{trans} + P_{dsp} + \eta \cdot P_{amp}) \\ + P_{rect} + P_{cool} + P_{bhl} \end{aligned} \tag{4}$$

$$\begin{aligned} P_{ABF} = N_{ant} \cdot (\eta \cdot P_{amp}) + P_{trans} \\ + P_{rect} + P_{cool} + P_{bhl} \end{aligned} \tag{5}$$

$$\begin{aligned} P_{HBF} = N_{ant} \cdot (\eta \cdot P_{amp}) + M_{trans} \cdot P_{trans} + P_{dsp} \\ + P_{rect} + P_{cool} + P_{bhl} \end{aligned} \tag{6}$$

With N_{ant} the number of BS antenna elements, M_{trans} the number of RF transceivers used, P_{trans} the power consumption of the RF transceiver unit (in W), P_{dsp} the power consumption of the DSP unit (in W), η the amplifier unit efficiency, P_{amp}

Table I
5G LINK BUDGET PARAMETERS [11]–[16]

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 BS 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	40 dB
mmWave atmospheric loss	3.2 dB
Implementation loss	3 dB
RX Noise figure	7 dB
Other losses (Shadow, fading)	20 dB

[1] Values of signal-to-noise ratio corresponding to [1/2 BPSK, 1/2 QPSK, 1/2 16-QAM], [17]

Table II
4G POWER CONSUMPTION PARAMETERS [19]

Parameters	Description	Values
P_{trans}	Power RF transceiver per antenna branch	100 W
η	Power amplifier efficiency	12.8%
P_{bhl}	Power backhaul	80 W
P_{cool}	Power cooling system	225 W
P_{rect}	Power rectifier	100 W
P_{dsp}	Power signal processing per antenna branch	100 W

Table III
5G POWER CONSUMPTION PARAMETERS [20]

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

the electrical input power of the amplifier unit (in W), P_{rect} the power consumption of the rectifier unit (in W), P_{cool} the power consumption of the air conditioning (in W) and P_{bhl} the power consumption of the backhaul link (in W).

E. Energy efficiency metrics

In this study, we 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, the capacity, etc. It is given by the following Equation [3]:

$$EE = \frac{A \cdot B \cdot U}{P_{el}} \tag{7}$$

Where A is the area covered by the BS (in km^2), U is the number of served users, B is the bit rate provided by the BS (in $Mbps$) and P_{el} is the power consumption of the BS (in W). The higher the EE value, the more energy-efficient the network is.

IV. RESULTS

A. 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 described above, whereby beamforming is not used at all (neither on BS nor on MS side). Fig. 3 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. However, 5G BSs are less power consuming than 4G ones. Power consumption is reduced by 50%, despite the higher number of BSs in the 5G networks (Fig. 3). This can be attributed to the new technologies developed by the manufacturers to build low-cost and power efficient RF front-end components [21].

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 offer 449.5 Mbps, as shown in Fig. 3. This is because the 5G networks use more BSs compared to the 4G ones, as explained above (Fig. 3).

Fig. 4 shows that the 4G reference network is less energy-efficient since it does have a smaller EE value compared to the considered 5G scenario (14.6 [km^2 · Mbps/W] for 4G and 30.6 [km^2 · Mbps/W] for 5G scenarios II.a). This better performance in term of EE is sustained by the power consumption of the 5G network that is 50% lower than the 4G reference network., Fig. 4.

B. Impact of the use of beamforming

Here, we examine the behaviour of the 5G scenarios II.b and II.c described in section III.A, when beamforming is utilized. We compare the performance of the different type of beamforming architectures. The results of the simulations are presented in Fig. 3.

When we make use of the digital beamforming architecture where a transceiver is behind each antenna element, the results show that the more antenna elements are used, the better the

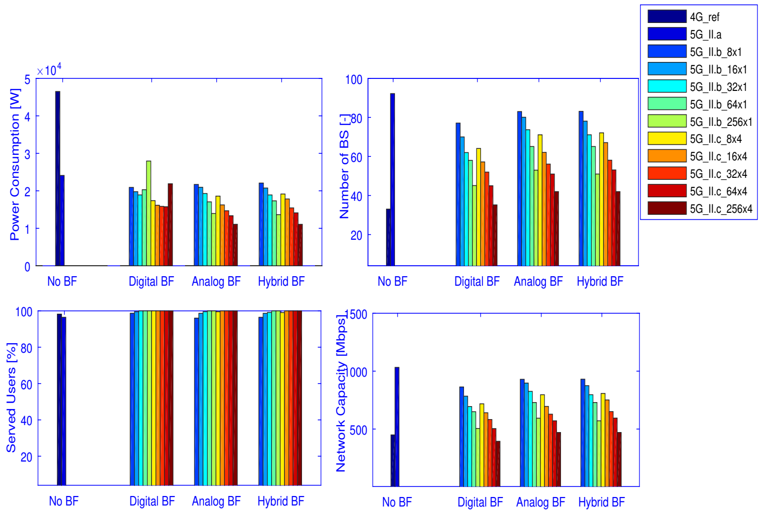

Figure 3. Comparison of different parameters when beamforming is used: number of BSs, percentage of served users, power consumption and capacity offered by the network

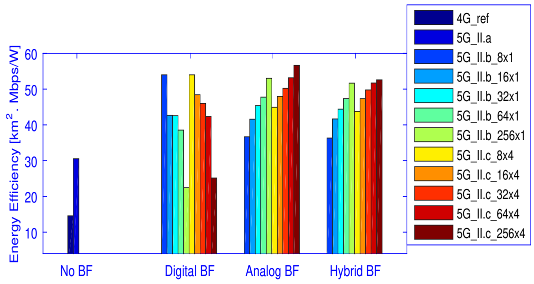

Figure 4. Energy Efficiency parameter for different beamforming architectures

coverage provided by the network is. Fig. 3 shows that the 5G networks require more BSs 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 the 256x4 scenarios, the range increases by 15.17%). So, when beamforming is applied at both sides, the number of BSs of 5G networks approaches that of the 4G ones, specifically when the number of antenna elements is getting larger and larger. Beamforming improves the performance of the 5G networks, in terms of both the area covered and the served users thanks to the additional gains provided by the multiple antenna elements the BSs are equipped with. In fact, the performance of the 5G networks approaches the 4G one (99% of served users) when it comes to the number of the served users: 99.6% of the users are served in scenario II.b (16x1) and 100% in scenario II.c (256x4). However, 4G networks still provide better performance: 98% of the considered area is covered while 5G covers 91.4% of the considered area.

Regarding the power consumption (Fig. 3), when multiple antennas are used on the BS side, the 5G networks consume almost 25% less power (HBF scenario II.c 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, Analog to Digital Converter (ADC), Digital to Analog Converter (DAC), mixers,....

When considering a RF beamforming architecture, we obtain similar results (compared to digital beamforming) in terms of number of BSs, served users and coverage area. However, 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), while RF beamforming covers only 81.9% of the same area. These performances are achieved since the beamforming function is implemented in the baseband stage where the 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 (Fig. 3), compared to RF beamforming. The increase in power consumption is mainly due to the excessive number of RF transceivers and the ADC and DAC required on each circuit power, whilst the analog beamforming uses only one RF chain to drive the antenna arrays. However, the analog beamforming which presents attractive power consumption results has some drawbacks: the phase shifters used in the RF domain have non-ideal 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 [22], [23]. 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 [24]. In this study, we consider a hybrid architecture with two transceivers. Fig. 3 shows that the results are similar (compared to digital beamforming) in terms of number of BSs, coverage area and served users. The requirement of power consumption is also met when we use the hybrid beamforming architecture. This latter consumes 2 times less power than the digital beamforming (scenarios II.b 256x1 and II.c 256x4).

Fig. 4 shows that the scenarios II.b and II.c are presenting higher energy efficiency, irrespective of the beamforming architecture considered, compared to the 4G reference network: 14.6 [km^2 · Mbps/W] for 4G, 22.5 [km^2 · Mbps/W] for 5G scenario II.b 256x1 and 25.1 [km^2 · Mbps/W] for 5G scenario II.b 256x4. However, the analog and hybrid beamforming architectures are more energy efficient than the digital beamforming: 56.6 [km^2 · Mbps/W] for ABF 256x4, 52.6 [km^2 · Mbps/W] for HBF 256x4 and 25.1 [km^2 · Mbps/W] for DBF 256x4. For the same user coverage (100%), the DBF is performing better in terms of number of BSs; 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 (81.9% 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.

V. Conclusions

In this study, we investigate the influence of the use of beamforming in the design of an energy-efficient 5G wireless access network. We propose a capacity-based network deployment tool that simulates realistic energy-efficient 5G networks which respond to the instantaneous bit rate required by the users, in the considered area of Ghent, Belgium. 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.

When beamforming is used, the results show that 5G networks 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). In addition, the digital beamforming presents better performance than the other two beamforming architectures but it does not satisfy 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 with the DBF in terms of coverage area, served users and number of BSs, while consuming 2 times less power. So, the hybrid beamforming architecture is a better alternative to digital beamforming to design and deploy 5G networks.

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