Abstract—One of the first implementations of 5th generation of mobile communication system (5G) will be Fixed Wireless Access (FWA), allowing to provide wideband Internet access to areas inaccessible for optical fiber. Early deployments of FWA in millimetre wave (mmWave) frequency range and with analog beamforming will require accurate evaluation of system performance to ensure that realistic performance in the field meets expectations. In this paper we show that simplified approach for link budget calculation, where the impact of mmWave channel angular spread and the directional antenna pattern are not sufficiently modeled, may lead to overestimation of cell edge capacity by over two times for 5G FWA network in suburban environment. Additionally, we demonstrate that optimization of antenna pattern, by modification of antenna array configuration for analog beamforming matched to angular spread in suburban radio channel, may lead to improvement of 5G FWA cell edge capacity by 60%.

Keywords—5G, angular spread, fixed wireless access, mmWave, suburban.

I. INTRODUCTION

Very first deployments of 5th generation of mobile communication system (5G) are concentrated on enhanced mobile broadband (eMBB) service to satisfy growing demands of end users. Due to limited availability of mobile user devices supporting 3rd Generation Partnership Project (3GPP) standard of New Radio (NR), the earliest deployments of 5G are aiming to provide several Gbps through Fixed Wireless Access (FWA) service. Large band channel width, of several hundreds of MHz, ensured by deployment in millimetre wave (mmWave) frequency range in connection with analog beamforming and multiple-input multiple-output (MIMO) technique allow to provide data throughput comparable to optical fiber access. FWA becomes a particularly convenient solution for mobile network operators (MNOs) who intend to provide eMBB services, like wideband Internet access, to areas where installation of optical fiber infrastructure is difficult or unprofitable.

5G market analysts predict significant growth of FWA deployments in the next few years, e.g. [1] claims the grow from USD 396 million in 2019 to USD 46,366 million by 2026, at a Compound Annual Growth Rate of 97.47% from 2019 to 2026. In the light of these significant investments, it is particularly important to ensure that FWA network is optimally designed and deployed, especially from the point of view of challenges introduced by analog beamforming and radio propagation in mmWave bands.

In this paper we present system level study of 5G mmWave FWA network of small cells in suburban area. We concentrate in particular on the interaction between the narrow beamwidth antenna array of Base Station (BS), via analog beamforming, and the angular spread in multipath environment as determined by Power Angular Spectrum (PAS). In Section II we clarify the difference between the nominal antenna pattern, as measured in anechoic chamber, and the effective antenna pattern, which is experienced in realistic propagation environment. This section introduces also the concept of antenna pattern optimization, which for given scattering environment helps to maximize the signal strength via analog beamforming. Section III includes system level simulation results of 5G FWA network performance, calculated for nominal and effective antenna patterns, and illustrates the improvement of the performance due to introduction of optimized antenna. Conclusion is presented in Section IV.

II. EFFECTIVE AND OPTIMAL ANTENNA PATTERNS

With increasing number of antenna elements in the array the nominal gain of the antenna array, as measured in anechoic chamber, increases and the half-power beam-width (HPBW) decreases. In scattering environment, the maximum realizable antenna array gain, the effective beam pattern and its associated HPBW differ from nominal values. Difference between the nominal and the effective patterns in the radio channel with scattering depends on the angular spread introduced by the real deployment scenarios. Results of measurement campaigns presented in [2] and [3] show that the effective azimuth gain degradation of 4.5 dB or more, in reference to the nominal gain of 14.5 dBi, can be experience by more than half of users in non-line-of-sight (NLOS) propagation conditions. This demonstrates the importance of using effective antenna patterns in non-free space propagation conditions. Fig. 1 illustrates a sample beam pattern of antenna with nominal gain of 14.5 dBi measured in a NLOS environment [4].

Differences between nominal and effective antenna patterns are particularly important in the context of simulation campaigns which aim to estimate performance of 5G system before the commercial deployment begins. Reliable simulation results ensure correctness of minimum requirements for 5G equipment and help to better optimize first 5G networks deployed in the field. Therefore, effective antenna pattern should be used during evaluation studies.

The impact of different propagation conditions on beamforming gain was observed in [5] where the effect of cluster of scatterers for sector beam was investigated.

The need for effective antenna pattern inclusion in system level simulations of mobile networks have been already indicated in [6], where the performance of 4G system was
evaluated via simulation using nominal and effective antenna patterns. Simulation results presented in [6] indicate that up to 40% deviation from realistic value of 4G downlink (DL) throughput can occur when nominal antenna pattern is assumed instead of effective antenna pattern. In [7] the performance of 5G system deployed in Urban Macro (UMa) and Urban Micro Street Canyon (UMi SC) environments, as defined by 3GPP in [8], was compared on the basis of system level simulations. In both cases it was observed that DL Signal to Interference plus Noise Ratio (SINR) can be overestimated by 10 to 17 dB in NLOS scenario when nominal beam pattern is used instead of effective pattern.

Effective antenna patterns assumed in [7] are also evaluated in this paper. Even though the array size and carrier frequency are the same in these two studies, the effective pattern is different due to change of propagation environment, i.e. from urban to suburban. In both cases the effective antenna pattern has been obtained as an average from 1000 convolutions of nominal antenna pattern with single realization of PAS generated according to statistical model describing given environment. Equations (2)-(4) of [7] define effective antenna pattern in 3D, azimuth cut and elevation cut, respectively.

One can notice that in TABLE I the azimuth angular spread is in all cases higher than the zenith angular spread and this relation is valid also in majority of other channel models. LOS states for line-of-sight conditions, whereas VLOS indicates Vegetation LOS, where direct visibility between radio transmitter and receiver is obstructed by vegetation, typical for suburban area.

As directional antenna is performing spatial filtering of electromagnetic energy from the space, it is reasonable to match the antenna pattern to PAS in given propagation conditions. In most of environments the angular spread in horizontal plane is higher than in vertical plane. Therefore, the optimal shape of antenna pattern, i.e. the one which will allow to maximize the energy radiated to or captured from the space, should be wide in horizontal plane and narrow in vertical. Fig. 2 in simplified way illustrates the relation between the shapes of standard (symmetrical) beam, channel angular spread and the optimal beam.

In [4] we presented detailed solution for determination of optimal antenna array geometry for uniform planar arrays in case of analog beamforming, i.e., where all antenna elements (radiators) are connected to a single transmission/reception chain. For convenience, the fundamental part of solution from [4] is disclosed below.

We assumed that $N$ antenna elements, arranged in rectangular/square shape, form a uniform planar array of size $(K_1; K_2)$, with:

$$K_1 K_2 \leq N \tag{1}$$

Array of $(K_1; K_2)=(1; N)$ corresponds to a horizontally deployed uniform linear array, whereas $K_2=1$ indicates a vertically deployed uniform linear array. Let $B_{v0}$ and $B_{h0}$ be the nominal beamwidths of the antenna elements whose gain is $G_e$. The ideal RMS beamwidths $B_{v0}$ and $B_{h0}$, which shall be observed in free space or anechoic chamber, of the analog beams formed by antenna array of size $(K_1; K_2)$ can be approximately described as:

$$B_{v0} = \frac{\theta_e}{K_1}, B_{h0} = \frac{\theta_e}{K_2} \tag{2}$$

Since the directional gain can be related to the RMS beamwidths [7], the effective beamforming gain can be determined based on the nominal antenna pattern and channel angular spread as:

$$G(N, B_{v0}, B_{h0}, \sigma_v, \sigma_h) = \frac{2}{\sqrt{\frac{\theta_e^2}{K_1^2} + \frac{\theta_e^2}{K^2}} + \sigma_v^2 + \sigma_h^2} \tag{3}$$

where $\sigma_v$ and $\sigma_h$ state for RMS azimuth spread of departure (ASD) and RMS zenith spread of departure (ZSD), respectively.

Since the effective gain (3) depends on the panel geometry $(K_1; K_2)$, and $B_{v0}$ and $B_{h0}$ are determined by the antenna element via $G_e$, we can optimize the array geometry $(K_1; K_2)$ to maximize the effective beamforming gain $G$ stated in (3) subject to the size constraint (1). Ignoring the in integer constraint on array dimension $K_1$ and $K_2$, the effective beamforming gain of (3) is upper bounded as:

$$G(N, B_{v0}, B_{h0}, \sigma_v, \sigma_h) \leq \frac{2}{\sigma_v^2 + \sigma_h^2} \tag{4}$$

with equality if and only if the array geometry is given by:

$$K_1 = \sqrt{\frac{N \theta_e \sigma_v}{\theta_e \sigma_v}}, K_2 = \sqrt{\frac{N \theta_e \sigma_h}{\theta_e \sigma_h}} \tag{5}$$
The nearest integer pair close to \( (K_1; K_2) \) as specified by (5) and satisfying the total elements constraint (1) gives the best analog beamforming gain.

Figs. 3 and 4 present antenna patterns in horizontal plane for LOS and NLOS/VLOS propagation conditions, respectively. Patterns have been obtained for antenna array with \( N=64 \) antenna elements per polarization, where for VLOS/NLOS the basic configuration of \( K_1K_2=8x8 \) provides effective gain of around 20 dB (the nominal maximum gain is 24 dB). The optimal configuration, i.e. the one which allows to maximize the effective antenna gain in suburban environment characterized by angular spread from TABLE I, is \( K_1K_2=32x2 \), obtained based on described procedure. However, the antenna array 32x2 has larger scanning loss in horizontal angle than 8x8 array (4.5 dB scanning loss of 32x2 as compare to 3 dB of loss in case of 8x8 array for +/- 60 degree of horizontal scanning angle range). Therefore, the \( K_1K_2=16x4 \) antenna array was selected as the tradeoff. The 16x4 array has only 0.5 dB higher scanning loss as compare to 8x8 array and the effective gain is only 0.2 dB lower than gain of 32x2 array.

Especially in case of 8x8 antenna patterns in NLOS/VLOS presented in Fig. 4, the effect of beam widening and gain drop (around 4 dB) of the main effective beam in comparison to main nominal beam is visible, which corresponds to measurement results presented in Fig. 1. The most interesting observation is the 2 dB increase in effective antenna gain, when antenna array configuration is changed from 8x8 to 16x4. Next section presents impact on 5G FWA performance when effective antenna pattern is used during simulation study instead of nominal antenna pattern for suburban propagation environment, and how much this performance improves when optimal pattern is assumed.

III. SYSTEM LEVEL SIMULATIONS OF 5G FWA IN SUBURBAN

A. Simulation Assumptions

In system level simulations we assumed a suburban area of approximate dimension 700 m \( \times \) 600 m, which consists of 16 blocks. Each block contains 20 houses, 10 per each side of the same street, and is served by 2-sectoral BS. It was assumed that 10% of houses, which are the closest to BSs, have indoor Customer Premise Equipment (CPE), whereas for the remaining 90% of houses an outdoor CPEs were assumed. Fig. 5 illustrates detailed topology of FWA network used for the system level simulations.

For path loss calculation we used empirical models presented in [3] and disclosed in TABLE II. It needs be noted that the path loss model is for omnidirectional antennas, and any study with assumed directional antennas and analog beamforming should either utilize full 3D channel model with angular spread statistics embedded, or effective directional antenna pattern should be used on top of omnidirectional path loss model.

In system level simulations we assumed VLOS conditions for wanted signal links towards outdoor CPEs and for interfering links from other sectors but placed on the same street. LOS path loss model with additional Outdoor-to-Indoor (O2I) penetration loss [11] has been assumed for serving links towards indoor CPEs. That is, VLOS conditions apply for 90% of all simulated wanted signal links, whereas remaining 10% stays in LOS conditions with additional O2I loss. NLOS conditions have been assumed in case of interfering links from BSs placed on other street than the street where victim CPE is placed. All remaining simulation assumptions are included in TABLE III.

![Fig. 2. The optimal beam pattern (and the underlining array geometry using uniform plenary array) should match the channel angular spread to maximize the effective antenna gain [4].](image)

![Fig. 3. Horizontal cuts of nominal and effective antenna patterns for 8x8 and 16x4 configurations in LOS.](image)

![Fig. 4. Horizontal cuts of nominal and effective antenna patterns for 8x8 and 16x4 configurations in NLOS/VLOS.](image)

<table>
<thead>
<tr>
<th>Propagation conditions</th>
<th>Path loss [dB] (d [m]: 2D distance between BS and CPE)</th>
<th>Shadow fading [dB]</th>
</tr>
</thead>
<tbody>
<tr>
<td>LOS</td>
<td>61.4 + 24.0 \cdot \log_{10}(d)</td>
<td>4.2</td>
</tr>
<tr>
<td>VLOS</td>
<td>45.1 + 40.6 \cdot \log_{10}(d)</td>
<td>6.4</td>
</tr>
<tr>
<td>NLOS</td>
<td>80.3 + 31.3 \cdot \log_{10}(d)</td>
<td>4.8</td>
</tr>
<tr>
<td>O2I loss</td>
<td>Mean 15.1 dB, standard deviation 2.5 dB [11]</td>
<td></td>
</tr>
</tbody>
</table>
Fig. 5. Topology of assumed 5G FWA network in suburban area.

B. Simulation Results

Simulation scenario assumes analog beamforming, which in each sector allows to serve only single CPE at a time. It means that all available resources are assigned to single CPE only and therefore the throughput obtained by single CPE is equivalent to the capacity of the whole sector. Maximum Ratio Combining (MRC) type of precoding has been used for determination of beam pointing direction per polarization/stream for analog beamforming.

For calculation of cell capacity the model from 3GPP [10] has been used and is described below (6). This model is based on SINR values obtained from simulation results.

\[
T(SINR) = \begin{cases} 
0, & \text{for } SINR < SINR_{min} \\
\alpha \cdot S(SINR), & \text{for } SINR_{min} \leq SINR < SINR_{max} \\
\alpha \cdot S, & \text{for } SINR \geq SINR_{max} 
\end{cases} \tag{6}
\]

Where:

\[
S(SINR) = \log_2(1 + SINR) - \text{Shannon bound,}
\]

\[
\alpha \cdot S, \text{ for } SINR < SINR_{min}
\]

\[
\alpha \cdot S, \text{ for } SINR \geq SINR_{max}
\]

TABLE IV includes values of \(\alpha\), \(SINR_{min}\) and \(SINR_{max}\) according to 3GPP assumptions from [10].

Simulations have been performed only for DL direction, and the power of interference has been calculated as the sum of DL power received from sectors other than the serving sector, i.e. we assumed only inter-cell interference.

Presented simulation results compare two approaches for system level modelling of propagation phenomena, especially angular spread, and directional antenna patterns for analog beamforming:

- **Nominal**: simulations assume nominal directional antenna pattern and omnidirectional statistical path loss model, without consideration of multipath propagation, especially angular spread. Such approach is allowed in case of link budget calculations for omnidirectional antennas but very often is wrongly assumed also for calculations with directional antennas.

- **Effective**: simulations assume full 3D channel model, where multipath propagation and associated angular spread is included and reflected in link budget calculations also for directional antennas. This approach is equivalent to the calculations with effective antenna pattern and omnidirectional path loss model.

Simulation results are presented in Figs. 6 – 10 and include both assumed antenna array configurations: basic 8x8 and optimized 16x4. For both antenna array configurations, the results for nominal and effective approach of modelling are presented.

Fig. 6 presents Cumulative Distribution Function (CDF) of DL received (Rx) power of wanted signal, i.e. for serving link from own BS. Red curves represent Rx power calculated according to nominal pattern approach, where maximum gains of nominal antennas on BS and CPE sides have been assumed. Due to that, in both cases of BS antenna array configurations, 8x8 and 16x4, the simulation results are the same, as nominal maximum gains of these configurations are identical. The difference between medians of CDF for nominal and effective approaches follow the difference between maximum antenna gains for VLOS presented in figure 4, as 90% of serving links...
are performed in VLOS conditions. In case of 8x8 configuration the difference is as high as 5.5 dB, but for optimal configuration it drops to 3.5 dB. Therefore, the effective Rx power of DL wanted signal increases by 2 dB, only due to change in BS antenna array configuration.

One can claim that optimal antenna, due to widened pattern in horizontal plane, would lead to higher interference and thus negligible benefits of antenna pattern optimization. However, this statement is not justified for noise limited environments, where power of interference between radio nodes is well below the power of noise. Indeed, in Fig. 7 we observe increase of DL interference power when antenna array configuration is changed from 8x8 to 16x4, but at the same time we can see in Fig. 8 that ratio of interference power to noise power (I/N) is below 0 dB for majority of simulated DL links. This proves that simulated FWA scenario is noise limited and improvement of system performance can be expected after antenna pattern optimization. It is also worth to mention the substantial increase of DL interference power when effective approach is used in place of nominal approach, which is caused directly by widening of main antenna beam and increase of side lobes levels, as illustrated in Fig. 4.

Fig. 9 illustrates CDFs of DL SINR, which due to limited interference, follow the shapes of CDFs of DL Rx power of wanted signal. Therefore, we can see that nominal approach leads to overestimation of DL SINR in comparison to effective approach. This can have negative impact on the first real deployments of 5G FWA networks in mmWave, as system performance evaluated wrongly by nominal approach would not be achievable in the field. Again, around 5.5 dB of SINR overestimation is obtained in case of 8x8 configuration, which drops to around 3.5 dB for 16x4 configuration. Looking at curves for effective approach, it can be concluded that optimization of BS antenna array, i.e. change of antenna array configuration from 8x8 to 16x4, allows to improve DL SINR in realistic network of 5G FWA in mmWave by 2 dB, for assumed deployment scenario. It has to be underlined that 2 dB of improvement has been achieved only by the change in antenna array configuration, without any change in Tx power of BS. Therefore, to obtain the same SINR as before antenna pattern optimization, the Tx power of BS can be decreased by 2 dB, e.g. for energy costs savings.
Using the link level performance model described by (6), the DL SINR from Fig. 9 has been translated into DL cell capacity presented in Fig. 10. The results show the spectral efficiency for single stream transmission from one polarization of antenna. In case of MIMO 2x2 the spectral efficiency can be doubled in most of the cases because the cross-polarization ratio (XPR) is quite high in most of the radio channels [8] and could guarantee low inter-stream interference even with open loop MIMO precoding schemes.

Again, the most noticeable are the overestimation of performance when nominal approach is used instead of effective approach and improvement of effective performance when optimal antenna pattern is assumed:

- Overestimation of median cell capacity is around 50% for 8x8 and around 30% for 16x4 antenna array configuration, and more than two times overestimation of cell edge throughput at 10%-tile. This illustrates how significant can be the difference between realistic 5G FWA system performance and simulation evaluations based on nominal approach, which could precede implementations in the field.

- Improvement of DL cell capacity due to antenna pattern optimization, is around 15% for the median and around 60% for 10%-tile of CDF, which can be understood as cell edge capacity.

Detailed comparison of SINR and cell capacity simulation results is included in TABLE V.

### IV. CONCLUSION

We have demonstrated differences in the system level simulation results of mmWave 5G suburban FWA system performance, when so-called nominal and effective approaches are used. It has been shown that simplified and commonly used nominal approach can overestimate realistic cell edge capacity over two times. In a bigger context, such overestimation can lead to inaccurate picture of system performance, capacity and coverage as well as may lead to suboptimal deployments of first 5G networks, which in most cases will be adjustable only after initial filed measurements under real operation conditions. Not only intra-system performance of first 5G deployments can be impacted by inaccurately determined co-existence requirements but also performance of other systems working in the same or adjacent frequency bands can be impacted, as underestimated or overestimated power of interference signals originated in 5G network may lead to wrongly concluded co-existence conditions. Therefore, this paper suggests the effective antenna pattern approach for realistic study of 5G system performance, obtained by accurate modelling of relation between mmWave propagation conditions and directional antenna patterns for analog beamforming.

It has been also presented that with the usage of the method proposed in [4] the performance of mmWave 5G FWA system can be easily improved due to optimization of antenna pattern. For presented simulation scenario the improvement has been obtained by the change in antenna array configuration from 8x8 to 16x4, which allowed to improve the cell edge capacity by around 60%.

### REFERENCES


[8] 3GPP Radio Access Network Working Group, “Study on channel model for frequencies from 0.5 to 100 GHz (Release 15)”, 3GPP TR 38.901 V15.0.0.

