

On the Sub-Terahertz 6G+ Cellular System Requirements for Near-Field Operation

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Abstract—Seeking higher data rates at the air interface, prospective wireless communications systems will eventually occupy the sub-terahertz (0.1-0.3 THz) band. Due to the use of large antenna arrays, a part of the Base Station (BS) coverage will be located in the Near-Field (NF) region, where traditional beamforming is no longer optimal. Beamforming is considered a viable solution for NF communications; however, it requires highly accurate positioning techniques and timely feedback. The aim of this poster is to assess the system-level requirements for cellular systems in terms of positioning accuracy and feedback delay for beamforming and beamfocusing in the NF region. Using mean spectral efficiency as the metric of interest, we characterize the gains as a function of carrier frequency, positioning accuracy, and feedback delay. Our results show that efficient use of beamforming in the NF region requires positioning accuracy below 1 mm and feedback delay below 0.1 ms, which impose very stringent constraints on its support in future cellular systems and question its practicality. Instead, beamforming, although originally designed for Far-Field (FF) conditions, may be well-suited for NF due to its reduced sensitivity to positioning errors.

I. INTRODUCTION

The use of the sub-terahertz frequency band (0.1-0.3 THz) is critical for further evolution of cellular systems. In addition to the impact of blockage, atmospheric absorption, and micromobility that is well documented so far [1], for the first time in cellular systems' evolution, they will be required to operate in the Near-Field (NF) region of the Base Station (BS) antenna [2]. The Received Signal Strength (RSS) in the NF region depends not only on the BS-to-User Equipment (UE) distance but also on the specific coordinates of the antenna array elements and fluctuates rapidly even under small rotations and displacements of the UE [3]. Thus, stable link operation may require waveform formation techniques different from relatively low-complexity beamforming utilized in the Far-Field (FF) [4], *e.g.*, beamfocusing and/or non-diffractive beams, such as Bessel beams [5].

Both beamfocusing and non-diffractive wavefronts are associated with their own challenges. Non-diffractive beams are currently limited in terms of propagation distance and difficult to generate using antenna arrays [6]. In contrast, beamforming can be easily generated using conventional arrays, making it a first-choice technique for NF operation. However, beamforming requires extremely precise and timely positioning information at the BS to operate efficiently.

The aim of this poster is to assess the requirements for 6G+ THz systems that will rely on the use of beamfocusing techniques for NF operation. Specifically, using Spectral Efficiency (SE) as the metric of interest, we study the effects of positioning accuracy and feedback delay. We cross-compare the results with those obtained using conventional and optimal beamforming techniques. Our main observations are:

- in ideal conditions, with a feedback delay of 0.1 ms and positioning accuracy of 1 mm, beamfocusing outperforms beamforming by 25-30% in terms of SE;
- beamfocusing performance falls by up to 60% when feedback delay increases to 10 ms, and beamforming shows a better SE for any positioning error in the range 1-10 mm;
- as the speed of users increases to higher than 5 m/s, beamforming becomes the best approach for NF operation.

II. METHODOLOGY

We consider a Multiple Input Single Output (MISO) system operating at $f=140$ GHz and $f=300$ GHz with a 128×128 element Uniform Rectangular Array (URA) with half-wavelength element spacing at the Transmitter (TX), and a single antenna at the Receiver (RX). The diagonal of the array is $D = 128\sqrt{2}\frac{\lambda}{2}$, which is 193 mm at 140 GHz and 90.5 mm at 300 GHz, and therefore the radiating NF limit is located at $\frac{2D^2}{\lambda} = 34.8$ m and $\frac{2D^2}{\lambda} = 16.4$ m, respectively. We set the initial distance between the TX and the RX to 1 m.

We generate the TX beamforming coefficients by four different schemes. (i) *Beamforming*, where each antenna element transmits the same amount of power, and the phases for each antenna are configured such that their signal constructively combines in the FF in the direction of the RX. (ii) *Beamfocusing*, where each antenna transmits the same power, and the phases are configured such that the signal constructively

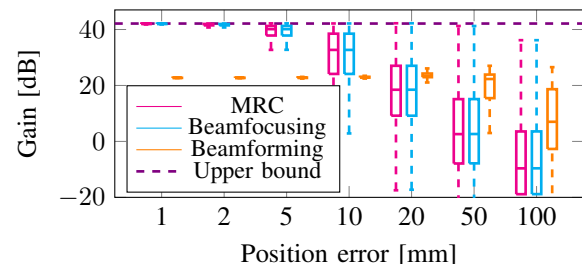
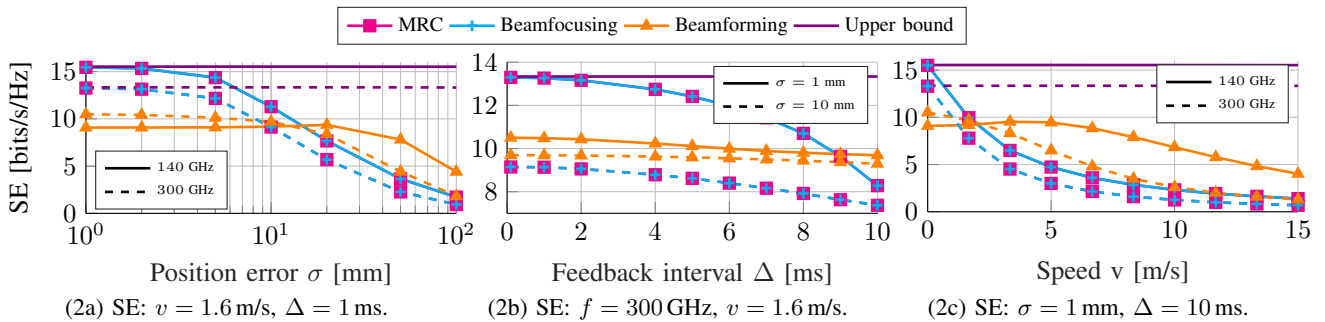


Fig. 1: NF gain degradation with the receiver at 1 m.



combines at the exact position of the RX. (iii) *Maximal Ratio Combining (MRC)*, where the phases are set as in beamfocusing, and the amplitudes are optimized according to [7]. (iv) *Upper bound*, which is equal to the MRC with exact locations, *i.e.*, not affected by positioning error.

We design the beam for a fixed RX location x_{RX} , and evaluate the received power under receiver position uncertainty, *i.e.*, at $\hat{x}_{RX} = x_{RX} + w$, where w is a three dimensional zero mean Gaussian random variable with covariance matrix $\sigma^2 \mathbf{I}$, where \mathbf{I} is the 3×3 identity matrix. The localization error σ is swept over a wide range, from perfect position knowledge up to errors on the order of several centimeters. In addition to position uncertainty, short-term mobility is introduced. The RX moves once over a short time interval Δ , corresponding to the feedback delay. The displacement magnitude is given by $v \cdot \Delta$, where v is the constant velocity. The motion direction is drawn randomly and uniformly, resulting in isotropic motion.

We repeat this procedure 10^5 times to densely cover the entire NF region and evaluate the resulting gains, which are then converted into signal-to-noise ratios assuming a system bandwidth of 20 GHz, a noise power spectral density of -160 dBm/Hz, and a transmit power of 23 dBm. By default, the feedback delay is set to $\Delta = 10$ ms and a RX mobility speed of $v = 1.66$ m/s. The ultimate performance metric is SE, computed using the Shannon formula and then averaged across all Monte Carlo trials.

III. RESULTS AND INSIGHTS

We begin with Fig. 1, which shows the gain degradation as a function of σ at 140 GHz. The result highlights how MRC and beamfocusing are efficient but sensitive to σ , whereas beamforming maintains a gain that is more robust—albeit lower for very accurate positioning with errors below 10 mm.

Fig. 2a shows the SE as a function of σ at 140 and 300 GHz with 1 ms feedback delay. For small values of σ , the SE is above 10 bits/s/Hz for all methods that may not yet be practically achievable due to hardware constraints. As σ increases, the performance of beamfocusing and MRC significantly degrades. In contrast, beamforming is less efficient in favorable conditions but more resilient to positioning error, resulting in higher SE for large values of σ .

The feedback delay of 1-10 ms is feasible for the modern cellular design, where it is tied to the notion of a frame. Fig. 2b¹ shows the dependence of SE on the feedback in-

terval at 300 GHz for a fixed user speed of 1.6 m/s and two position errors (1 and 10 mm). Beamforming in the NF is almost insensitive to feedback delay, whereas beamfocusing is strongly affected, particularly at very small positioning errors. In particular, with a 10 ms feedback delay, beamforming outperforms beamfocusing even under near-perfect positioning accuracy (*i.e.*, 1 mm). This highlights that beamforming is much less demanding in terms of feedback delay.

The speed of the user is a critical parameter that may affect the performance of wavefront formation techniques. To this end, Fig. 2c shows the impact of user speed for a positioning error of 1 mm and realistic feedback delay of modern cellular systems – 10 ms. Beamforming consistently outperforms beamfocusing for speeds above 3 m/s (approximately cycling speeds), particularly at 140 GHz. This trend is also relevant for higher speeds, albeit with a reduced gain. Given that cellular systems must support user speeds of up to 30 m/s, *the practical efficiency of beamfocusing in the NF region is questionable.*

While these are preliminary results and a more general evaluation is needed, the results show that *beamforming, despite being designed for FF conditions, can be well suited for NF thanks to its lower sensitivity to positioning errors.*

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¹Note that the scale is different from other figures for better readability.