

Providing Extreme Mobile Broadband Using Higher Frequency Bands, Beamforming, and Carrier Aggregation

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Abstract—To meet future demands on user experience and traffic volumes, mobile networks need to evolve towards providing higher capacities and data rates. In this paper we investigate the feasibility of incorporating higher frequency bands (15 GHz) and beamforming to support this evolution. We see that using user-specific beamforming, the challenging propagation conditions at higher frequencies are mitigated and outdoor-in coverage is often possible. In places where 15 GHz coverage is not satisfactory, swift fallback to a lower frequency band is essential. This is seamlessly provided by carrier aggregation with a 2.6 GHz band. Together these components provide a ten-fold increase in capacity over a reference system operating only at 2.6 GHz.

I. INTRODUCTION

The next generation of mobile communication, 5G, needs to extend far beyond previous generations in order to cope with new use cases and increased demands on data rates, capacity, latency, and reliability. This will be realized by continued development of the 3GPP long-term evolution (LTE) in combination with new radio access technologies. Today, we foresee that an overall 5G wireless access consists of two key elements; backwards-compatible LTE evolution, and a new radio access technology, here denoted 5G-NX. 5G-NX will likely be deployed at new spectrum, primarily above 6 GHz, mainly due to the availability of larger bandwidth. Since 5G-NX primarily aims at new spectrum bands, it may be non-backwards compatible to LTE, enabling higher flexibility to achieve the 5G requirements [1].

Extending operation to higher frequencies gives opportunities to use large bandwidth but also poses challenges due to worse radio wave propagation conditions. For example, the diffraction and building propagation losses increase considerably with frequency. One way to mitigate the increased propagation loss is to use beamforming at the base stations (BSs). Since the effective antenna area decreases with frequency, it is possible to employ antenna arrays with many elements while keeping the physical size relatively small.

In this paper, we investigate the potential of using a macro deployment at 15 GHz in a dense urban scenario. The potential of using massive beamforming to mitigate the high propagation loss at 15 GHz is evaluated. To enable coverage for places where the massive beamforming is not sufficient, carrier aggregation with a 2.6 GHz carrier is also considered.

These systems are compared with a reference system without beamforming operating at 2.6 GHz.

II. NETWORK LAYOUT AND SYSTEM MODEL

A. Scenario

We evaluate user and system performance of a reference LTE system operating at 2.6 GHz and a model of a potential 5G-NX system operating at 15 GHz. Furthermore, carrier aggregation of LTE at 2.6 GHz with an LTE system operating at 15 GHz, and carrier aggregation of LTE at 2.6 GHz with 5G-NX at 15 GHz is evaluated. The simulations have been performed using an in-house static system simulator with a model of a dense urban scenario. A synthetic city model has been created, inspired by the downtown areas of large Asian cities such as Tokyo and Seoul. The constructed model consists of a 2×2 km² square area where there are 1442 multi-floor buildings with different heights, distributed between 16 m and 148 m. The city model is depicted in Fig. 1.

We assume that the traffic is served by a macro network with an inner and an outer layer, with different inter-site distances (ISDs) and average antenna installation heights. The BS antennas are located at rooftop edges of average-height buildings. For the inner layer with high-rise buildings, 7 three-sector macro sites with 45 m average installation height are considered. In the inner layer, the average ISD is 200 m, while the outer layer consists of 28 three-sector macro sites with an average 30 m installation height, and an average ISD of 400 m. The site positions are shown in Fig. 1. The LTE and 5G-NX systems are assumed to be deployed on the same site grid. 80% of the traffic demand is assumed to be generated inside the buildings. Traffic is simulated in the entire 2×2 km² area but, in order to mitigate the border effects of simulating a finite network, performance is evaluated only for the users located inside the central 1×1 km² square. Hence, the evaluated performance is dominated by the users located in the high-rise city center.

B. Beamforming

A key technical component of 5G-NX is user equipment (UE)-specific beamforming. This has potential to mitigate the increased propagation loss at higher frequencies and to increase the performance by spatially focused transmission and reception [1], [2]. UE-specific beamforming is also included

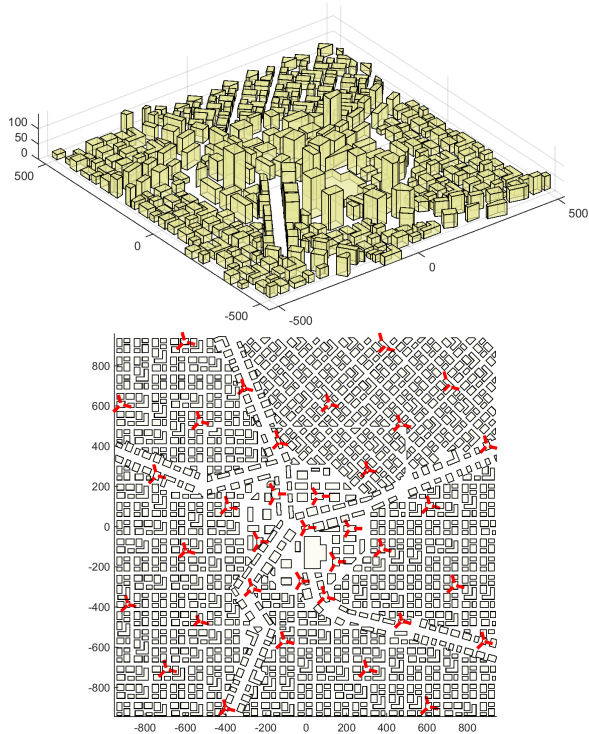


Fig. 1: City model in the evaluation area (top) and site deployment in the entire simulation area (bottom).

in the LTE standard, but we foresee that 5G-NX will provide better support for beamforming with a large number of antenna elements than in current LTE releases.

In this paper, a long-term, wideband covariance-based grid-of-beams beamforming approach is considered for the 5G-NX system. The beam grid is created by applying discrete Fourier transform (DFT) weight vectors over the antenna elements. The beamforming is separable in azimuth and elevation so that separate DFT vectors are applied over the antenna array columns and rows. For each UE, the beam in the grid that gives the highest beamforming gain is selected. The beamforming gain for a candidate beam in a given cell is proportional to the power, P , that would be received by the UE if that beam was used for transmission. This is calculated according to

$$P = \mathbf{w}^H \mathbf{R} \mathbf{w} \quad (1)$$

where \mathbf{w} is the candidate beamforming weight vector and \mathbf{R} is the channel covariance matrix between the BS antenna elements and the first antenna on the UE.

The channel covariance matrix is calculated using the propagation models introduced in Section II-C. We assume that the antenna array at the base station has dual-polarized antenna elements. The UE-specific beamforming is performed per polarization and it is assumed that the channel for the two polarizations are uncorrelated. The two polarizations are used for single- or dual-layer transmission, depending on the channel conditions. In the 5G-NX simulations we assume a rectangular array with 5 columns and 20 rows of dual-polarized elements.

In the evaluations of LTE performance we assume that the LTE system does not employ UE-specific beamforming. Although there is support for UE-specific beamforming in LTE, and this support will be extended in future releases, many LTE systems deployed today use two transmitters connected to two antenna ports with orthogonal polarization so that beamforming is not utilized. Hence, the evaluated LTE performance is not supposed to represent LTE performance in the time-frame when 5G-NX will be deployed, but rather the performance of an early LTE deployment.

C. Propagation Model

The propagation model is composed of several sub-models taking into account free-space propagation in line-of-sight (LoS), diffraction modeling in non-line-of-sight (NLoS), reflections, building penetration loss (BPL), and indoor loss [3]. The basis for each of these sub-models has been taken by selecting appropriate models described in the COST 231 Final Report [4]. To account for angular spread, parts of the ITU statistical cluster model in [5] is also used.

Furthermore, frequency-dependent models for BPL and indoor loss are adopted based on [3] with some modifications as described below. In this model, the BPL is defined based on the type of the building characterized by building material (e.g. the percentage of concrete walls and glass walls, the thickness and type of the walls, etc.). Two different building types are considered, referred to as old and new. The old buildings are assumed to consist of 20% two-layered glass windows and 80% concrete and is more common in the low-rise area of the city, whereas the new buildings consist of 90% infrared reflective glass (IRR) and 10% concrete and has a higher occurrence in the high-rise area of the city.

The indoor environment is assumed to be open, with standard, alternatively plaster, indoor walls. The loss model per wall is calculated as a function of the carrier frequency and an average wall distance (D_w) based on (3a), (3b), and (2). The basic approach in the model is to assume different values for the indoor loss per meter, L , for indoor distances that are below a certain threshold and for those that exceed this threshold according to

$$L = \begin{cases} \alpha_1, & \text{if } d \leq d_{break} \\ \alpha_2, & \text{for } (d - d_{break}) \text{ if } d > d_{break} \text{ and } f > 6 \\ \alpha_1, & \text{if } d > d_{break} \text{ and } f < 6 \end{cases} \quad (2)$$

where f is the frequency expressed in GHz. Furthermore,

$$\alpha_1 = (0.15f + 1.35)/D_w \quad [\text{dB}] \quad (3a)$$

$$\alpha_2 = \alpha_1 / (0.05f + 0.7) \quad [\text{dB}] \quad (3b)$$

where D_w is the distance in meters between two walls.

D. Antenna Model

In the LTE simulations, the BS antenna is assumed to be a standard macro antenna with electrical and mechanical tilt, with an antenna gain of 18 dBi. The BS antennas are assumed to have a 65° azimuth half-power beam width (HPBW) and 6.5° elevation HPBW. The radiation pattern is modeled with a

Gaussian main beam and constant sidelobe floors according to [6], but with other parameter settings¹. Cell-individual tilt values were set based on internally developed tilting guidelines. We assume the same BS antenna radiation pattern model for LTE at 2.6 GHz and 15 GHz, using the same antenna gain. This implies a correspondingly physically smaller antenna at 15 GHz.

In the 5G-NX simulations, the BS antenna is assumed to be a rectangular array with 5 columns and 20 rows of dual-polarized antenna elements separated by 0.7 and 0.6 wavelengths in the horizontal and vertical dimensions, respectively. This corresponds to a physical antenna size of $7 \times 24 \text{ cm}^2$. The radiation pattern of a single antenna element is modeled by the same model as described for LTE above, but with 65° azimuth HPBW, 90° elevation HPBW, and 8 dBi gain. Thus, the maximum antenna gain is 28 dBi.

The UEs are assumed to be equipped with two receive (Rx) branches and one transmit (Tx) branch. For LTE, the UE antennas are assumed isotropic with 0 dBi gain. For systems operating at 15 GHz, we expect that directive UE antennas will be used. We assume that the UE can select the best antenna between several, physically displaced, directive antennas covering different angular sectors. In this way, some body obstruction loss can be mitigated. We assume 6 dBi antenna gain and 3 dB losses for 5G-NX and LTE operating at 15 GHz, while for LTE at 2.6 GHz we assume 8 dB losses.

E. Node Selection

In the LTE evaluations, node selection is based on highest reference signal received power (RSRP). In the 5G-NX evaluations, we assume that the UE is served by the best beam, providing the highest received power, in the entire network. Since a search over all beams in the network for all UE positions is too computationally demanding in the simulator, we adopt a simplified approach consisting of a two-stage procedure. In the first step, the best node is found based on the radiation pattern of a single antenna element. In the second step, we select the best beam offered by the node by picking the beam with highest received power according to (1). With the used system model, this approach will give essentially the same result as a full search.

F. Carrier Aggregation

With carrier aggregation, BSs can schedule UEs on both the 2.6 GHz and the 15 GHz band. This enables higher data rates, corresponding to the sum of the data rates of the aggregated carriers. In addition, carrier aggregation balances the load between the carriers. This is of extra importance in scenarios with unequal coverage between the aggregated carriers. In this study, the traffic for a UE allocated to each carrier is proportional to the data rate on the carriers. Hence, carrier aggregation “offloads” each layer from traffic from the UEs requiring the most resources. In the case of aggregating co-sited 2.6 GHz and 15 GHz carriers, the UEs with the worst

channel gain will steer most of their traffic to the 2.6 GHz band, resulting in the 15 GHz band being more efficiently used.

III. SIMULATION SETUP AND RESULTS

A. Simulation Setup and Methodology

In the reference scenario, the traffic is assumed to be served by a frequency division duplex (FDD) LTE system with 2×2 MIMO configurations operating at 2.6 GHz with 40 MHz bandwidth. This case represents the performance of typical current deployed networks. We also consider three futuristic systems that are relevant for year 2020 and beyond. First, we assume an LTE carrier aggregation scenario with 140 MHz total bandwidth of which a 40 MHz FDD carrier is at 2.6 GHz and a 100 MHz time division duplex (TDD) carrier is at 15 GHz, each with 2×2 MIMO configurations. The reason for choosing TDD for the 15 GHz carrier is that spectrum around 15 GHz will probably be unpaired. Additionally, TDD simplifies beamforming since channel reciprocity can be utilized. This case might represent a transition scenario where LTE has been evolved to allow higher bit rates and carrier frequencies. Moreover, we consider two cases using the new, 5G-NX system which is characterized by massive UE-specific beamforming. The 5G-NX system is assumed to operate in TDD mode. In one case, the 5G-NX stand-alone system is deployed at 15 GHz using an 5×20 antenna array to cope with the traffic demand in the network. In another case, we assume that 5G-NX at 15 GHz is deployed together with the existing LTE at 2.6 GHz using carrier aggregation. When using carrier aggregation, traffic is divided between the carriers proportional to the data rate of the carriers. The aggregated data rate is the sum of the data rates per carrier. Other models, e.g. propagation and antenna models, are not affected by carrier aggregation.

In summary, the following four simulation cases are considered:

- Case 1: Stand-alone LTE operating at 2.6 GHz (LTE@2.6)
- Case 2: Carrier aggregation of one LTE system operating at 2.6 GHz and one LTE system operating at 15 GHz (LTE@2.6+LTE@15)
- Case 3: Stand-alone 5G-NX operating at 15 GHz (5G-NX@15)
- Case 4: Carrier aggregation of an LTE system operating at 2.6 GHz and a 5G-NX system operating at 15 GHz (LTE@2.6+5G-NX@15)

The performance of these systems is evaluated considering the network layout presented in Fig. 1. For the carrier aggregation cases, all sites and UEs in the network are assumed to have the multi-RAT capability. We consider that all systems are employing a frequency reuse of one, i.e., the same time and frequency resources are used for transmission in each cell, and there is no cooperation among sites. The detailed assumptions on simulation parameters are listed in Table I.

¹The following sidelobe floors have been used: horizontal pattern = -25 dB, vertical pattern = -17 dB, combined pattern = -30 dB.

TABLE I: Simulation Assumptions

Parameter	Value			
	(Case 1/Case 2/Case 3/Case 4)			
Carrier frequency	2.6 / 2.6+15	/ 15 / 2.6+15	GHz	
Bandwidth	40 / 40+100 / 100 / 40+100		MHz	
Duplex scheme	FDD / FDD+TDD / TDD / FDD+TDD			
UE antenna gain incl. body obstruction loss	-8 / -8 + 3 / 3 / -8 + 3		dB	
Beamforming at BS	None / None+None / UE-specific / None			
Max BS antenna gain	18 / 18 + 18 / 28 / 18 + 28		dB	
Tx power, BS			46 dBm	
Tx power, UE			23 dBm	
Number of UE Rx/Tx branches			2 / 1	
TDD configuration			5	
Noise figure, UE			9 dB	
Noise figure, BS			2.3 dB	
Traffic Model	Packet download, equal buffer			
Indoor traffic			80%	
Distance between two indoor walls			$D_w=4$ m	
Indoor threshold distance			$d_{break}=10$ m	

B. Signal-to-Noise Ratio

Fig. 2 shows cumulative distribution functions (CDFs) of downlink (DL) signal-to-noise ratio (SNR) for LTE@2.6, LTE@15, and 5G-NX, respectively. The figure shows that increasing the frequency from 2.6 GHz to 15 GHz, while keeping the same BS antenna radiation pattern, gives a large SNR loss due to the increased propagation loss. At the 5-percentile, the SNR of LTE@15 is 32 dB lower than LTE@2.6. A small part (4 dB) of this loss is due to that the bandwidth is also increased from 40 MHz to 100 MHz when increasing the carrier frequency, while the total Tx power is the same. This results in 4 dB reduced Tx power spectral density. Operating LTE@15 stand-alone in this scenario does not give satisfactory performance due to the very low SNR values.

With 5G-NX, UE-specific beamforming together with a higher maximum BS antenna gain makes the median SNR the same as for LTE@2.6. There is a larger spread in SNR among UEs for 5G-NX compared to LTE@2.6 since there is a larger difference in propagation loss between indoor/NLoS UEs and outdoor/LoS UEs at the higher frequency. At the 5-percentile, the SNR for 5G-NX is 6 dB lower than for LTE@2.6. For a few UEs, the SNR goes even below -20 dB due to large BPL and indoor loss. For a majority of the UEs, however, the SNR is very high; above 30 dB. This is due to that a majority of the UEs have LoS to the serving node antenna, where LoS for indoor UEs means that there is LoS from the external wall to the serving node antenna.

SNR does not give the complete picture on performance since interference is also important to consider, especially at high traffic load. UE-specific beamforming is useful also for mitigating interference in the system. In the next section, the impact of interference is taken into account by presenting results on user throughput and traffic capacity.

C. User Throughput and Capacity

The DL end-user performance of the evaluated systems is illustrated in Fig. 3 as 5-percentile and 50-percentile user throughput vs. area traffic demand. A typical traffic demand year 2014 for the modeled scenario is estimated to around 200

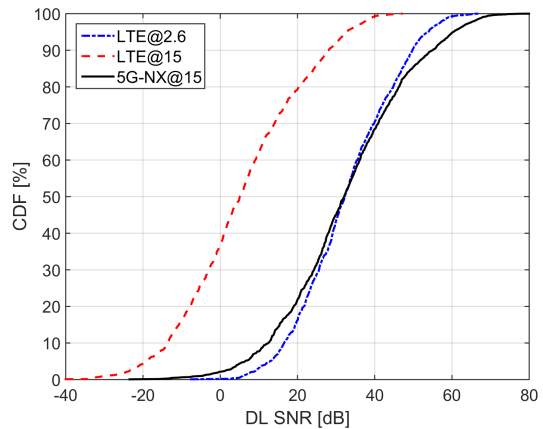


Fig. 2: CDFs of DL SNR for LTE@2.6, LTE@15, and 5G-NX.

Mbps/km². The figure shows that, for this area traffic demand, LTE@2.6 provides approximately 30 Mbps 5-percentile user throughput while 5G-NX provides 100 Mbps. Corresponding numbers for the 50-percentile are 80 Mbps and 300 Mbps, respectively. With the used simulation assumptions, 300 Mbps is actually close to the peak rate of 5G-NX. This is due to the very high SNR at the 50-percentile (32 dB) seen in Fig. 2 and that the resource utilization is very low at this traffic demand.

According to [7] the mobile data traffic is anticipated to increase a factor of eight from 2014 to 2020. For the scenario considered in this paper, this would correspond to a 2020 area traffic demand of 1.6 Gbps/km². Fig. 3 shows that LTE@2.6 cannot handle this load, with the spectrum assumed to be available for LTE@2.6. One way to improve performance is to add spectrum. Since spectrum is scarce, in particular at lower carrier frequencies, carrier aggregation with an LTE carrier at 15 GHz is used to illustrate this option. Fig. 3 shows that this improves performance. However, performance is not satisfactory; only 5 Mbps 5-percentile user throughput is achieved at 1.6 Gbps/km² traffic demand. The next option is to replace the LTE@15 system with 5G-NX and perform carrier aggregation between LTE@2.6 and 5G-NX. This improves the performance significantly. Now, 80 Mbps 5-percentile user throughput is achieved at 1.6 Gbps/km². Operating 5G-NX standalone performs significantly better than LTE@2.6, but it cannot handle the 1.6 Gbps/km² traffic demand with the assumed deployment.

The capacity, here defined as the supported area traffic demand for a 5-percentile user throughput requirement of 20 Mbps, of LTE@2.6 is 240 Mbps/km², for 5G-NX 950 Mbps/km², and for LTE@2.6+5G-NX 2800 Mbps/km². Hence, for this user throughput requirement, a more than ten-fold improvement of capacity is obtained with LTE@2.6+5G-NX compared to LTE@2.6. Note also the synergy effect of aggregating LTE@2.6 with 5G-NX. When aggregated they are able to carry much more traffic than the sum of the individual corresponding stand-alone systems.

Corresponding uplink (UL) performance is shown in Fig. 4. At 200 Mbps/km² traffic demand, 5G-NX and LTE@2.6 has

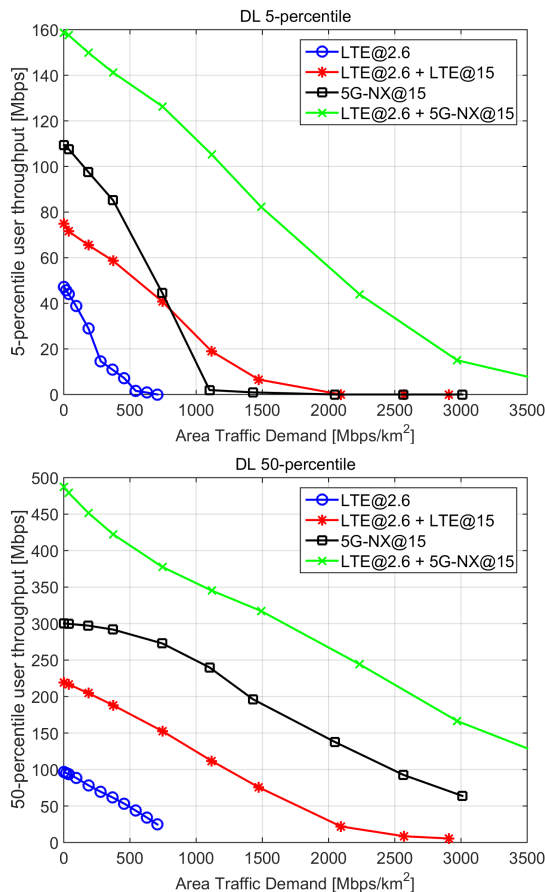


Fig. 3: DL 5-percentile (top) and 50-percentile (bottom) user throughput vs. area traffic demand.

similar 5-percentile user throughput. At lower load, LTE@2.6 has higher throughput and at higher load, 5G-NX has higher throughput. The 50-percentile user throughput is significantly higher for 5G-NX at all loads. With carrier aggregation of LTE@2.6 and 5G-NX, around 17 Mbps UL 5-percentile throughput is achieved at 200 Mbps/km² and 5 Mbps at 1600 Mbps/km².

IV. CONCLUSIONS AND FUTURE WORK

In this paper, we have investigated the feasibility of incorporating higher frequency bands (15 GHz), UE-specific beamforming and carrier aggregation to support the evolution of mobile networks to meet future demands on user experience and traffic volumes. By system simulations using a synthetic city and site-specific propagation model, we evaluated user and system performance of four different systems at different traffic demands in a dense urban scenario. We found that a reference system without beamforming, operating at 2.6 GHz with 40 MHz bandwidth was not able to handle the expected 2020 traffic demand. Carrier aggregation with a 100 MHz carrier at 15 GHz improved performance but, without beamforming, performance was not satisfactory due to the challenging propagation conditions at 15 GHz. By employing massive beamforming on the 15 GHz carrier, the propagation

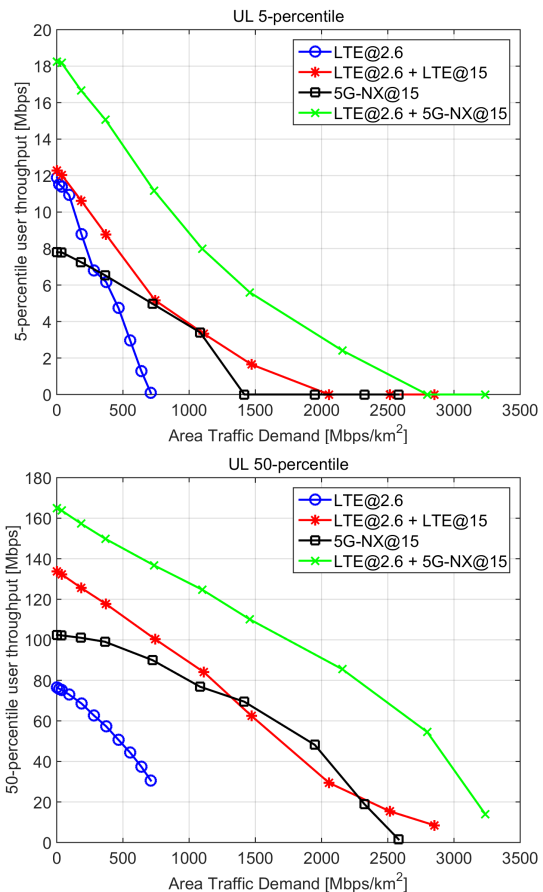


Fig. 4: UL 5-percentile (top) and 50-percentile (bottom) user throughput vs. area traffic demand.

effects were mitigated and high user experience was achieved at the expected 2020 traffic demand. This system provided a ten-fold increase of system capacity compared the reference system operating at 2.6 GHz.

Future work will focus on studying more scenarios, alternative deployments, other services, and to validate the models that have been used.

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