Comparative Performance Evaluation of mmWave 5G NR and LTE in a Campus Scenario

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***Abstract*—The extremely high data rates provided by communications in the millimeter-length (mmWave) frequency bands can help address the unprecedented demands of next-generation wireless communications. However, atmospheric attenuation and high propagation loss severely limit the coverage of mmWave networks. To overcome these challenges, multi-input-multi-output (MIMO) provides beamforming capabilities and high-gain steerable antennas to expand communication coverage at mmWave frequencies. The main contribution of this paper is the performance evaluation of mmWave communications on top of the recently released NR standard for 5G cellular networks. Furthermore, we compare the performance of NR with the 4G long-term evolution (LTE) standard on a highly realistic campus environment. We consider physical layer constraints such as transmit power, ambient noise, receiver noise figure, and practical antenna gain in both cases, and examine bitrate and area coverage as the criteria to benchmark the performance. We also show the impact of MIMO technology to improve the performance of the 5G NR cellular network. Our evaluation demonstrates that 5G NR provides on average 6.7 times bitrate improvement without remarkable coverage degradation.**

***Index Terms*—mmWave, 5G NR, LTE, MIMO, beamforming, Spatial Multiplexing.**

I. INTRODUCTION

Network operators are *densifying* existing wireless networks to address the anticipated capacity demands of next-generation cellular networks. Small cells are currently considered a promising solution to increase cellular network capacity [1]. This solution leverages short-range communication for interference reduction and includes low-power cellular radio access nodes (RAN) such as femtocells, picocells, and microcells. The unprecedented benefit of small cells is more effective frequency re-use. Moreover, small cells benefit from using beamforming techniques to focus antenna patterns on a very specific area to improve coverage.

Joint with the usage of small cells, communication in the millimeter-wave (mmWave) frequency band offers multi-gigahertz bandwidth, works best in short ranges, and provides higher performance through beamforming [2], [3]. This is because mmWave communications are hindered by many impairments, including the scarce efficiency of RF amplifiers, limited transmission power, atmospheric attenuation and high propagation loss [4]. These constraints make mmWave communication suitable for short-range communication. In addition, attenuation, loss and material absorption decrease multipath between the transmitter and the receiver. Such channel sparsity characteristic can be leveraged to further reduce interference and contribute to the frequency reuse objective of small cells. As such, mmWave and the small cell concept go well together to provide high capacity coverage in denser areas along side to traditional “sub 6 GHz” communications (Fig. 1). A further benefit of using mmWave is that millimeter wavelengths make dense phased array antennas feasible, enabling MIMO technology, which in turn, makes mmWave communication practical.

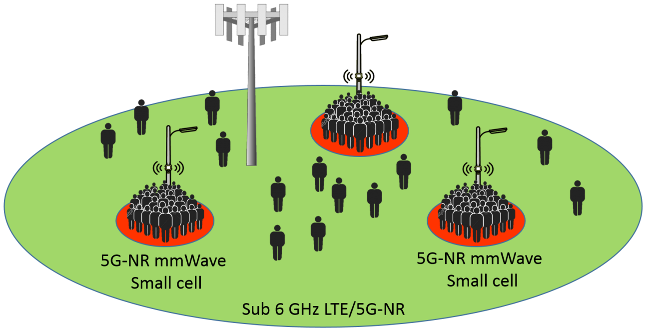

Fig. 1. Small Cell and mmWave technology for dense areas.

A. Related Work

The main contribution of this paper is to compare the performance of mmWave technology in compliance with the recently released 5G NR standard with that of LTE, the prevailing technology for cellular communications. This comparison has also been investigated in a few prior works [5], [6], [7], [8]. Specifically Giordani et al. compare 5G NR technology with LTE in the context of vehicle-to-network (V2N) networking, investigating achievable datarate, communication stability, and outage probability [6]. The authors utilize path loss channel models to estimate SNR and consider Line of Sight (LOS) probability for accurate estimation. Eventually, the achievable datarate is estimated through the Shannon formula. Mastrosimone and Panno compare mmWave technology and LTE in moving networks scenario, focusing on small cell in buses or trains [7]. The achievable bitrate performance analysis is

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based on mmWave and LTE path loss models for the signal-to-interference-plus-noise ratio (SINR), which is mapped to the corresponding modulation scheme by a lookup table. Finally, the bitrate is estimated by considering the number of Resource Blocks (RB), the number of symbols per RB, and the duration of a time slot as well as the presence of interference. The scenario considered by Busari et al. is that of a city (urban scenario [8]). The channel capacity is calculated using the Shannon formula. The SINR is estimated using 3GPP channel models for LTE macro cells and mmWave small cells, taking into account endpoint antenna gains, noise density and noise figures. Shafi et al. compare the performance of 5G NR systems operating at both mmWave and C-band (Sub-6 GHz) frequencies through actual measurements in central Auckland, NZ. Their work provides useful insights into 5G NR performance since it is based on field measurements on coverage and throughput at both bands from the same location. Measurements are performed only on selected routes, which makes reports on coverage and bitrate very site specific. Furthermore, there is no comparison with coverage via LTE.

B. Contributions

The main focus of our work is predicting and comparing the downlink performance of mmWave with LTE technology deployed in the same environment, using the same location for the Base Station (BS), unavailable in most previous work. We consider the main campus of Northeastern University in Boston, MA as our simulation setup. We select $4,618$ outdoor points as possible receiver locations in a commercial ray tracer simulator, namely, Remcom's Wireless Insite [9]. Differently from prior works, this sophisticated ray-tracer gives us the advantage of applying realistic mmWave antenna beam patterns modeling the spatial characteristics of the channel, including angle of arrival (AOA) and Angle of Departure (AOD). Therefore, we are able to investigate MIMO beamforming and spatial multiplexing and their impact on mmWave performance. We map the collected channel data to link-level bit rate metrics and obtain a site-specific high-resolution coverage map. In contrast to prior works that apply the Shannon formula, our bitrate analysis is based on suitable selection of Modulation and Coding Scheme (MCS) for the estimated SINR. We further apply 3GPP guidelines to calculate bitrate for a given MCS and consider the physical layer overhead.

We considered two mmWave system designs, low-cost SISO and high-end MIMO. For the MIMO scenario we further considered two beamforming configurations: Maximum Ratio Transmission (MRT) and Spatial Multiplexing (SM). Our results can be summarized as follows:

- SISO mmWave design shows significant bitrate drop in Non-Line-of-Sight (NLOS) regions due to diffraction loss in the mmWave band, which reduces the SINR dramatically.
- Quantitatively speaking, and in comparison to LTE, although SISO design improves the average bitrate by 72%, its coverage drops almost by half. This observation reveals that low-cost SISO design is suitable for more open areas.
- In order to compensate for diffraction loss we consider high-end MIMO design with phased array antenna and beamforming capabilities. Its MRT configuration significantly improves the coverage in both LOS and NLOS regions, nearing the coverage of LTE. This MIMO configuration is suitable for highly dense areas with larger NLOS regions.
- Configuring MIMO to use SM improves the maximum bitrate by 27 time and the average bitrate by 6.7 times, with only 24% coverage degradation with respect to the MRT configuration. This configuration is suitable for limited NLOS areas that require very high bitrate.

The remainder of the paper is organized as follows. In Section II we describe the simulation tool and the evaluation environment with its parameters. Section III describes the performance evaluation methodology and presents coverage and bitrate results with varying physical layer parameters and the simulation setup. We conclude the paper in Section IV.

II. EXPERIMENTAL SETUP

Tools and Environment. To evaluate the performance of mmWave 5G NR, we utilize *Wireless Insite*, a professional ray-tracer software [9]. Our investigation concerns the outdoor environment of a portion of the the Northeastern University (NU) that we imported into the ray tracer as a high-resolution 3D shapefile. For accurate ray tracer results, material properties for carrier frequencies are obtained from the recommended ITU model [10]. We positioned small cells Base Stations (BS) at the corners of the Ell Hall building and of the Curry Student Center at NU. For channel modeling and for estimating channel parameters we covered the campus area of interest by a grid of receivers using 5 meter spacing, resulting in a total of 4,618 possible positions for User Equipment (UE) devices. The downlink bitrate is estimated for these positions.

Wireless (physical layer), noise and antenna parameters are summarized in Table I, and described below.

TABLE I
SIMULATION PARAMETERS

Parameters	mmWave 5G NR	LTE
Carrier frequency (GHz)	28	2.3
BS signal bandwidth (MHz)	100	20
Transmit power (dBm)	30	30
Ambient noise density (dBm)	-165.1	-167.1
UE noise figure (dB)	7.8	5
SISO BS antenna gain (dBi)	8	5
SISO UE antenna gain (dBi)	3	0
BS MIMO antenna array config.	8x8	-
UE MIMO antenna array config.	4x4	-
MIMO BS antenna element gain (dBi)	6	5
MIMO UE antenna element gain (dBi)	6	0

Wireless parameters. We chose physical layer parameters to obtain a fair and realistic comparison of mmWave 5G NR and LTE link performance. The transmit power for both scenarios is set to 30dB, which is typical for LTE picocells [11]. This is an important parameter that affects both SINR at the UE and also the downlink bitrate, which is estimated from the strongest SINR of the BSs. Despite the high propagation loss in the mmWave band, we keep the transmitter power equal to that of LTE, using practical high gain antennas to compensate for the propagation loss. This allows us to evaluate the impact of MIMO antennas and offers practical mmWave insights to network operators since transmitter power directly impacts the BS power consumption and related costs. To ensure compliance to the standard the mmWave channel bandwidth is set to 100MHz [12]. This allows us to prevent overestimating mmWave performance and enables multiple operator in the 5G NR mmWave spectrum. In the LTE scenario the bandwidth is set to 20MHz, which is the maximum bandwidth supported by the 3GPP standard.

Noise parameters. Ambient noise and UE noise alter SINR and bitrate at the UEs. The ambient noise parameter has been set according to urban scenario results from measurement campaigns across the United States [13]. By considering the carrier bandwidth, the ambient noise level at the receiver can be calculated to be -94 and -85 dBm for mmWave 5G NR and LTE, respectively. This shows a significant 9dBm increase in the noise level for the mmWave scenario. The UE total noise value includes the RF component noise of the receiver amplifier and filter. The receiver noise value increases with increasing frequency, so the noise figure of the mmWave receiver is higher than that of LTE. Designing a mmWave receiver with lower noise is still an open research area. Anderson et al. expect noise values of 5 and 7.8dB for mmWave and LTE, respectively, to be achieved by end of 2021. These are the values that we use in our simulations.

Antenna parameters. As antenna apertures are inversely proportional to the square of the wavelength, a single element antenna at 28GHz mmWave frequency captures 100 times less energy than the same antenna used at the LTE frequency. This reduction of captures energy needs to be offset for the mmWave antenna, which can be done by using directionality or multiple antennas [4]. Accordingly, in our simulations we consider two different communication link configurations, namely, Single-Input Single-Output (SISO) and Multi-Input Multi-Output (MIMO). For SISO, we use a realistic mmWave sector antenna for the mmWave BS that offers 120-degree Half-Power Beam-Width (HPBW) and 8dBi gain [14]. Since the BSs are mounted to the wall of the building in our campus scenario, this antenna performs better than an omnidirectional antenna because it provides higher gain by focusing the energy and eliminating radiation to the wall. For the mmWave UE we use an omnidirectional antenna that delivers a 3dBi gain, which is almost angle independent and removes the problem of beam alignment [15]. Omni-directionality is achieved by sacrificing 3dB gain degradation with respect to the patch antenna element in the phased array used for the MIMO scenario. The MIMO configuration requires multiple phase shifters and transceivers. For this configuration, we consider patch antennas because this type of antenna can be easily integrated into the devices with dimensional constraints such as UE and low-power small cells BS. Moreover, it can provide a 6 dBi antenna element gain, which is much higher than the typical 0 dBi gain of the LTE UE antenna [4]. Two arrays of a dual-polarized patch antenna are modeled in Wireless Insite with 8x8 and 4x4 configuration for the BSs and UE, respectively.

III. METHODOLOGY AND SIMULATION RESULTS

In the ray-tracer approach, we can further connect the site-specific channel model to the link-level bitrate performance metric. First, the ray-tracer finds the paths between the transmitters and receivers and calculates the time of arrival and energy of the radiated signals that come from each path with respect to the antenna gain value for the specific path angular properties. This process turns to estimate Channel Impulse Response (CIR) and calculate the received power that contributes to the signal of SINR. Similarly, the received signal of other BSs consider as the interference, and the ambient noise and receiver noise figure are also considered to calculate SINR. For the MIMO configuration, the ray-tracer calculates the channel coefficient H matrix for all combinations of transmitter and receiver antenna elements. Beamforming methods will further applied to maximize the SINR or to maximize bitrate through spatial multiplexing.

Eventually, a lookup table is used to map the estimated SINR to a modulation and coding scheme (MCS). This mapping is a vendor-specific process and varies for different radios. Finally, for each MCS, an estimation of bitrate can be calculated at each receiver position by taking the channel overhead into the account which is discussed by the 3GPP documents, [16] and [17] for LTE and 5G NR respectively. For a complete evaluation, two beamforming methods were applied in the MIMO configuration. First, Maximum Ratio Transmission (MRT) at the BSs and Maximum Ratio Combining (MRC) at the UE is considered to maximize the SINR at the UE and second method, used Singular Value Decomposition (SVD) to find isolated streams and maximize bitrate [18].

A. NU Campus Coverage Maps

The coverage maps of the investigated NU campus scenario are shown in figures 2 to 4 for LTE, mmWave 5G NR SISO, and mmWave 5G NR beamforming MIMO, respectively.

For bitrate-SINR mapping we considered the bitrate of the MCSs for both 5G NR and LTE according to the 3GPP standard. The minimum and maximum bitrate and corresponding MCS for all the scenarios are represented in Table II.

Beside of these site-specific visualizations, an objective criterion is also required to benchmark the performance of these communication methods. Thus, we report the empirical CDF distribution of the estimated bitrate at all UE locations in Fig. 5. We define coverage as a Key Performance Indicator (KPI), where a minimum bitrate can be obtained, and the minimum bitrate is defined as the deliverable bitrate by the least order of MCS in each particular 3GPP standard. By these definitions, the coverage of all the studies can be quantitatively extracted from the CDF plot, which is shown in Fig. 6.

LTE covers almost 97% of the campus, but it only delivers a maximum of 75 Mbit/s. On the contrary, mmWave 5G NR

TABLE II
MINIMUM AND MAXIMUM BITRATE AND RELATED MODULATION AND CODE-RATE

Standard	Min bitrate (Mbit/s)	Modulation, Code rate	Max bitrate (Mbit/s)	Modulation, Code rate
LTE	4.58	QPSK, 1/5	75.38	64QAM, 9/10
mmWave 5G NR SISO	53.87		538.71	
mmWave 5G NR MRT-MRC	53.87	QPSK, 0.40	538.71	256QAM, 1.00
mmWave 5G NR SVD	53.87		2047.10	

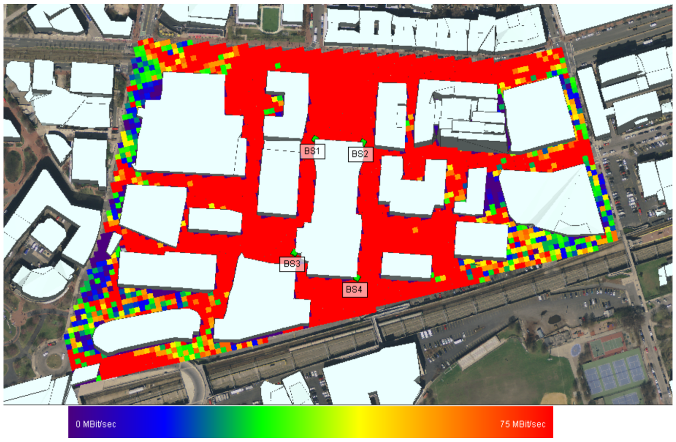

Fig. 2. LTE SISO coverage map of Northeastern University.

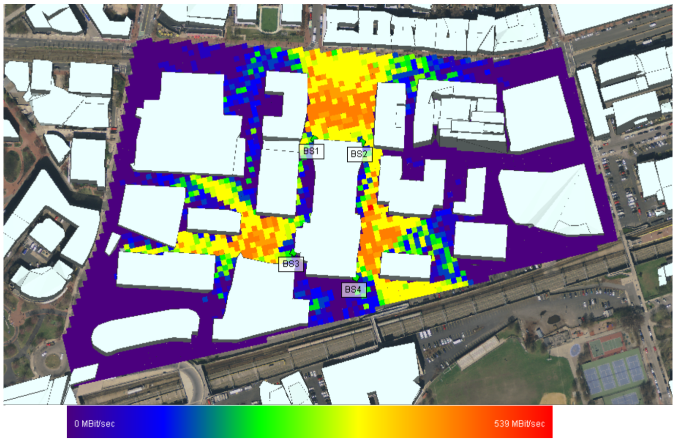

Fig. 3. mmWave 5G NR SISO coverage map of Northeastern University.

SISO delivers a maximum of 539 Mbit/s, but just in a very limited LOS area, and its coverage is almost half of the LTE. However, MRT-MRC beamforming method can significantly improve the mmWave coverage not only in LOS, but also in NLOS regions with the hardware costs of MIMO implementation. In the defined KPI context, its coverage slightly degraded by 15% with respect to LTE. Furthermore, SVD spatial multiplexing improves the bitrate by 27 times with only 24% coverage degradation with respect to the MRT-MRC beamforming method. Since its coverage map was similar to the MRT-MRC result with multiple time bitrate increases, it is not included here for the sake of conciseness.

Coverage is directly related to the defined bitrate KPI value.

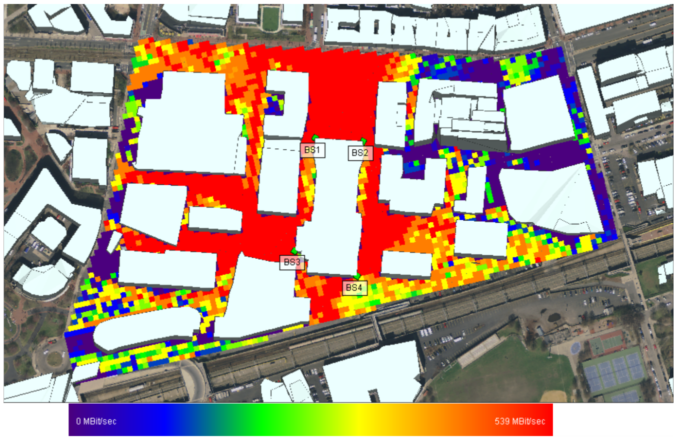

Fig. 4. mmWave 5G NR MIMO coverage map of Northeastern University using beamforming, MRT at BS and MRC at UE.

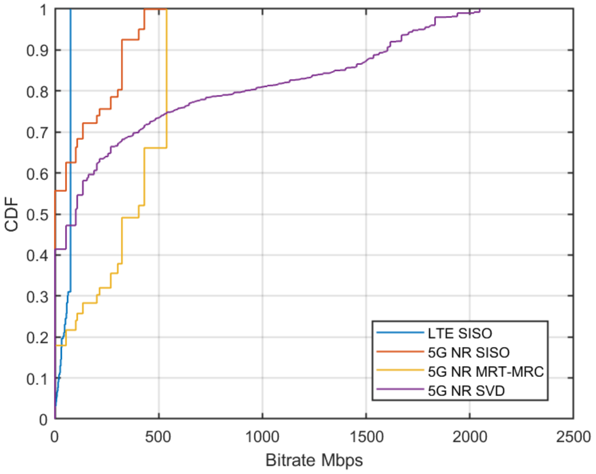

Fig. 5. Cumulative Distribution Function of bitrate for 4,618 receiver points.

To have an independent criterion we also consider the average bitrate to compare the considered communication methods. As can be seen in Fig. 7, the 5G NR SISO configuration increases the average bitrate by 1.72 times with respect to that of LTE. Moreover, the beamforming MRT-MRC and spatial multiplexing increase the average bitrate by 5.27 times and 6.71 times, respectively. This bitrate gain shows improvement in the order of the increased availability of bandwidth in the mmWave band since in the simulations we consider the typical mmWave 5G NR bandwidth (100 MHz), which is a 5

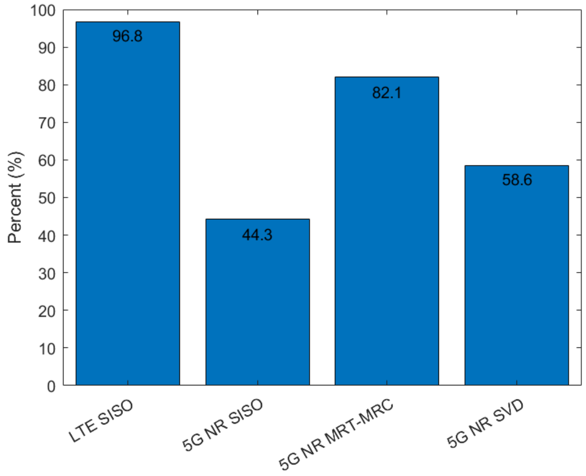

Fig. 6. Coverage benchmark by minimum bitrate KPI

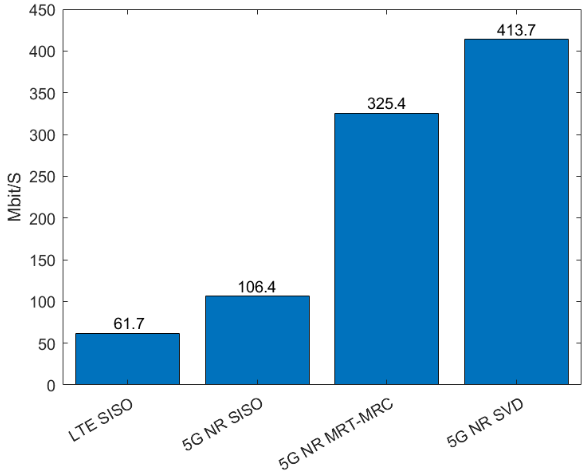

Fig. 7. Average Bit-rate benchmark.

times the available bandwidth of current LTE system. Further gains would require multiple transmitters for spatial multiplex streams, which would highly increase hardware costs.

IV. Conclusion

mmWave communication systems rely on directional transmissions to compensate for high propagation loss and receiver noise. In this paper, we evaluate the performance of mmWave communications with a standard-compliant and practical approach to configure the simulation toward obtaining realistic results. We use a ray-tracer simulator to provide a high-resolution coverage map for thousands of locations in the area of interest. We use a mapping approach to bridge the site-specific ray-tracer channel model to estimate bitrate. We demonstrate the performance of low-cost SISO and high-end MIMO communication configuration and emphasize how MIMO can improve mmWave performance in coverage and bitrate. Despite all the challenges in mmWave, we observe that it is a promising solution in environments with small cells where it increases the capacity over current 4G LTE systems, especially if MIMO and spatial multiplexing are used.

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