DATA RATE PERFORMANCE OF MMWAVE COMMUNICATION SYSTEMS IN 5G OUTDOOR SCENARIOS

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Abstract: Millimeter wave (mmWave) communications are expected to be the forerunner in achieving 5G data rate performance requirements. As mmWaves communications can provide channel bandwidths in the order of GHz, they can fulfill those demands. In this paper we have tested data rate performance of mmWave communication systems operating at 28GHz and 73GHz, in the outdoor environment, using the ns-3 simulator, in both single user and multi user scenarios. We focused on data rate, as one of the most important service quality indicators. Obtained results have confirmed that mmWave communications can meet 5G expectations and provide services to low mobile users in outdoor environment, at distances up to few hundred meters, with no significant obstacles between the transmitter and the receiver.

1. INTRODUCTION

Rapid growth of data traffic and overall number of Internet connected devices over mobile cellular networks is a certain sign of technology advancement, but it sets up various challenges and raises expectations for future wireless communication systems. In many developed countries, having a great number of "heavy data users" pushes performance of mobile networks to the limits, which accentuates the necessity of a revolution in network design: starting from new solutions on physical layer, up to radical changes in network topology. According to *Cisco's 2020 Mobile Forecast Highlights*, [1], mobile data traffic

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will grow 8 times from 2015 to 2020 (from 3.7 exabytes per month in 2015 to 30.6 exabytes per month in 2020) and in 2020 it will be equivalent to 15x the traffic of the entire Global Internet in 2005.

This immense forecasted growth comes with higher expectations from users as well: in terms of availability, reliability, latency and data rates. Latency requirements are as low as 1 ms on radio link; peak data rates in the order of Gbps and data rates at cell edge in the order of tens of Mbps with very high reliability, [2]. High reliability means that moderate rates should be sustained even in crowded locations, in rural areas, or at high mobility. Some of the most promising techniques contributing to the fulfillment of these goals are: network densification, wide channel bandwidths at millimeter wave bands, massive Multiple Input Multiple Output (MIMO) systems with 256x256 antenna elements, narrowband transmission like Filter-Bank Multi-Carrier (FBMC), multiple access scheme like Sparse Code Multiple Access, more prominent use of Time Division Duplex (TDD) mode in a dynamic manner, coordination among cells with reduced Transmission Time Interval (TTI), etc, [2,3].

With commercial rollout of 5G planned for 2020, leading vendors and operators are working intensely on defining new solutions. Although there are still not many confirmed details, there are few indicators of a general direction in which 5G revolution will go. Frequency bands of interest span from just few hundreds of MHz up to 100 GHz. Large amounts of spectrum, in the order of 1 GHz or more, are only available in the mmWave range, from 30 GHz to 300 GHz (suitable for providing high peak data rates in specific areas where traffic demands are very high).

Propagation properties of millimeter waves are suitable for 5G requirements: the smaller wavelength of mmWave signals means that more antennas can be fit into the same physical area which enables greater antenna gain for the same physical area. And, although path loss increases with the frequency, highly directional beamforms with large antenna array gain are the key in combating those losses.

Reflection mechanism is fairly consistent for all frequencies in the mmWave band and hence it is the most reliable way of receiving signals in non-line of sight (NLOS) conditions. Foliage loss increases with frequency and will be a detriment in mmWave communications, but it can be overcome with reflections and/or rapid rerouting to a different access point. Effects of diffraction around obstacles are mostly negligible in this range.

In higher ranges, few frequency bands have already stood out as eligible: 28 GHz and 73 GHz, which have already been intensively tested in urban environment of Manhattan, New York, [4]. Both frequency bands show good propagation characteristics, with signal being detected at least 100 to 200 meters from the potential cell site, even in absence of line of sight (LOS) connectivity. Based on this statistical channel model, New York University's Wireless team has created first 5G millimeter wave simulator, [5], implemented as a separate module in *ns-3* simulator, [6]. Using this new *ns-3* module, we analyze whether mmWave communications, in the specified frequency bands, can meet 5G requirements in terms of data rate for different real-case scenarios assuming outdoor propagation environment.

The paper is organized as follows: Section 2 introduces the *ns-3* simulator, as well as the millimeter wave module with its abilities and limitations. Section 3 describes different scenarios that were tested. In section 4, simulation results are presented, for both mmWave frequencies of interest and both LOS/NLOS propagation models. Section 5 summarizes the results and compares them to 5G expectations.

2. SIMULATION TOOL

Simulation tool used in this research paper is *ns-3*, C++ based network simulator. 5G millimeter-wave support is implemented as a separate module and it was developed by New York University's Wireless team led by Theodore Rappaport [7].

Lack of defined standard for 5G physical layer caused the simulator to heavily reside on LTE, primarily on its Orthogonal Frequency Division Multiplexing (OFDM) model (which will probably suffer major changes for 5G, if chosen at all), but with significant modifications which facilitate achieving 5G requirements. Since it is expected that 5G will be directed towards TDD operations, in order to reduce the latency over the air interface, the implemented TDD frame structure is fully customizable - from symbol length to guard interval and carrier frequency, as given in Table I.

Table I
Parameters for configuring mmWave frame structure

Parameter Name	Default Value	Description
SymbolPerSlot	30	Number of OFDM symbols per slot
SymbolLength	4.16μs	Length of one OFDM symbol in μs
SlotsPerSubframe	8	Number of slots in one subframe
SubframePerFrame	10	Number of subframes in one frame
NumReferenceSymbols	6	The number of reference OFDM symbols per slot
TDDControlDataPattern	“ccdddddd”	The control (c) and data(d) pattern
SubcarriersPerSubband	48	Number of subcarriers in each sub-band
SubbandsPerRB	18	Number of sub-bands in one resource block
SubbandWidth	13.89e6	The width of one sub-band in Hz
NumResourceBlock	4	Number of resource blocks in one slot
CenterFreq	28 GHz	The carrier frequency in Hz

Allocated bandwidth is 1 GHz in both analyzed frequency bands, which, given the default parameters in Table I, comes down to 103 680 subcarriers available to user data.

In order to properly capture characteristics of mmWave propagation, several other features of the physical layer have been implemented. Radio characterization includes small and large scale channel variations. Link budget is given by, [7]:

$$P_{RX} = P_{TX} + G_{BF} - PL - SW \quad (1)$$

where P_{RX} is the total received power in dBm, P_{TX} is the total transmit power, G_{BF} is the beamforming gain, and finally PL and SW represent the path loss and shadowing, respectively. Transmit power used in simulations is 30 dBm.

Path loss and shadowing (expressed in dB) are calculated using the formula, [7]:

$$PL(d) = \alpha + \beta * 10 * \log_{10}(d) + \zeta, \zeta \sim N(0, \sigma^2) \tag{2}$$

where ζ represents shadowing, *d* is the distance from receiver to transmitter (in meters), and the values of α, β, and ζ are given in [3], and are presented in Table II.

Table II
Path loss parameters

	LOS at 28 GHz	**NLOS at 28 GHz**	**LOS at 73 GHz**	**NLOS at 73 GHz**
α	61.4	72	69.8	82.7
β	2	2.92	2	2.69
ζ	5.8	8.7	5.8	7.7

mmWave signals are extremely susceptible to shadowing effect. For example, materials such as brick can attenuate signals 40–80 dB and attenuation through the human body can result in a 20–35-dB loss, [8, 9].

The beamforming gain from transmitter *i* to receiver *j* is given as, [7]:

$$G(t, f)_{ij} = \left| w_{rx_{ij}}{}^{*} * H(t, f)_{ij} * w_{tx_{ij}} \right|^2 \tag{3}$$

where: $H(t,f)_{ij}$ is the channel matrix of ij_{tx} link, $w_{tx_{ij}}$is the beamforming vector of transmitter i, when transmitting to receiver j and $w_{rx_{ij}}$ is the beamforming vector of receiver *j*, when receiving from transmitter *i*.

Small-scale fading is generated based on the number of clusters, number of sub-paths per cluster, Doppler shift, power spread, delay spread and angle of arrival. Decoding error model is also implemented at the receiver. Interference is calculated in a way which takes into account the beamforming directions associated with each link i.e. treating other base stations as source of interference. Channel Quality Index (CQI) Feedback loop is also included, similar to the one used in existing LTE systems, same as CQI to modulation and coding scheme mapping. Medium Access Control (MAC) layer is also implemented in the simulation tool, taking care of scheduling and resource allocation, as well as adaptive modulation and coding.

Apart from the physical and link level details listed above, there are several other parameters than can be adjusted: propagation loss model, channel model, mobile station moving pattern, transmitter's power, receiver's noise figure, number of antennas in base station and mobile station, enabling small scale fading, enabling Hybrid automatic repeat request (HARQ), requested Bit Error rate, etc. Environment surrounding the network is also customizable in terms of possibility to: add obstacles, define number of floors and rooms in building, and define its type and material used.

3. SIMULATION SCENARIOS

Due to the limited range of mmWave signals, most of the cellular applications for mmWave systems focus on small-cells, assuming outdoor deployments with LOS connectivity. In order to evaluate performance of the system described in Section 2 and its ability to deliver data rates expected from 5G systems, we created four real case scenarios.

As peak data rates advertised for 5G are primarily targeting low mobile users (stationary or walking), two scenarios include those user types and other two test performance of the system for medium mobile users. All scenarios were tested for both considered frequency bands.

Three assumed scenarios are set in hypothetical city square, with signal coverage from two base stations. Base stations' positions, as well as mobile stations' starting positions, are depicted in Figure 1. Simulated data transfer time in these three scenarios is 80 seconds.

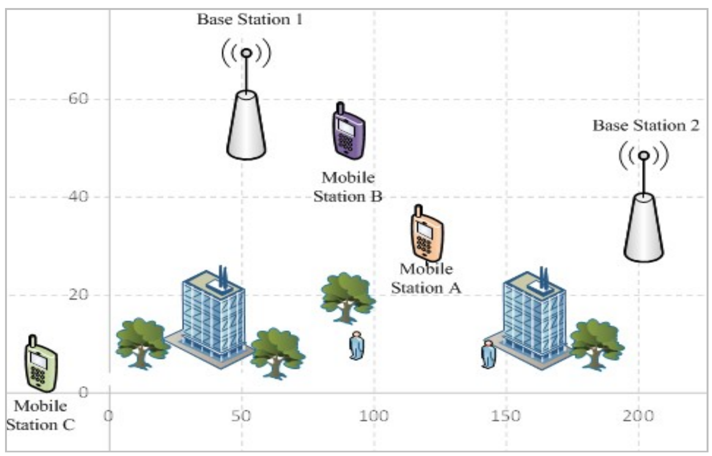

Figure 1: Test network for single user scenarios (A, B, C)

The following scenarios are discussed:

A. Scenario A

Scenario A implements *Random Walk* model, i.e. pedestrian walk. It includes mobile station moving at constant velocity of 1.5 m/s at the defined area at random directions. During 80 seconds of simulation, the position is changed 120 times. Starting position of MS that follows this model is given in Fig. 1 and is labeled as "*Mobile station A*".

B. Scenario B

Scenario B implements *Constant Velocity* model, i.e. MS moving at constant velocity of 36 km/h along x axis. Given that the simulation time was 80 seconds, the MS in this scenario travelled 800 meters. Starting position of MS that follows this model is given in Fig. 1 and is labeled as "*Mobile station B*".

C. Scenario C

Scenario C implements *Constant Position* model, defined in such way that every 2 seconds static MS is moved 5 meters along x axis. This model also includes obstacles: two buildings and six obstacles which model people and trees. Both buildings are defined as residential, with 4 floors and 1 room per floor. Exterior walls are defined as *Concrete With Windows*. Starting position of MS that follows this model is given in Fig. 1 and is labeled as "*Mobile station C*".

D. Scenario D

This scenario is a multi-user scenario, with 10 MSs that are placed on x axis at the distances uniformly distributed from 20 meters to 200 meters from BS. They are moving away from BS, along *x*-axis, at a constant speed of 1.5 m/s.

4. SIMULATION RESULTS

Scenario A: Simulation results obtained in this scenario are showing that in case of low mobile users, with good coverage and LOS propagation, achieved average data rates do not change as carrier frequency increases. In fact, in both cases, data rates are constant and maximal possible for this simulation tool. This is because in LTE, for all Signal-to-(Interference+Noise) Ratio (SINR) values higher than 20.5 dB, the system uses highest available signal constellations, thus achieving maximal data rates. For NLOS connectivity case, average data rates are also constant, but significantly lower. Also, propagation characteristics at different frequency bands came to light, so the average SINR at 73 GHz is 55% smaller than the one obtained at 28 GHz. The results are encouraging, as this is the primary scenario which 5G mmWave frequencies are focusing on: outdoor open spaces with few to none obstacles, but with lot of connected devices, such as main squares, concert and sport events, etc. Results are given in Fig. 2.

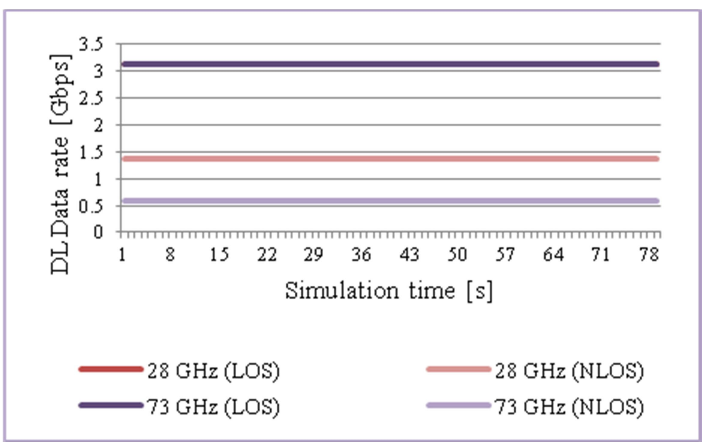

Figure 2: Scenario A results

Scenario B: This scenario shows the impact of MS-BS distance on average downlink data rate. As depicted in Figure 3, data rates for both 28 GHz and 73 GHz are constant only while that distance is less than 100m. After that, data rate decreases, reaching 60% of initial data rate at the ending position, 830m from the BS. At 73 GHz, data rate degradation pace is higher, resulting in 70% reduction. But, even at 830 meters from the BS, users could still achieve significant data rates, around 2 Gbps at 28 GHz and 1 Gbps at 73 GHz. For NLOS connections measurement results from [4] are confirmed: signals were detected even further than 100m from the potential cell site (230m for 28 GHz and 130m for 73 GHz).

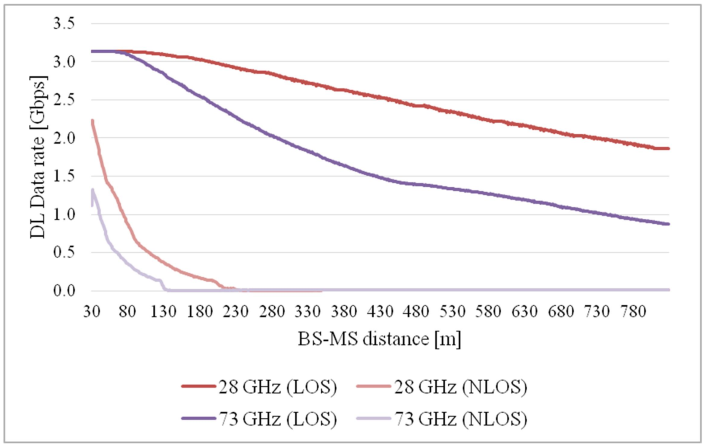

Figure 3: Scenario B results

Scenario C: This is the only scenario considered, in which obstacles were included. Results show that any kind of obstacle significantly deteriorates performance: first degradation of achieved data rate is due blockage by building, but the second blockage (at 55m) occurs because of trees and people present.

These results are in line with previously described propagation characteristics of mmWave bands, proving itself as a very susceptible to any kind of blockage, due to the short wavelengths.

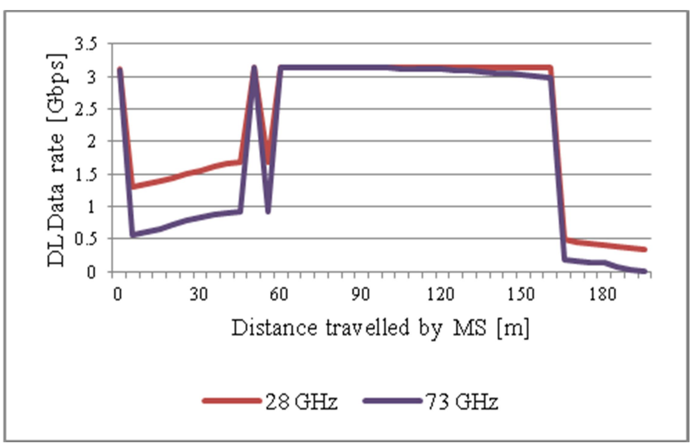

Figure 4: Scenario C results

Scenario D: This is the only multi user scenario analyzed. Results in Fig. 5 and Fig. 6 show that even when resources are shared between 10 MSs, we can still expect significant data rates to be achieved: in the order of hundreds of Mbps for MSs closest to the BS and in the order of tens of Mbps for the MSs at cell edges.

Comparison of data rate performance between the systems with 28 GHz and 73GHz carrier frequencies, shows that the latter has higher peak data rate per MS (for MSs closest to the BS), but also much lower data rate for MSs at the cell edges. These results are expected, having in mind propagation characteristics at both frequency bands.

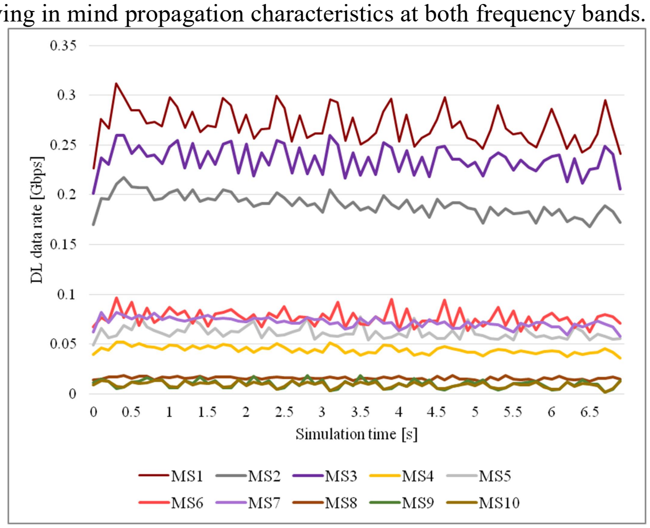

Figure 5: Scenario D results for 28 GHz (NLOS)

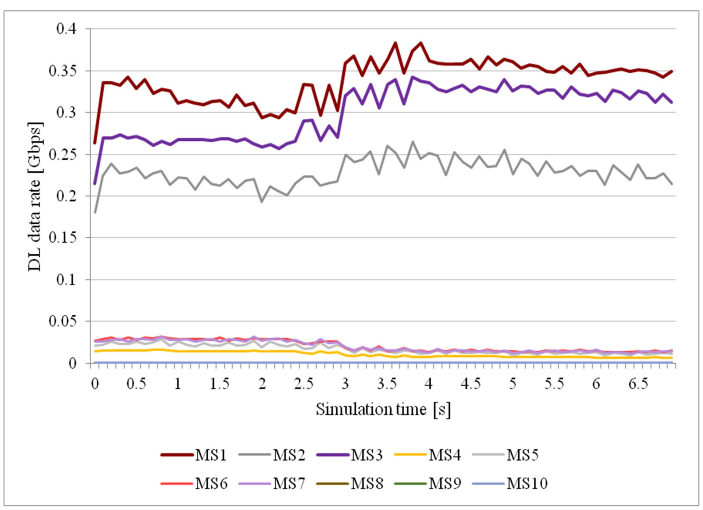

Figure 6: Scenario D results for 73 GHz (NLOS)

With deeper analyis, the propagational differences of two bands arise. It confirms that at cell edges, 28 GHz band has better results than 73 GHz band: 39% of measured data falls below 50 Mbps at 28 GHz band versus 70% at 73 GHz band. As for higher data rates: 10% of collected data at 28 GHz has data rate above 0.25 Gbps, compared to 20% at 73 GHz.

In Table 3, we summarize achieved results for all three single-user scenarios in both assumed frequency bands, in terms of average SINR values and average data rates in LOS and NLOS conditions. We observe that increasing carrier frequency has had almost the same effect in Constant Velocity model and Random Walk model, reducing data rates for more than a half for NLOS connections. For LOS connections, these degradations were much lighter, from 10% to 30%. From these results, we can conclude that in NLOS Constant Velocity scenario, mmWave model cannot fulfill 5G required performance targets. Its results are in the order of LTE data rates, which confirm earlier statement that mmWave communications are primarily intended for excellent and stabile radio conditions, not for mobile users. On the other hand, all tested LOS scenarios showed excellent performance, proving that in such conditions, 5G requirements can be met through mmWave communications.

Table III
Simulation results

Scenario	Propagation	28 GHz		73 GHz	
		Average DL data rate [Gbps]	**Average SINR [dB]**	**Average DL data rate [Gbps]**	**Average SINR [dB]**
Scenario A (Random Walk Model)	LOS	3.13	39.89	3.13	31.49
	NLOS	1.36	11.22	0.58	5.04
Scenario B (Constant Velocity Model)	LOS	2.53	21.30	1.75	14.29
	NLOS	0.16	-11.52	0.07	-16.34
Scenario C (Fixed Position Model + Obstacles)	N/A	2.25	24.54	2.00	17.05

5. CONCLUSIONS

Following the adoption of 5G requirements, new techniques and approaches have been proposed and analyzed as possible solutions for their fulfillment. When 5G enhanced mobile broadband services are considered, one of the most promising candidate for achieving very high data rates are mmWave communications. The vast amount of available spectrum in these bands promises up to ten times greater capacity compared to 4G mobile communication systems. And although the propagation characteristics at mmWave bands represent limiting factor, there are many application scenarios, where the required 5G peak data rates could be delivered.

In this paper, we tested data rate performance of mmWave communication systems operating at 28GHz and 73GHz frequency bands, in outdoor communication environment.

Four real case single user and multi user scenarios are tested. It is shown that the basic 5G system employing legacy OFDM is capable of delivering average user data rates which are more than 10 times higher comparing with the ones achievable in LTE systems, and several times higher than the ones in LTE-Advanced systems, all LOS environments. These kind of results in mmWave communication systems are attained assuming the transmit power of 1W at BS, which is far much lower than the transmit powers used for outdoor base stations in LTE and LTE-Advanced systems.

This paper provides useful insight into the achievable data rate performance of simplified mmWave network. Our research results show that by exploiting the benefits of communications at mmWave bands and finding solutions for overcoming their inherit drawbacks, 5G requirements for very high data rates (such as 10 Gbps per low mobility users and 100 Mbps at cell edge) can be met.

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