Journal of Engineering Science and Technology
Vol. 17, No. 2 (2022) 1150 - 1161

CAPACITY ANALYSIS OF WIRELESS SYSTEMS IN URBAN AND RURAL SCENARIOS

M. PREMKUMAR[1,*], M. ARUN[1], M. P. CHITRA[1], N. KARTHIKA[2]

[1]Department of Electronics and Communication Engineering,
Panimalar Institute of Technology, Chennai, Tamil Nadu, India
[2] Wipro Technologies Ltd, Chennai, Tamil Nadu, India
*Corresponding Author: ermpremkumar@yahoo.co.in

Abstract

This paper attributes to capacity analysis of wireless systems in urban and rural scenarios which can be beneficial to upcoming 5G and 6G wireless systems. Though 5G and 6G systems employ antenna arrays or Multiple Input Multiple Output (MIMO) technology in the Base Station (BS) and multiple antennas in User Equipment (UE) as that of an intelligent Personal Digital Assistant (PDA) such as smart mobile phones, tablets and iPads, information transfer into a wireless channel from a transmitter to a receiver is significant irrespective of urban or rural scenarios as smart cities have evolved globally. In urban scenarios as most of the time it is Non-Line-Of-Sight (NLOS) communication between UE and the BS or vice versa and it can follow well known Rayleigh distributed fading channel. Moreover, in rural scenarios it is Line-Of-Sight (LOS) communication following Rician distribution due to the presence of dominant path or specular component. Simulation results are obtained in Matrix Laboratory (MATLAB) testbed for capacity of wireless systems in urban and rural scenarios against Signal to Noise Ratio (SNR) between UE and BS where always LOS rural scenario gives increased capacity in comparison to NLOS urban scenario, due to the presence of Line-Of-Sight component *KdB* as shown in the graphical section of this research paper. Also, for MIMO technology the results have been obtained and presented which can be beneficial for further research work aiding 5G, and 6G systems in wireless world.

Keywords: Capacity, MIMO, Rural, SNR, Urban.

1. Introduction

In the arena of wireless world in present day scenario of 5G and 6G, transmission of information data into wireless channel is of prime concern which deals with the metric of capacity [1] for wireless systems in Physical (PHY) layer or network layer perspective for wireless networks [2].

Wireless networks such as Wireless Fidelity (Wi-Fi), Worldwide Interoperability for Microwave Access (WiMAX), Wireless Local Area Networks (WLAN), Wireless Personal Area Networks (WPAN) or any wireless networks [3], capacity analysis [4, 5] are significant for determining the number of bits a channel [6] can pass though fading arises. Higher data rate requirements of the order of Megabits per second (Mbps) and Gigabits per second (Gbps) are required for wireless systems/networks in 5G and 6G systems.

Also, massive MIMO systems which are evolving, are based on the modulation scheme and amount of information holding capacity in a wireless system [7, 8]. Irrespective of the upcoming wireless transceiver chains, applications such as audio, video, multimedia, environment monitoring using microwave application sensors [9] where electronic circuitry using combinational circuits [10] and sequential circuits are employed, information flow in a channel pertaining to capacity gains significance.

In addition, in emergency/disaster management situations like that of cognitive radio [11] applications, information-oriented bounds in the form of capacity are needed. Whatever might be the application, signal propagation may be either Line-Of-Sight (LOS) [12, 13] or Non-Line-Of-Sight (NLOS) [14] for any wireless application/scenario. It is well known that NLOS occurs in urban scenarios and LOS predominantly in rural scenarios and for such systems analysis, metrics are capacity in bits/second or spectral efficiency in bits/s/Hz.

Figure 1 shows wireless system scenario portraying NLOS and LOS between user equipment to the base station which in turn is connected to a cloud environment which can also be in tandem with Internet of Things (IoT) and Public Switched Telephone Network (PSTN). Further, Multiple Input Multiple Output (MIMO) systems which employ multiantenna technology can also improve spectral efficiency, coverage and reliability.

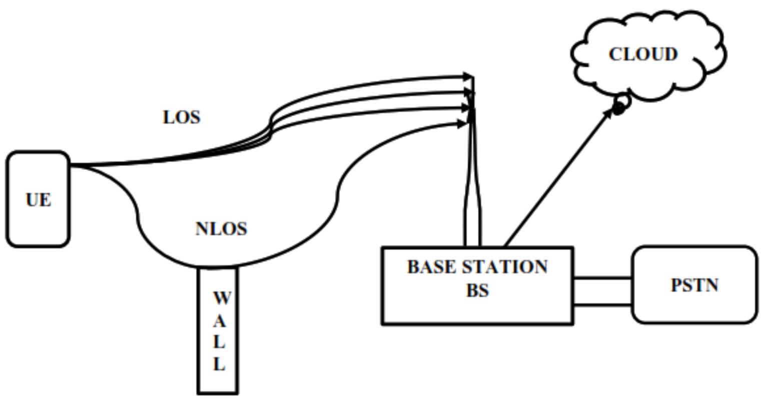

Fig. 1. Wireless system scenario for urban scenario NLOS and rural scenario LOS.

Several research articles have been proposed for capacity analysis of wireless systems [13-22]. Research work [13] deals with MIMO capacity for an indoor scenario whereas [14] presents Line-Of-Sight and Non-Line-Of-Sight environments capacity nearing Gigahertz frequency ranges.

Also, [15] gives wireless system capacity of users depending on time, whereas [16] is related to capacity of smart antenna systems, [17] presents Rician fading channel-based analysis of capacity. The research paper of [18] deals with capacity in cellular networks. Research work of [19] is concerned with capacity under various composite fading channels and [20] addresses capacity of Non-Orthogonal Multiple Access (NOMA) multiuser MIMO system used for 5G systems.

Literature [21] deals with capacity planning for 5G and [22] analyses delay for mobile Adhoc networks with social aware perspective. However recent trends in 5G systems such as Massive MIMO [23], Millimetre-Wave (MMWave) technologies [24] where a greater number of antennas are to be employed for achieving data rates of the order of Mbps and Gbps, capacity analysis needs to be done. Also upcoming 6G systems [25, 26] where data rates of the order of more than Gbps are expected metric of capacity analysis attains significance.

Though the works from [13-22] are excellent research literatures for capacity of wireless systems with different technologies and various aspects, this proposed research paper gives capacity of wireless systems in urban and rural scenarios between a user equipment and base station.

This research paper is written in the manner that introduction is given in Section 1, Section 2 presents proposed system model in urban and rural scenarios with its MIMO technology. Section 3 outlines capacity of urban and rural scenarios. Section 4 presents the obtained simulation results for capacity analysis and Section 5 gives conclusions to the research paper.

2. Proposed System Model in Urban and Rural Scenarios

The proposed system model considers a User Equipment (UE) with a single antenna and Base Station (BS) with multiple antennas. When the user equipment as shown in Fig. 1 transmits a signal *d*, at a particular given time instant *t*, the received signal r_{urban} for an urban scenario in Non-Line-Of-Sight (NLOS) channel h_{urban} following Rayleigh distribution [27] is given by

$$r_{urban} = h_{urban} d + n_{urban} \tag{1}$$

The urban scenario NLOS channel is Rayleigh distributed and has a Probability Density Function (PDF) given by

$$f(h_{urban}) = \begin{Bmatrix} \frac{h_{urban}}{\sigma^2} \exp\left(\frac{h_{urban}^2}{2\sigma^2}\right); & 0 \le h_{urban} \le \infty \\ 0 & ; \ (0 < h_{urban}) \end{Bmatrix} \tag{2}$$

where σ^2 is the statistics related to average power of the received signal. Similarly, the received signal r_{rural} for a rural scenario Line-Of-Sight (LOS) channel follows Rician distribution [27] and it is expressed as

$$r_{rural} = h_{rural} d + n_{rural} \tag{3}$$

The rural LOS channel is Rician distributed has a PDF which is written as

$$f(h_{rural}) = \begin{cases} \frac{h_{rural}}{\sigma^2} e^{\frac{-\left(h_{rural}^2+V^2\right)}{2\sigma^2}} I_0\left(\frac{V h_{rural}}{\sigma^2}\right); & \text{for}(V \geq 0; h_{rural} \geq 0) \\ 0 & ; \text{for } (h_{rural} < 0) \end{cases} \quad (4)$$

where V is amplitude, and it plays a role in the dominant factor or specular component in LOS. Similarly, the proposed system for urban and rural scenarios can be extended to MIMO systems where it can increase the spectral efficiency to a greater extent. In continuation with above expressions, the $N_r \times N_t$ MIMO urban received signal matrix $\boldsymbol{R_{urban}}$ is observed as

$$\boldsymbol{R}_{urban} = \boldsymbol{H}_{urban}\boldsymbol{D} + \boldsymbol{N}_{urban} \quad (5)$$

where $\boldsymbol{H_{urban}}$ is $N_r \times N_t$ MIMO channel matrix and $\mathbf{D}$ is $N_t \times N_t$ data signal matrix, $\boldsymbol{N_{urban}}$ is the $N_r \times N_t$ Additive White Gaussian Noise (AWGN) matrix. Also, MIMO rural received signal matrix $\boldsymbol{R_{rural}}$ is given as

$$\boldsymbol{R}_{rural} = \boldsymbol{H}_{rural}\boldsymbol{D} + \boldsymbol{N}_{rural} \quad (6)$$

The expressions of the received signal in the base station for urban and rural scenarios are given by Eqs. (1) and (3) and the MIMO received signal matrix for urban and rural scenarios are represented in Eqs. (5) and (6) from which capacity analysis can be derived which is dealt in Section 3. The following algorithm stated in below steps are used find the capacity [28] as follows:

Step1:

Capacity is the maximization of Mutual Information [28] and it is obtained in bits/s as specified in Eq. (7).

Step2:

Determine the Mutual Information based on the transmitted data signal and received data signal which is difference of differential entropy of received signal and conditional entropy or noise entropy as specified in Eq. (8)

Step3:

Obtain the differential entropy of the received signal and conditional differential entropy or the noise entropy for the given statistics as specified in Eqs. (9) and (16).

Step4:

From the obtained entropies in step 3 determine Mutual Information for the given scenario as per Eq. (17).

Step 5:

Compute the Capacity for a given scenario as in Eqs. (21) or (22)

3. Capacity Analysis in Urban and Rural Scenarios

To derive the capacity of wireless system urban scenario, consider Eq. (1) where capacity or instantaneous capacity is considered to be maximization of the mutual information [28] which is formulated as

$$c_{urban} = \max_{f_{d(d)}} |I(d; r_{urban})| \quad (7)$$

where $I(d; r_{urban})$ is the mutual information between the transmitted data symbol or data signal and received signal in urban scenario from UE to BS is mathematically given as

$$I(d; r_{urban}) = h_e(r_{urban}) - h_e\left(\frac{r_{urban}}{d}\right) \quad (8)$$

where $h_e(r_{urban})$ is the differential entropy of the received signal and $h_e\left(\frac{r_{urban}}{d}\right)$ is the conditional entropy of the received signal with data signal or noise entropy. Following the footsteps above stated further, the differential entropy of the received signal [28] is given as

$$h_e\,(r_{urban}) = \frac{1}{2}\log_2 2\pi e\left|\sigma^2_{r_{urban}}\right| \quad (9)$$

where $\sigma^2_{r_{urban}}$ is the variance of the urban received signal in the BS where it is given as

$$\sigma^2_{r_{urban}} = E[r_{urban} r^H_{urban}] \quad (10)$$

Substituting Eq. (1) in Eq. (10) it reaches to

$$\sigma^2_{r_{urban}} = E\left[(h_{urban}d + n_{urban})\left(h_{urban}d + n_{urban}{}^H\right)\right] \quad (11)$$

Cross multiplying the terms and representing it further, we get four terms and cross correlation between data signal and noise signal are independent of each other and it is zero. Considering only the autocorrelation terms it is given as

$$\sigma^2_{r_{urban}} = E[(h_{urban} dd^H h^H_{urban})] + E[nn^H\ ] \quad (12)$$

It is further given as

$$\sigma^2_{r_{urban}} = E[h_{urban} h^H_{urban}]E[(dd^H)] + E[n_{urban} n^H_{urban}\ ] \quad (13)$$

where $E[(dd^H) = \|d\|^2 = P_s]$ is the signal power from data signal which is scalar; $E[h_{urban} h^H_{urban}]$ is the urban channel coefficient magnitude $E[h_{urban} h^H_{urban}] = \|h_{urban}\|^2$; and $E[n_{urban} n^H_{urban}\ ] = \|n_{urban}\|^2 = N_o$ is the noise power.

Substituting the above stated values in Eq. (13) the variance of the received signal is

$$\sigma^2_{r_{urban}} = \|h_{urban}\|^2 P_s + N_0 \quad (14)$$

The differential entropy of the received signal using (14) is observed as

$$(r_{urban}) = \frac{1}{2}\log_2 2\pi e\left|\|h_{urban}\|^2 P_s + N_0\right| \quad (15)$$

Also, the noise entropy or conditional differential entropy is related to only using noise terms and it is

$$h_e\,\left(\frac{r_{urban}}{d}\right) = \frac{1}{2}\log_2 2\pi e|N_o| \quad (16)$$

Substituting Eqs. (15) and (16) into Eq. (8) it results in

$$I(d; r_{urban}) = \frac{1}{2}\log_2 2\pi e\left|\|h_{urban}\|^2 P_s + N_0\right| - \frac{1}{2}\,log_2 2\pi e|N_o| \quad (17)$$

Simplifying further, in terms of log division rule

$$I(d; r_{urban}) = \frac{1}{2}\frac{\log_2 2\pi e}{\log_2 2\pi e}\left(\frac{\|h_{urban}\|^2 P_S + N_0}{N_o}\right) \quad (18)$$

Further Simplification reaches to

$$I(d; r_{urban}) = \frac{1}{2}\frac{\log_2 2\pi e}{\log_2 2\pi e}\left(\frac{\|h_{urban}\|^2 P_S}{N_0} + \frac{N_o}{N_0}\right) \tag{19}$$

The mutual information for urban channel scenario is

$$I(d; r_{urban}) = \frac{1}{2}\log_2\left(\frac{\|h_{urban}\|^2 P_S}{N_0} + 1\right) \tag{20}$$

The capacity of wireless system in urban scenario is derived to be

$$c_{urban} = \max_{f_{d(d)}}\left|\frac{1}{2}\log_2\left(1 + \frac{\|h_{urban}\|^2 P_S}{N_0}\right)\right| \tag{21}$$

Also, the capacity of wireless system in rural scenario can also be obtained and straightforward it is written as

$$c_{rural} = \max_{f_{d(d)}}\left|\frac{1}{2}\log_2\left(1 + \frac{\|h_{rural}\|^2 P_S}{N_0}\right)\right| \tag{22}$$

where h_{rural} is the rural channel exhibiting Line-Of-Sight (LOS) propagation in which a dominant component is present which is always a complex entity and has a factor of *KdB*. Stating the fact, rural scenario channel can also be addition of Non-Line-Of-Sight component and dominant component. On the other hand, proceeding in above fashion, the MIMO urban wireless capacity and MIMO rural wireless capacity can also be found to be as

$$c_{MIMOurban} = \max_{f_{\boldsymbol{D}}(\boldsymbol{D})}\left|\frac{1}{2}\log_2\left(\boldsymbol{I} + \frac{\|\boldsymbol{H_{urban}}\|^2 P_S}{N_0 N_t}\right)\right| \tag{23}$$

$$c_{MIMOrural} = \max_{f_{\boldsymbol{D}}(\boldsymbol{D})}\left|\frac{1}{2}\log_2\left(\boldsymbol{I} + \frac{\|\boldsymbol{H_{rural}}\|^2 P_S}{N_0 N_t}\right)\right| \tag{24}$$

4. Results and Discussion

This section presents the simulation results for capacity analysis of wireless systems in urban scenario and rural scenario and also its MIMO capacity graphical analysis. Capacity against Signal to Noise Ratio (SNR) is observed in MATLAB simulation testbed where the urban scenario is Non-Line-Of-Sight (NLOS) following Rayleigh distribution and the rural scenario is Line-Of-Sight (LOS) following Rician distribution given by various Line-Of-Sight factors such as K = 5 dB,10 dB,15 dB and 20 dB. Also, MIMO wireless systems capacity in urban scenario and rural scenario is also analysed for various antenna configurations. The frequency of operation of the wireless systems is 800 MHz which is commonly used in cellular wireless systems.

Figure 2 shows the obtained capacity in urban NLOS Scenario following Rayleigh distribution and LOS Scenario following Rician distribution where it has a predominant LOS component. As per the inference from graph in Fig. 2, to achieve higher capacity values for 8 dB the capacity obtained in urban scenario is 1.2×10^9 bits/s/Hz and capacity of 4.8×10^9 bits/s/Hz for rural scenario. This increase in capacity of wireless system in rural scenario is due to the presence of Line-Of-Sight or specular component (or) dominant component namely K = 5 dB which contributes to increase the capacity which can be a complex constant.

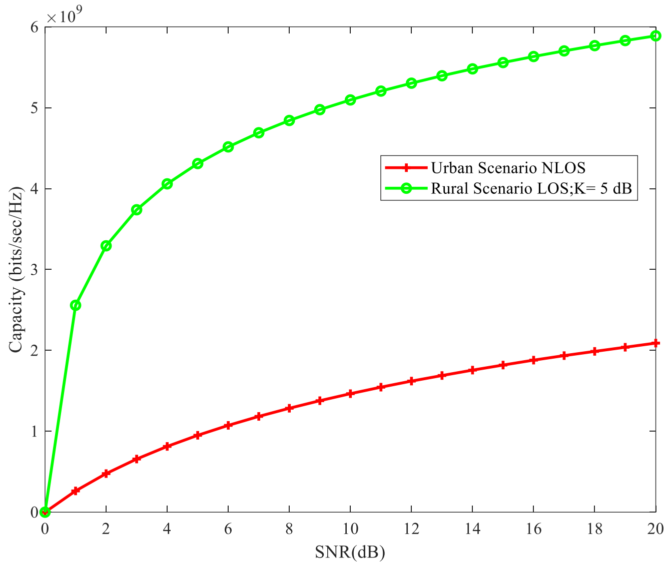

Fig. 2. Capacity in urban scenario NLOS and rural scenario LOS.

Figure 3 graphically gives capacity in LOS Scenario following Rician distribution for various Line-Of-Sight components such as K = 5 dB, 10 dB, 15 dB and 20 dB. As the LOS component (or) dominant component value increases the capacity of the wireless system increases which shows the contribution of having LOS component which is present in rural environments and outdoor environments. Table 1 shows the obtained capacity in rural LOS scenario for various K factors as portrayed in Fig. 3.

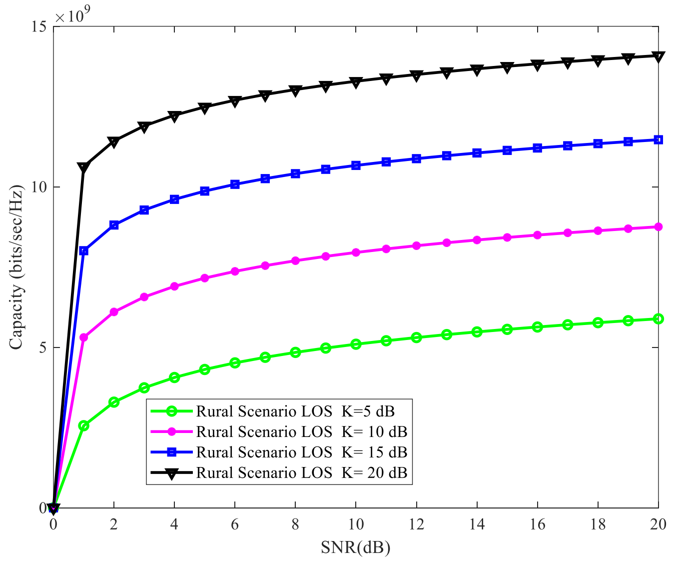

Fig. 3. Capacity analysis in rural scenario LOS for various *K* factors.

Table 1. Capacity analysis in rural scenario LOS

Rician Channel Factor *K*	**Capacity (bits/s/Hz)**
SNR= Eb/No = 10 dB; BW= 800 MHz	
5 dB	5×10^{9}; bits/s/Hz
10 dB	8×10^{9}; bits/s/Hz
15 dB	10.0×10^{9}; bits/s/Hz
20 dB	13.3×10^{9}; bits/s/Hz

Figure 4 shows MIMO wireless system capacity analysis, in NLOS urban scenario where capacity increases as the number of transmit antennas and receive antennas increases. The increase in capacity is due to diversity gain which is the product of number of transmit antennas N_t and receive antennas N_r. For comparison, capacity analysis in Additive White Gaussian Noise (AWGN) channel and Single Input Single Output (SISO) case is also shown which can be analysed while developing and designing IoT smart cities incorporating cloud networks. Also, when increasing the number of transmit antennas, receive antennas $N_t = N_r$, for 2, 4, 8, 12 and 16 and when examined via simulation results, capacity increases with increase in SNR which can be useful for development and analysis of 5G and 6G systems.

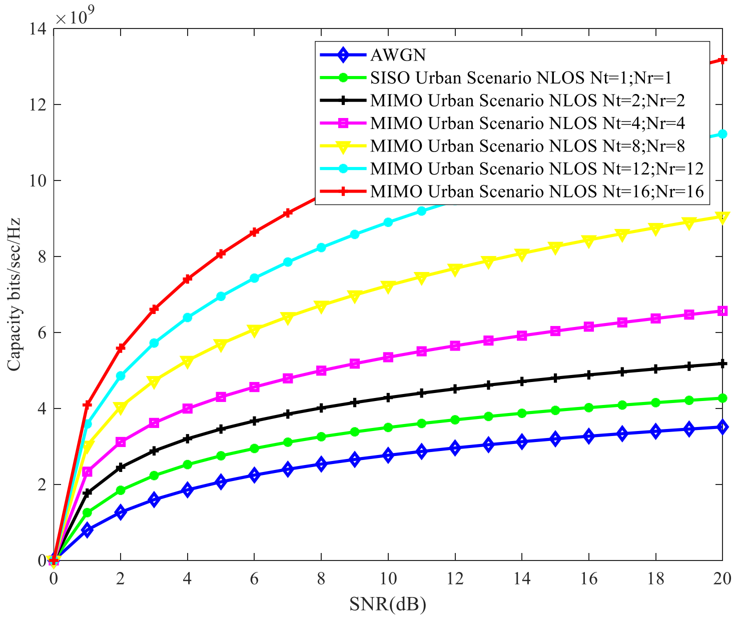

Fig. 4. MIMO capacity analysis in urban scenario NLOS.

Figure 5 shows MIMO capacity analysis in LOS rural scenario for various LOS components given by Rician component factors K =5 dB, 10 dB, 15 dB and 20 dB. As the Line-Of-Sight component value increases and the MIMO antenna configuration size increases the capacity also increases due to the fact of diversity gain provided by the antennas which is the product of number of transmit antennas N_t and N_r receive antennas. The obtained results can be used for development of 5G and 6G systems [21-26]where data rate in terms of Gbps are expected for various applications.

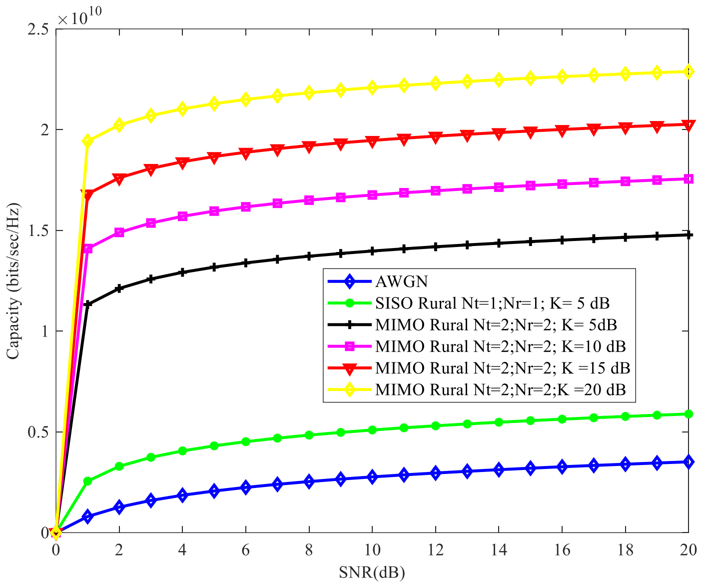

Fig. 5. MIMO capacity analysis in rural scenario LOS.

5. Conclusions

This research paper gives valuable information regarding the capacity of wireless systems in urban and rural scenarios. As smart cities with IoT enabled embedded technologies in urban and rural scenarios are becoming a driving force globally worldwide, the results presented here will be highly beneficial to develop applications relating to capacity analysis and other performance metrics such as bit error rate and outage probability. The obtained results can be employed for designing future wireless 5G and 6G systems where high data rate applications are expected to cater the needs of multimedia applications of the order of Gbps. In future this work can be extended to multiuser systems and interference limited systems.

Nomenclatures

c	Channel capacity between UE and BS in bits/s/Hz
d	Data signal between UE and BS
$\boldsymbol{D}$	Data signal matrix between UE and BS
$\boldsymbol{H}$	MIMO channel matrix between UE and BS in urban/rural scenario
h	Channel between UE and BS in urban/rural scenario
$\|\|h\|\|^2$	Norm squared value
h_e	Differential Entropy of the received signal /noise signal
$\boldsymbol{I}$	Identity matrix
$I(.)$	Mutual Information between UE and BS in bits/s
$\|I\|$	Determinant value of any entity
No	Noise Power at BS in Watts
N_r	Number of receive antennas
N_t	Number of transmit antennas
Ps	Signal Power in Watts

Greek Symbols

σ^2	Variance of the received signal

Abbreviations

AWGN	Additive White Gaussian Noise
BS	Base Station
Gbps	Gigabits per second
IoT	Internet of Things
LOS	Line-Of-Sight
MATLAB	Matrix Laboratory
Mbps	Megabits per second
MIMO	Multiple Input Multiple Output
MMWave	Millimeter-Wave
NLOS	Non-Line-Of-Sight
NOMA	Non-Orthogonal Multiple Access
PDA	Personal Digital Assistant
PSTN	Public Switched Telephone Network
SNR	Signal to Noise Ratio
UE	User Equipment
Wi-Fi	Wireless Fidelity
WLAN	Wireless Local Area Network
WPAN	Wireless Personal Area Network

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