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Low Cost Communication for High Speed Railway

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Abstract
The demand for wireless communication has widely increased in high-speed railway (HSR). The people demand high capacity and efficient communication independent of their location and speed. As the HSR provides more convenience to people, so the main attention is given to provide the reliable communication inside the train. It is the challenging task due to the high mobility of train and frequent need of handoff. To reduce the number of handoffs, the modified Hata model has been used in this paper. The performance of system is evaluated in terms of outage probability, coverage probability, transmission capacity and number of base stations. Results show improvement in coverage probability, transmission capacity and reduction in the outage probability and number of base stations. Hence, the cost of communication for high mobility vehicles can be reduced by decreasing the number of base stations.

Keywords Coverage probability · Outage probability · Hata model · High-speed railway (HSR) · Path loss

1 Introduction

Due to growing technology, the passengers inside the train demand for the high-speed internet access [1] and best voice quality [2]. In the recent years, several types of research are going on the railway communication. Conventional Global System for Mobile Communications (GSM) is adapted for the railway-specific application which is termed as the GSM-R [3]. But it becomes successful only for voice communication in the high-speed railway (HSR) not for data service. It doesn't support data rate services for high mobility of trains. To compensate the drawbacks of GSM-R, another technology i.e. Enhanced Data Rates for GSM Evolution (EDGE) provide better service quality as compared to GSM-R [4]. But it cannot support high speed video and other real time services. So, to compensate the demand of real time services, long-term evolution (LTE) is developed. LTE offers significant improvement such as best network availability and reduced handoff rate. But as the traffic increases, the LTE network cannot provide the sufficient data rate for high mobility

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vehicles [5]. So, there is the need of next-generation wireless network which provides the sufficient data rate for high mobility vehicles also [6]. The mobility is the key aspect of the 5G network. It is expected to provide the 150 Mbps or more data rate at the speed of 500 km/h [7].

The high mobility communication has still challenges in the next generation wireless network [8]. The different path loss model i.e. WINNER [9], 3GPP [10], ITU-R [11] and COST [12] model are used. But in these models, only three environments i.e. urban, rural and suburban are considered. But in real life, only three scenarios are not enough because the train has to go through the viaduct, cutting, station, mountain and river environment also. There are a lot of research is done on viaduct [13] and cutting [14] scenario but other environments are still a challenge for the researcher. The problem is solved in this paper by considering the effect of all the real-time scenarios.

The main issue in the HSR communication is Doppler shift [15], vehicle penetration loss (VPL) and frequent handoff. The problem of Doppler shift occur due to the relative motion of the train versus their serving base station (BS) and can be resolved by using the guard band [16, 17]. The second problem encountered in the HSR is VPL which occurs due to metallic body of the train [18]. The problem of VPL can be removed by placing the antenna on the top of the train [19]. The third problem encountered with the HSR is the frequent handoff. The process of handoff from one network to another network happens when the selected BS does not provide the required QoS for the specific application [20]. It is the important parameter which improves the network performance by reducing the different parameters such as call drop rate, call block rate etc. Due to the high mobility of trains, the handoff occurs frequently in the HSR which increase the burden to the base station (BS) and a mobile station (MS) [21].The handoff is broadly classified into two types i.e. hard handoff and soft handoff. In the hard handoff, firstly disconnected with the previous BS before making the connection with the target BS while in the soft handoff, firstly connect with the target BS before disconnecting with the previous BS [22]. Handoff decision is taken based on the different parameters such as received signal strength (RSS), signal to noise ratio (SNR), bit error rate (BER) etc. Here for simplicity, RSS parameter of previous and target BS is compared [23].

In the RSS with threshold method, the RSS of previous BS is compared with the threshold value for handoff decision. If the RSS of previous BS is less than the threshold value and RSS of target BS is greater than the previous BS, then handoff decision is initiated [24]. The choice of the threshold value is a difficult task. A higher threshold value results the unnecessary handoff while a lower threshold value results the dropped call [25]. So, the proper choice of threshold value is chosen because a tradeoff exists between these two parameters.

The different handoff scheme such as group handoff [26], relay assisted handoff [27] are proposed for HSR. In the group handoff [28] process, the handoff occurs for hundreds of active users at the same time which suffer the problem of signaling storm. The group handoff problem is removed by mobile relay. Multiple relays [29] can be used on the top of the train roof which provide the seamless handoff and reduce handover time. But the investment cost of multiple relay in HSR communication become high. So, the relay assisted handoff is not reliable for HSR communication.

To ensure best services to the user, there is a need to improve the handoff process in the HSR. Due to the high mobility of trains, the handoff occurs frequently in the HSR which increase the burden to the base station (BS) and a mobile station (MS) [21]. So, for reducing the load of BS and MS, the modified Hata model has been used which has the advantage of a reduced number of handoff. The handoff directly affects the communication cost of MS and BS. So, by reducing the number of handoffs, the communication cost of HSR can be reduced [30].

The contributions of this paper are outlined as:

1. The modified Hata model is compared with the Hata model in terms of path loss and received power.
2. The performance of modified Hata model is analyzed in terms of outage probability, coverage probability, transmission capacity and a number of base stations.
3. The modified Hata and Hata model are compared for different frequencies. As the 5G network will work on the millimeter waves i.e. in GHz range of frequency, so this model is also tested for GHz frequency range.
4. The analytical results are also verified by the simulation results by using Monte-Carlo simulator.

The remainder of this paper is organized as follows: Sect. 2 describes the Hata model and modified Hata model for a different scenario. In Sects. 3 and 4, the system model and performance parameters are introduced respectively. In Sect. 5, the simulation results are discussed. Finally, in Sect. 6, the conclusion is given.

2 Path Loss Models

For railway communication, different path loss models are designed such as WINNER, 3GPP, ITU-R and COST model [31]. Each model has the specific frequency range and supports different types of mobility. For high mobility communication, Hata model is most commonly used. This model is most commonly used propagation model for predicting the path loss in an outdoor environment and considered the three different environments i.e. urban, rural and suburban area [13]. The standard Hata model for the urban, rural and suburban environment is as follows:

$$PL(Hata)_{urban} = 74.52 + 26.16\log_{10}(f) - 13.82\log_{10}\left(h_b\right) - 3.2\left(\log_{10}\left(11.75h_m\right)\right)^2 + \left[44.9 - 6.55\log_{10}\left(h_b\right)\right]\log_{10}(d) \tag{1}$$

$$PL(Hata)_{rural} = PL(Hata)_{urban} - 4.78(\log_{10}(f))^2 + 18.33\log_{10}(f) - 40.94 \tag{2}$$

$$PL(Hata)_{suburban} = PL(Hata)_{urban} - 2\left(\log_{10}\left(\frac{f}{28}\right)\right)^2 - 5.4 \tag{3}$$

where $PL(Hata)_{urban}, PL(Hata)_{rural}, PL(Hata)_{suburban}$ is the path loss in urban, rural and suburban area respectively, f is the frequency, h_b is the effective antenna height of BS, h_m is the mobile station antenna height, d is the distance between the transmitter and receiver in kilometers.

In real life, only three scenarios are not enough for high-speed railways. As the train has to go through the different scenarios i.e. station, tunnel, viaduct etc. So, all these scenarios must be considered in the HSR environment. The Hata model is modified by the least square regression method [32] in a different environment. Some corrections are done in the Hata model for reducing the path loss. The modified Hata model after the correction factor is given by

$$\begin{aligned} PL(modHata)_{urban} = 54.05 + 26.16\log_{10}(f) - 13.82\log_{10}\left(h_b\right) \\ - 3.2\left(\log_{10}\left(11.75h_m\right)\right)^2 + \left[43.08 - 6.55\log_{10}\left(h_b\right)\right]\log_{10}(d) \end{aligned} \tag{4}$$

$$\begin{aligned} PL(modHata)_{rural} = 44.08 + 26.16\log_{10}(f) - 7.39\log_{10}\left(h_b\right) \\ - 3.2\left(\log_{10}\left(11.75h_m\right)\right)^2 + \left[38.19 - 6.55\log_{10}\left(h_b\right)\right]\log_{10}(d) \end{aligned} \tag{5}$$

$$\begin{aligned} PL(modHata)_{suburb} = 44.1 + 26.16\log_{10}(f) - 8.08\log_{10}\left(h_b\right) \\ - 3.2\left(\log_{10}\left(11.75h_m\right)\right)^2 + \left[38.18 - 6.55\log_{10}\left(h_b\right)\right]\log_{10}(d) \end{aligned} \tag{6}$$

where $PL(modHata)_{urban}$, $PL(modHata)_{rural}$ and $PL(modHata)_{suburb}$ are the path loss for the urban, rural and suburban area. The corrections in Hata model is done to compensate the effects of path loss exponent of different environments and to achieve a sufficient fit. The path loss is also modified for different environment which is given by

$$\begin{aligned} PL(modHata)_{viaduct} = 53.1 + 26.16\log_{10}(f) - 13.82\log_{10}\left(h_b\right) \\ - 3.2\left(\log_{10}\left(11.75h_m\right)\right)^2 + \left[35.28 - 6.55\log_{10}\left(h_b\right)\right]\log_{10}(d) \end{aligned} \tag{7}$$

$$\begin{aligned} PL(modHata)_{cutting} = 55.74 + 26.16\log_{10}(f) - 13.82\log_{10}\left(h_b\right) \\ - 3.2\left(\log_{10}\left(11.75h_m\right)\right)^2 + \left[-34.09 - 44.79\log_{10}\left(h_b\right)\right]\log_{10}(d) \end{aligned} \tag{8}$$

$$\begin{aligned} PL(modHata)_{station} = 3.77 + 26.16\log_{10}(f) + 20.47\log_{10}\left(h_b\right) \\ - 3.2\left(\log_{10}\left(11.75h_m\right)\right)^2 + \left[36.04 - 6.55\log_{10}\left(h_b\right)\right]\log_{10}(d) \end{aligned} \tag{9}$$

$$\begin{aligned} PL(modHata)_{mount} = 0.75 + 26.16\log_{10}(f) - 80.08\log_{10}\left(h_b\right) \\ - 3.2\left(\log_{10}\left(11.75h_m\right)\right)^2 + \left[-61.89 - 90.69\log_{10}\left(h_b\right)\right]\log_{10}(d) \end{aligned} \tag{10}$$

Table 1 Shadow fading model in different HSR environment

Scenarios	Standard deviation (σ)
Urban	3.32
Rural	4.03
Suburban	2.93
Viaduct	2.84
Cutting	3.74
Station	2.76
Mountain	4.85
River	3.55

$$PL(modHata)_{river} = 40.53 + 26.16\log_{10}(f) - 8.79\log_{10}\left(h_b\right) - 3.2\left(\log_{10}\left(11.75h_m\right)\right)^2 + \left[41.97 - 6.55\log_{10}\left(h_b\right)\right]\log_{10}(d) \quad (11)$$

where $PL(modHata)_{viaduct}$, $PL(modHata)_{cutting}$, $PL(modHata)_{station}$, $PL(modHata)_{mount}$ and $PL(modHata)_{river}$ are the path loss for viaduct, cutting, station, mountain and river area. Every scenario has the different effect on the transmitted signal. So, the standard deviation is different for every scenario and is given in Table 1. The mountain scenario has the highest standard deviation and station has the minimum standard deviation as shown in Table 1.

3 System Model

The two base-stations with their coverage area are shown in Fig. 1. Let us consider the train is moving a distance d km from the BS1 along the straight line. BS1 and BS2 are located at the center of the cell [33]. Let the radius of the hexagonal cell is 'R' and two BSs are situated at the distance of 'D'.

In the RSS based handoff scheme, the handoff is initiated if the RSS of target BS is greater than the previous BS.

$$P_r^{tar} > P_r^{prev} \quad (12)$$

where P_r^{tar} is received power of target BS and P_r^{prev} is the received power of previous BS. The received power is calculated by

$$P_r(d) = P_t - PL(d) \quad (13)$$

where P_t is the transmitted power and PL is the path loss which is defined in Sect. 2.

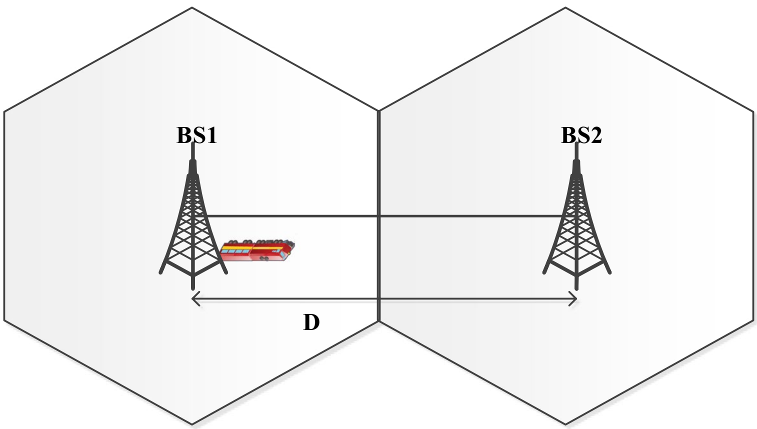

Fig. 1 System model of two base stations

4 Performance Parameters

Due to the high mobility of train, the handoff occurs frequently in HSR environment as compared to the conventional mobile communications [34]. The frequent handoff causes several problems in HSR system [35]. So, in this paper, the number of handoffs is minimized by reducing the path loss. The performance of handoff is defined in terms of coverage probability, outage probability, transmission capacity and a number of base stations.

4.1 Outage Probability and Coverage Probability

In the coverage area of a cell, if MS does not meet the minimum requirement, then handoff occurs. The handoff decision can be taken based on the various parameters such as signal to noise ratio (SINR), throughput, received power etc. [36]. The parameter is compared against the threshold value i.e. if the parameter range is less than the threshold value, then handoff occurs. The coverage probability and outage probability performance depends mainly on the threshold value and choosing the proper value of the threshold is a challenging task [37].

The coverage probability can be defined as a percentage that the RSS is greater than the minimum received power P_{min} required for communication. The coverage probability for the P_r received power is defined as

$$C_a = p\left(P_r(d) \geq P_{min}\right) \tag{14}$$

If the received power is greater than P_{min}, then the coverage probability is maximum. But as the received power fall below the minimum received power then the coverage probability start decreasing [38]. Due to shadowing, the received signal fluctuates and sometimes falls below the minimum received power P_{min} which causes the handoff or outage. The outage probability p_{out} is defined as

$$p_{out}\left(P_{min}, d\right) = p\left(P_r(d) < P_{min}\right) \tag{15}$$

where P_r is the received power which is a function of the separation distance between the transmitter and receiver and P_{min} is the minimum received power set as a threshold value at the receiver [39]. According to Eq. (15), the outage occurs if the received power P_r falls below the P_{min}. By combining the effect of path loss and shadowing the Eq. (15) can be written as

$$p\left(P_r(d) < P_{min}\right) = 1 - Q\left(\frac{P_{min} - P_r(d)}{\sigma}\right) \tag{16}$$

4.2 Transmission Capacity

The transmission capacity is a parameter that defines the performance of wireless network [40]. The maximum average number of successfully transmitted data per unit area is called the transmission capacity. For successful transmission, it is necessary that the user should reside within the coverage area. As the user come out from the coverage area i.e. the call is disconnected from the previous base station and handoff or outage occurs [41]. So, there is always a tradeoff between outage probability and transmission capacity. The transmission capacity is defined as

$$T_c = \mu.p\left(P_r(d) \geq P_{min}\right) \tag{17}$$

where $p\left(P_r(d) \geq P_{min}\right)$ is the coverage probability and μ is the MS density which is defined as the number of users per unit area.

$$\mu = \frac{N_u}{\pi R^2} \tag{18}$$

where N_u is the active number of users. As the area covered by the hexagonal cell is approximately equal to circular cell area, so for simplicity circular cell is considered. Here R is radius of cell.

4.3 Number of Base Stations

In the modified Hata model, there are fewer path losses as compared to the Hata model. Due to fewer path losses, the signal can propagate over the long distance. Therefore, the number of the base station [42] required reduces by using the modified Hata model. The ratio of required number of base station by using modified Hata model and Hata model is given by

$$\frac{N1}{N2} = 10^{-2(PL1-PL2)/(10\beta)} \tag{19}$$

where $N1$ and $N2$ are the required number of base stations using modified Hata model and Hata model respectively, $PL1$ and $PL2$ is the path loss using modified Hata model and Hata model respectively and β is the path loss exponent in different environment [43].

5 Results and Discussion

The effectiveness of HSR communication depends upon the RSS. The RSS increases by using the modified Hata model. The simulations are implemented on MATLAB with the different parameters as listed in Table 2.

The path loss calculated by the Hata model and modified Hata model in an urban area from two BSs is shown in Fig. 2. The path loss reduces for the modified Hata model as compared to the Hata model due to the correction factor. The path loss increases with the increase in distance from the BS. As the user goes away from the BS1, comes across with BS 2, the path loss increases for BS 1, and decreases for BS 2 as shown in Fig. 2. The received power obtained by two BSs in an urban area has been shown in Fig. 3. The

Table 2 Simulation parameter

Parameters	Value
Transmitted power	25 dBm
BS antenna height	20 m
Mobile antenna height	4 m
Radius of cell	10 km
Frequency	9 MHz
RSS threshold	− 120 dBm
Number of active users	100

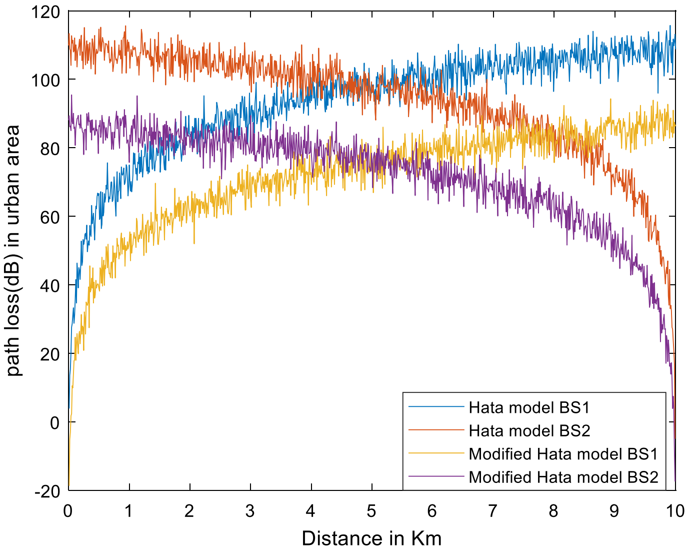

Fig. 2 Path loss from two base stations

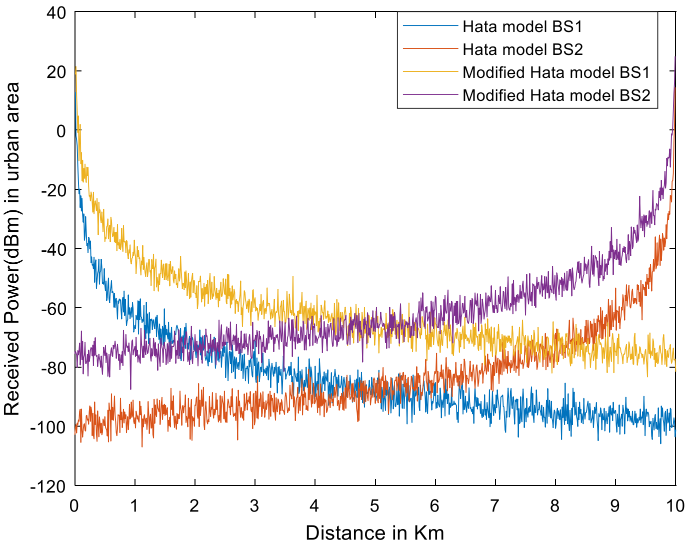

Fig. 3 Received power from two base stations

received power is calculated by Eq. (13) for Hata and modified Hata model. The received power decreases with the increase in separation distance.

The path loss calculated by the Hata model [44] and modified Hata model in an urban, suburban and rural area without averaging and with averaging is shown in Figs. 4 and 5. The difference between the two is averaging over different samples. The averaging is done using Monte-Carlo simulation and Fig. 5 shows that the curve becomes smoother after averaging. Usually, the handoff decision is taken after the averaging. The path loss

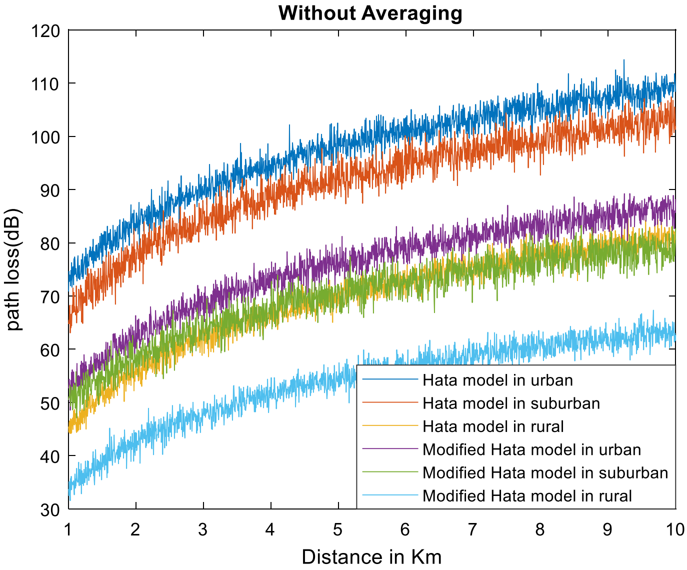

Fig. 4 Comparison of path loss in urban, rural and suburban area using Hata and modified Hata model without averaging

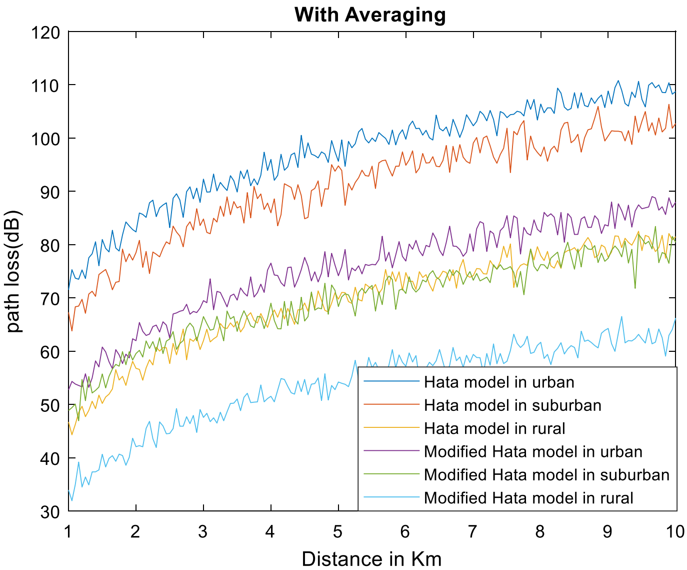

Fig. 5 Comparison of path loss in urban, rural and suburban area using Hata and modified Hata model with averaging

decreases with the increase of separation distance between transmitter and receiver. The handoff is more frequent in the urban area due to larger BS distribution density. The path loss calculated by the Hata model is more as compared to the modified Hata model in all

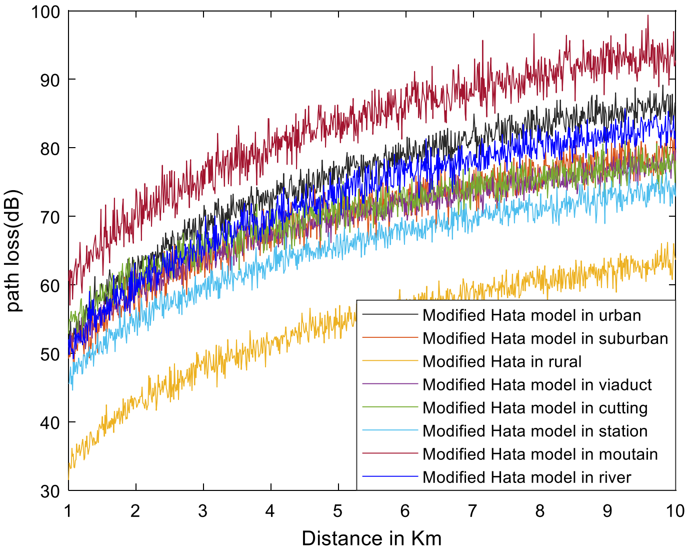

Fig. 6 Comparison of path loss in different scenarios

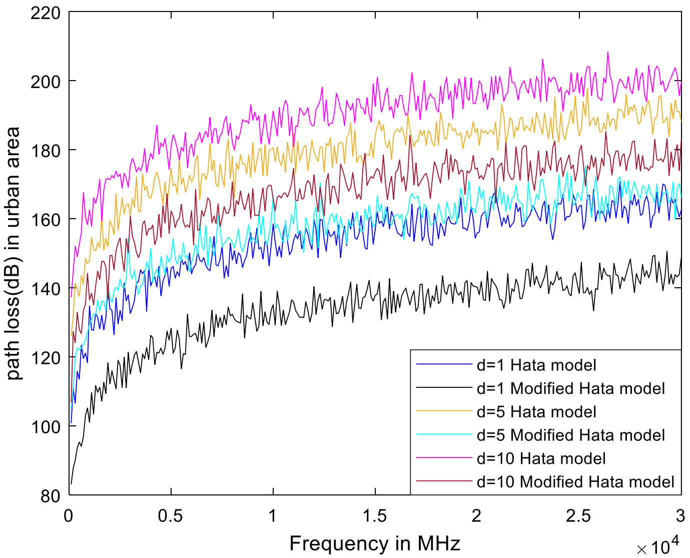

Fig. 7 Path loss v/s frequency for different distance of BS and MS

the three areas. The losses are reduced in the modified Hata model due to the correction factors.

One more drawback of the Hata model is that, it is only valid for the urban, suburban and rural areas while in the railway communication, there are various other areas through which the trains pass. In the modified Hata model, other areas are also considered such as viaduct, cutting, station, mountain, and river. Viaduct [45] and cutting [46] area are very popular in the research work. The path loss calculated in the different area is shown in Fig. 6. The path loss increases with the increase of separation distance between the transmitter and receiver and it is maximum in the mountain area and minimum in the rural area.

The path loss calculated for different frequency is shown in Fig. 7 because path loss also depends on the frequency. As the frequency range increases, the path loss also increases. But one thing is clear in Fig. 7, that the path loss is less in the modified Hata model for higher frequency also. As the 5G network work on the higher frequencies [47], so this model can also valid for 5G network.

The performance of handoff in modified Hata model is measured by the different parameters. In this paper, the handoff decision is made on the basis of received signal strength. For handoff decision, the received signal power is compared against the threshold value. If the received signal power falls below that threshold value, the handoff decision is taken otherwise the call is dropped. The computer-based simulation has been done to validate the analytical results for both Hata and modified Hata model. Monte Carlo simulations on MATLAB are used and the results are averaged over 10,000 iterations.

The outage probability for simulation and analytical results is shown in Fig. 8. The difference between the analytical and simulation results are small enough to be ignored. As discussed above, there is less path loss and more received power with the modified Hata model, so there are fewer chances of the outage. The outage probability depends upon the transmitted power, received power and threshold value. For lower transmitted power, there is less received power, so the outage probability become large. For higher transmitted power, there are fewer losses, and the received power is more, so the outage probability become small. The threshold value also plays a big role in outage probability. If the threshold value increases for the same received power, the number of outage increases. The outage occurs if the received power is less than the threshold. So, as the threshold increases, the received power remains same, so it cannot cross the threshold value and outage occurs.

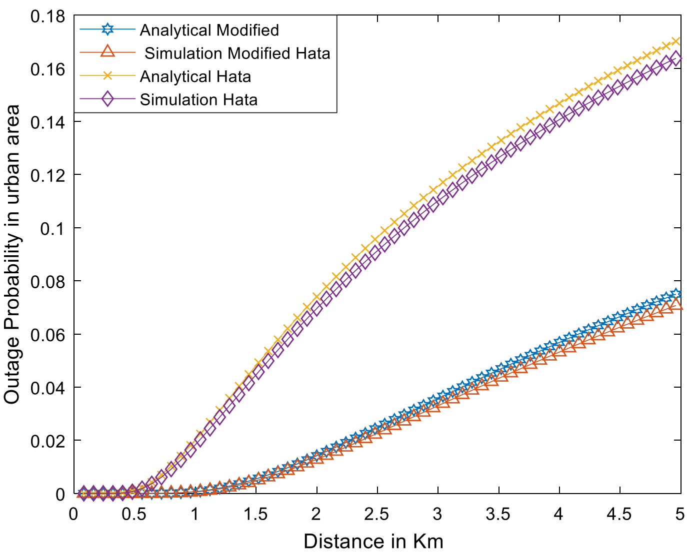

Fig. 8 Outage probability for analytical and simulation results

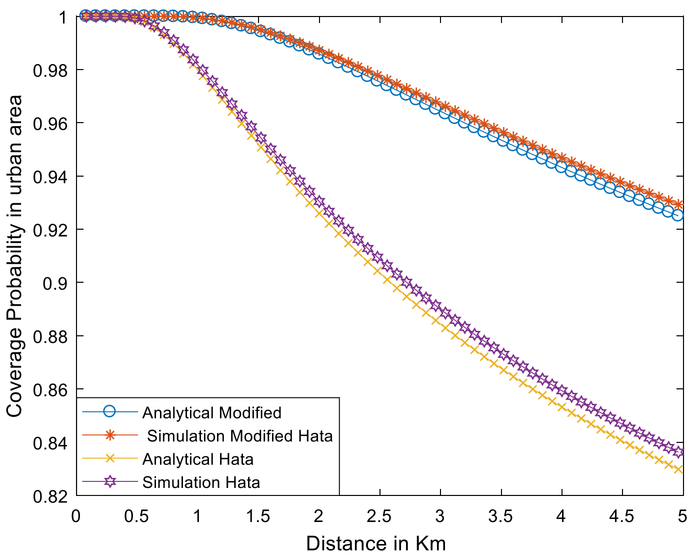

Fig. 9 Coverage probability for analytical and simulation results

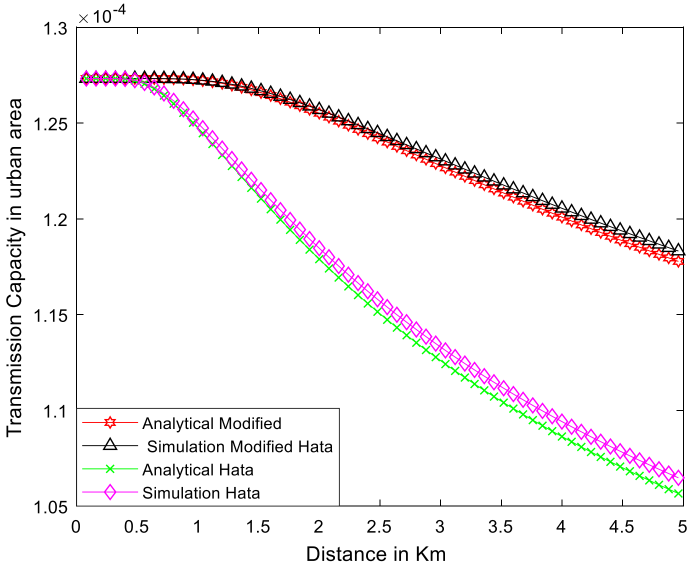

Fig. 10 Transmission capacity for analytical and simulation results

In comparison with Hata model, there are fewer chances of outage in modified Hata model due to decreased losses.

The coverage probability for simulation and analytical results is shown in Fig. 9. If the user receives the minimum power or greater than the minimum power, then it remains within its coverage area and coverage probability become large. The coverage probability

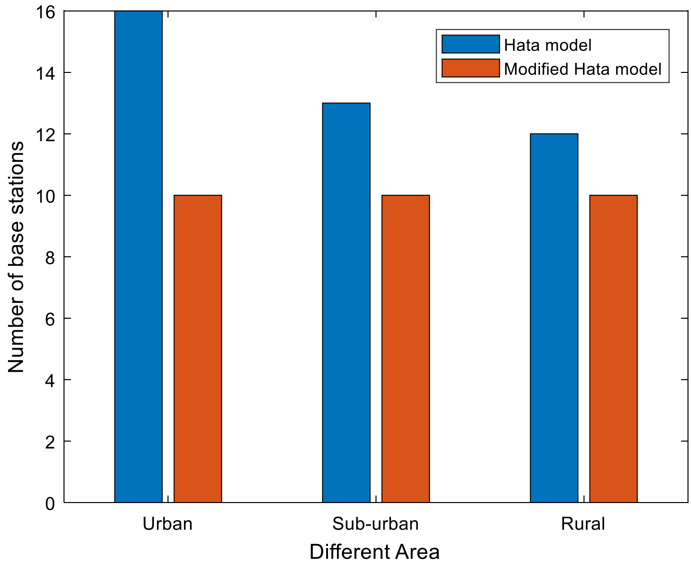

Fig. 11 Required numbers of base station in different area

increases with the decrease in the threshold value and vice versa. The reason behind the increase in coverage probability in the modified Hata model is the fewer path losses.

The transmission capacity for different thresholds using Hata and modified Hata model is shown in Fig. 10. The modified Hata model has the greater transmission capacity as compared to the Hata model due to the more coverage area. The transmission capacity is the successful number of transmission per unit area. So, the lager transmission capacity means the more efficient model for data transmission.

Due to less path loss in the modified Hata model, the signal can propagate over the long distance. Therefore, the number of the base stations reduces by using the modified Hata model. The reduced numbers of the base station are shown in Fig. 11. The effect of the reduced number of the base station is maximum in the urban area because the urban area has maximum losses. Same number of base stations can support more users due to path loss reduction. Reduction of the base station is maximum in the urban area if network planning is done with modified Hata model instead of Hata model. The number of the base stations reduces up to 38% in urban area, 23% in suburban area, and 17% in rural area. The number of base stations directly related with the cost. Therefore, the modified Hata model reduces cost. Thus in every point of view, modified Hata model is better than the Hata model.

6 Conclusion

In this paper, the modified Hata model is analyzed in terms of path loss and received power and compared with the Hata model. The simulation results illustrate that the mountain environment has the maximum losses and the rural environment has minimum losses. The performance of two models have been compared in terms of outage probability, coverage probability, transmission capacity and a number of base stations. The analytical results are compared with Monte-Carlo simulation and results illustrate that the modified Hata model reduces the outage probability and increase the coverage area and transmission capacity. In comparison to Hata model, the number of the base stations reduces up to 38% in urban area, 23% in suburban area, 17% in rural area, so the cost of BS reduces by using the modified Hata model. The improvement in performance parameters is due to less path loss in the modified Hata model as compared to the Hata model. Further, the path loss for the higher range of frequencies shows that the modified Hata model gives the lesser path loss as compared to the Hata model. As the next generation wireless network will work on GHz frequency range, so results of this paper may be useful for the next-generation wireless network.

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