Chapter

# Stochastic versus Ray Tracing Wireless Channel Modeling for 5G and V2X Applications: Opportunities and Challenges

*Sulaiman Tariq, Hussain Al-Rizzo, Md Nazmul Hasan, Nijas Kunju and Said Abushamleh*

## Abstract

Due to the rapid development of wireless communication applications, the study of Multiple Input Multiple Output (MIMO) communication systems has gained comprehensive research activities since it can significantly increase the channel capacity and link reliability without sacrificing bandwidth and/or transmitted power levels. Researchers tend to evaluate the performance of their MIMO antenna arrays using various channel modeling tools. These channel models are mainly categorized into either deterministic channels based on Ray Tracing (RT) tools or Stochastic Channel Models (SCM). In this chapter, we compare these two categories in terms of the MIMO channel capacity using a complete description of the antennas at the transmitting and receiving ends in terms of 3D polarimetric radiation patterns and scattering parameters. The performance is evaluated for 5G New Radio (NR) Enhanced Mobile Broadband (eMBB) and Ultra-Reliable Low-Latency Communication (URLLC) services and Vehicle-to-Everything (V2X) systems using state-of-the-art commercial SCM and RT tools to provide information regarding the capabilities and limitations of each approach under different channel environments and the Quality of Experience (QoE) for high data rate and low latency content delivery in the 5G NR sub-6GHz mid-band Frequency Range-1 (FR1) N77/N78 bands.

**Keywords:** MIMO, channel capacity, ray tracing channel modeling, stochastic channel modeling, 5G, V2V, V2X

## 1. Introduction

MIMO communication systems have received significant research activities both in industry and academia since the emergence of 3G systems and are currently attracting many developers of 5G and 6G systems [1–3]. Services such as eMBB and URLLC have played an important role in the development of the 5G NR and Intelligent Transport System (ITS) and their network performance in V2X communications which incorporates Vehicle-to-Vehicle (V2V), Vehicle-to-Infrastructure (V2I) and Vehicle-to-Pedestrians (V2P) communication modes. Wireless channel modeling plays a significant role in designing, assessing, and optimizing the performance of the systems components including the physical layer, networking protocols, and the antenna arrays at the Transmitter (Tx) and Receiver (Rx) using either RT or SCM tools [4–7]. However, very little research has been reported on the differences between these two channel modeling approaches including their strength, limitations and how they consequently affect the evaluation of the MIMO channel capacity for realistic scenarios [8–14].

Comparisons between deterministic and SCM are reported in [8–14]. However, none of them provided sufficient comparison based on a rigorous representation of the antenna arrays in terms of circuit parameters and 3D far-field patterns for both the co- and cross-polarized vector field components. In [8], the difference in the MIMO channel capacity between the SCM COST 259 and a deterministic urban city model simulated using RT for 3G cellular system is reported. However, only omni-directional antennas with no consideration for the mutual coupling are used and the results are only simulated in outdoor scenarios under one SNR. In addition, the testing scenarios are not identical, as for the RT model, they used varying heights for the base station towers, but for the SCM, fixed heights are used.

A comparison of the angles of arrival between 3GPP 3D statistical channel model and a deterministic urban channel model is presented in [9]. However, the MIMO channel capacity and throughput results are not evaluated. The authors in [10] considered a large-scale massive MIMO system to compare the downlink throughput between an outdoor urban deterministic model and the statistical i.i.d. Rayleigh model. However, the i.i.d. Rayleigh model is not suitable to represent urban channel models. In addition, the i.i.d. Rayleigh model uses data generated from the RT software.

An evaluation of the MIMO channel capacity is presented in [11] using deterministic and stochastic indoor channel models. TGn C, D and E are used as indoor office SCM and a close representation is created and used in an RT scenario as the deterministic model. The RT channel capacity show close comparison to the results from the TGn stochastic model E. However, in the deterministic channel model, the Mobile Terminal (MT) antennas are placed in only two rooms while ignoring other locations in the building which would subsequently affect the accuracy of the calculated results. Considering the asymmetric distribution of rooms and the small size of the model, the results should be studied for different locations of Tx and a complete distribution of Rx antennas in the entire model's area.

In [12], the difference between RT and SCM for network connectivity is reported. Neither capacity nor throughput results are presented, and all the simulations are for Single-Input Single-Output (SISO) scenarios. A massive MIMO study is presented in [13] comparing RT generated MIMO channel capacity with results from i.i.d. Rayleigh statistical channel model. Similar to [10], the i.i.d. Rayleigh is not a realistic representation of indoor nor urban channel models. The results were also calculated for only one SNR. Lastly, in [14], the authors presented a survey about different channel modeling approaches and the challenges that accompany them in 5G networks. However, the paper did not present comparison data nor case studies.

The main objective of this chapter to provide a fair comparison between the two channel modeling techniques in terms of the MIMO channel capacity. To this end, several important parameters have to be taken into consideration when evaluating the channel capacity, such as the 3D radiation patterns of transmitting and receiving antennas for both the co- and cross-polarized components, the scattering parameters of the antenna arrays under consideration to invoke direct and mutual coupling between the antenna elements, the distribution of the Tx and Rx components using different channel environments (indoor and outdoor) for the 5G NR and the ITS V2X systems. We utilize state-of-art commercial channel modeling tools for our case studies. MIMObit [15] is used for SCM and Wireless InSite [16] is used to represent deterministic models. MIMObit is an electromagnetic propagation simulator that utilizes standardized stochastic spatiotemporal channel models and uses rigorous analytical electromagnetic formulation to produce precise antenna-to-antenna channels and evaluate the performance of MIMO systems in different propagation models [15]. Wireless InSite is a 3D RT wireless electromagnetic solver that considers the physical characteristics of the materials in an environment and uses shooting and bouncing rays as electromagnetic waves to track their reflection, diffraction, transmission and scattering through objects and evaluate the received power, capacity and throughput at each point in a study area [16].

The new contributions of this chapter can be summarized as follows. A comprehensive research of the capabilities and limitations of stochastic and deterministic channel modeling tools is presented for the first time in different indoor and outdoor channel environments. The effects of the antenna's 3D radiation patterns and scattering parameters on the MIMO channel capacity for 5G and V2X applications are considered using cutting-edge SCM [15] and RT [16] tools. It should be noted that all the simulations included in this chapter are intended for the downlink transmission utilizing the 2.45 GHz ISM band and the 3.7 GHz 5G NR FR1 N77/N78 bands.

The rest of the chapter is organized as follows. In Section 2, we present a case study involving the evaluation of the SISO and MIMO channel capacity for the Two-Ray model using Wireless InSite and MIMObit in order to validate the results against analytical formulation. In Section 3, we study the MIMO channel capacity in an indoor office environment using RT and SCM. Section 4 presents an evaluation of the MIMO channel capacity in an outdoor scenario using RT and SCM. In Section 5, the performance of the two channel modeling tools is presented for a V2X scenario involving a fixed gNodeB base station (gNB) and a moving vehicle. Finally, the chapter is concluded in Section 6.

## 2. Case study 1: two-ray model

Initially, the accuracy of the RT and SCM tools are verified using a simple scenario involving the channel capacity of the classical Two-Ray channel model over a flat Perfect Electrically Conducting (PEC) surface since an analytical solution is already available. Wireless InSite by Remcom is used for the RT approach while MIMObit is used to calculate the channel characteristics for a set of Tx and Rx antennas inserted in a half free-space environment above an infinite PEC surface.

To test the various settings and parameters for the proper operation of both software tools, the first case focused on evaluating the SISO channel capacity in a Two-Ray model and compare it to the theoretical calculations. The Two-Ray model consists of a single large flat layer of PEC. A single half-wavelength dipole transmitting antenna operating at 2.45 GHz and an identical receiving antenna are placed 30 m apart at a height of 2 m. The model consists of two rays, a Line-of-Sight (LOS) component and a Non-Line-of-Sight (NLOS) component that is reflected over the ground plane. **Figure 1** shows the two rays between the Tx antenna and the Rx antenna.

To evaluate the received power at the receiver, Eq. (1) is used [17].

$$P_r = 4P_t\left[\frac{\lambda}{4\pi d}\right]^2 G_t G_r \cos^2\left(\frac{\Delta\varnothing}{2}\right) \quad (1)$$

where $\mathbf{P_r}$ is the received power in W, $\mathbf{P_t}$ is the transmitted power in W, $\boldsymbol{\lambda}$ is the wavelength, $\mathbf{d}$ is the distance between the Tx and Rx, $\mathbf{G_t}$ and $\mathbf{G_r}$ are the gain of the

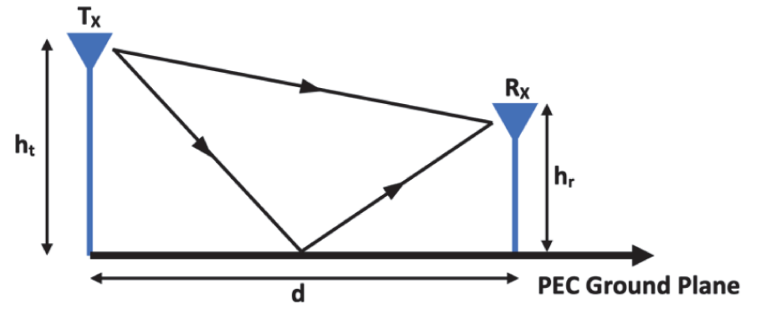


**Figure 1.**
*Two-ray model.*

Tx and Rx antennas, respectively, and the phase difference, $\boldsymbol{\Delta\phi}$, can be calculated using Eq. (2).

$$\boldsymbol{\Delta\phi} = \frac{2\pi\left(\sqrt{(h_t + h_r)^2 + d^2} - \sqrt{(h_t - h_r)^2 + d^2}\right)}{\lambda} \tag{2}$$

The Shannon capacity formula is used to find the SISO channel capacity [18] as shown in Eq. (3).

$$C = B\ \log_2(1 + SNR) \tag{3}$$

where **C** is the channel capacity in bits/s, **B** is the channel bandwidth in Hz and **SNR** is the Signal to Noise Ratio. The thermal noise is assumed to be equal to −100.99 dBm which is the standard used in [15, 16]. The geometry of the model simulated using Wireless InSite is shown in **Figure 2**. An equal total noise and interference of −100.99 dBm is used for both software tools. The channel capacity obtained from the three approaches are displayed in **Table 1**.

**Table 1** shows a close agreement between the SISO channel capacity results obtained from the RT tool, SCM tool and analytical calculations. A difference of

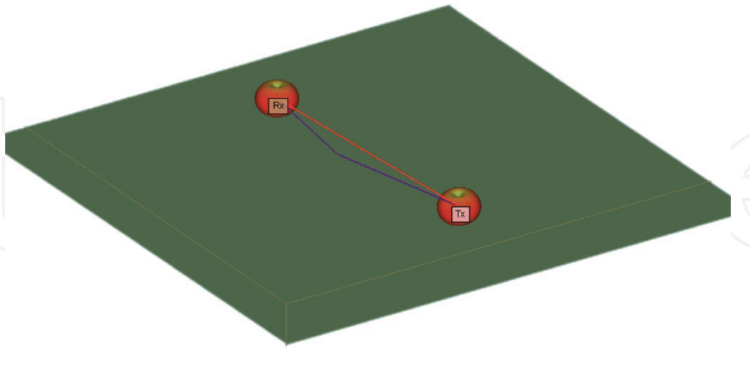

**Figure 2.**
*Two-ray model in wireless insite.*

| Model | Channel capacity (bps/Hz) | Difference % compared to theoretical calculations |
|---|---|---|
| Theoretical Calculations | 22.98 | — |
| Wireless InSite | 23 | 0.09% |
| MIMObit | 22.87 | 0.48% |

**Table 1.**
*Two-ray SISO model.*

0.09% is noted between the RT tool and theoretical channel capacity while 0.48% difference is observed between the SCM capacity and the theoretical one. This provides impetus to perform precise channel modeling comparisons when moving to the more realistic indoor and outdoor environments.

To provide further validation over the reliability of the software tools, the next comparison uses the same Two-Ray model, however, this time using a 2x2 MIMO scenario. Two-vertically polarized, half-wavelength dipole antennas with a separation of 2λ between the elements, operating at 2.45 GHz are used as the Tx and Rx antennas, centered at the same locations as the SISO two-ray model, separated by 30 m horizontally at a height of 2.5 m and 1.5 m, respectively. A single LOS ray and a single NLOS ray propagate from each Tx antenna element to each Rx antenna element, resulting in a total of eight rays in the model. The MIMO channel capacity can be expressed as shown in Eq. (4) [19]:

$$C = B \log_2 \left| I + \frac{SNR}{N_t} HH^H \right| \tag{4}$$

where **I** is the identity matrix, $\mathbf{N_t}$ is the number of transmitting antenna elements and **H** is the channel matrix between the Tx and the Rx.

The achieved MIMO channel capacity is 24.92 bps/Hz in RT and 23.01 bps/Hz in SCM with a difference of 7.98% which further validates the operation of these channel modeling tools.

## 3. Case study 2: indoor channel modeling

The second case concerns the evaluation of the MIMO channel capacity in a deterministic indoor channel model and comparison against a stochastic indoor channel model. The indoor floor plan shown in **Figure 3** is provided by Remcom. It has a width of 66 m, a length of 35 m and a height of 3 m and consisting of 23 offices, one main lobby and two big office areas containing 22 desks. Wood, concrete, glass, drywall and metallic materials were used to build the model. It provides a multipath-rich environment which is essential for MIMO applications. A corresponding SCM is created in MIMObit with similar dimensions using TGn 802.11n channel model B which is used to represent indoor office environments with NLOS conditions. A two-element MIMO antenna array is used as a transmitter and two-element half-wavelength dipole arrays are used as the receiving antennas in both models.

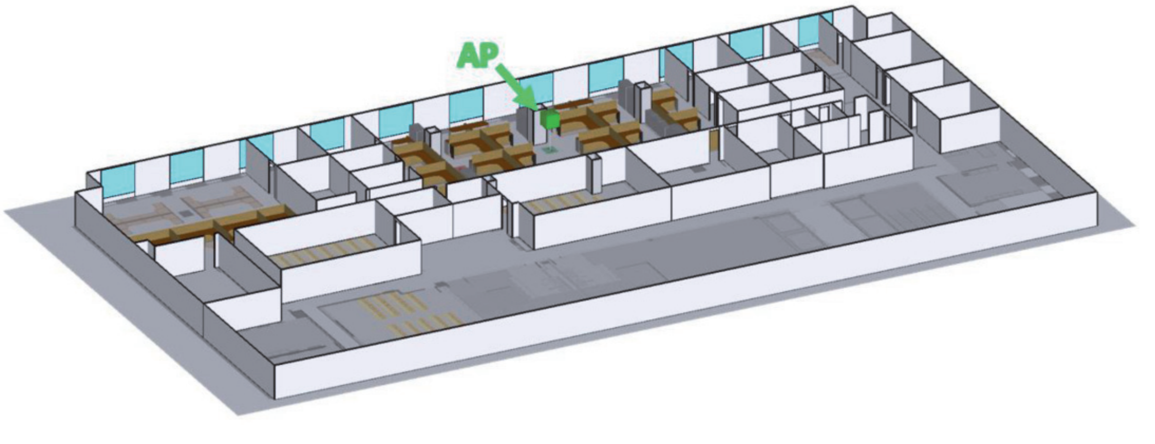


**Figure 3.**
*RT indoor model.*

The transmitting antenna array used in both the RT and SCM tools is a modification of the design reported in [4] which is a miniaturized two-element monopole antenna array decoupled using a frequency selective structure, mounted on a grounded dielectric substrate and fed by two coaxial cables. The array operates at 3.7 GHz with a bandwidth of 160 MHz extending from 3.62 GHz to 3.78 GHz as determined by the S-parameters presented in **Figure 4**. The antenna has a minimum S11 of −30.7 dB and a reduced mutual coupling below −20 dB with a minimum of −38 dB over the operating bandwidth. The array achieves orthogonality between the main lobes of the 3D radiation patterns of the antenna elements as shown in **Figures 5** and **6**, which is favorable for spatial diversity and multiplexing. Each element pattern has a maximum gain of 7.01 dBi at boresight.

The array is placed 36 m from the west main wall and 6.5 m below the north wall of the floor plan (blue spot in **Figure 3**) at a height of 2.5 m and is rotated 180° across the length as an Access Point (AP) with an input power of 1 W. 1056 two-element half-wavelength dipole antenna arrays operating at 3.7 GHz are uniformly distributed over the model at a height of 1.5 m and are used as the MT receiving antennas. The MT dipole elements are separated by 2λ where λ is the free-space wavelength at the operating frequency. The maximum number of ray reflection,

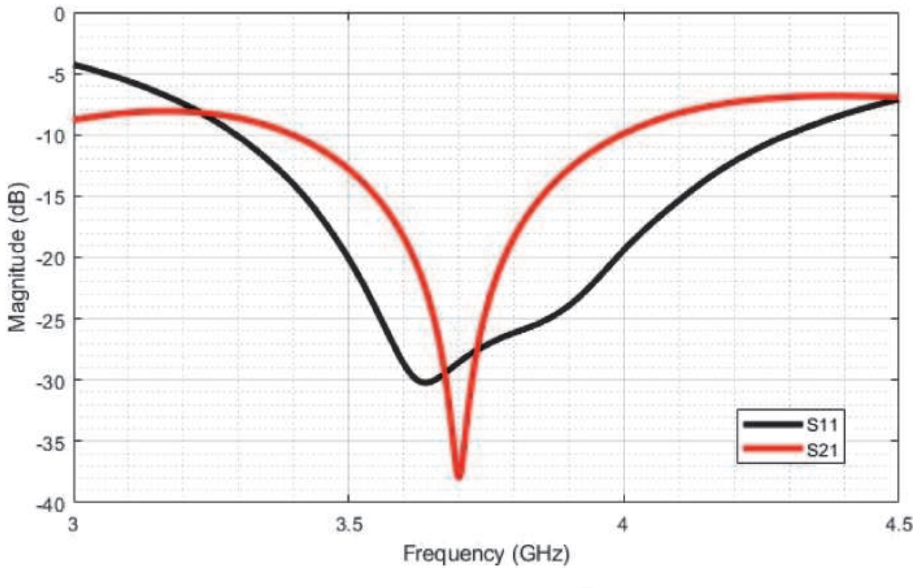


**Figure 4.**
*Tx/Rx antenna S-parameters.*

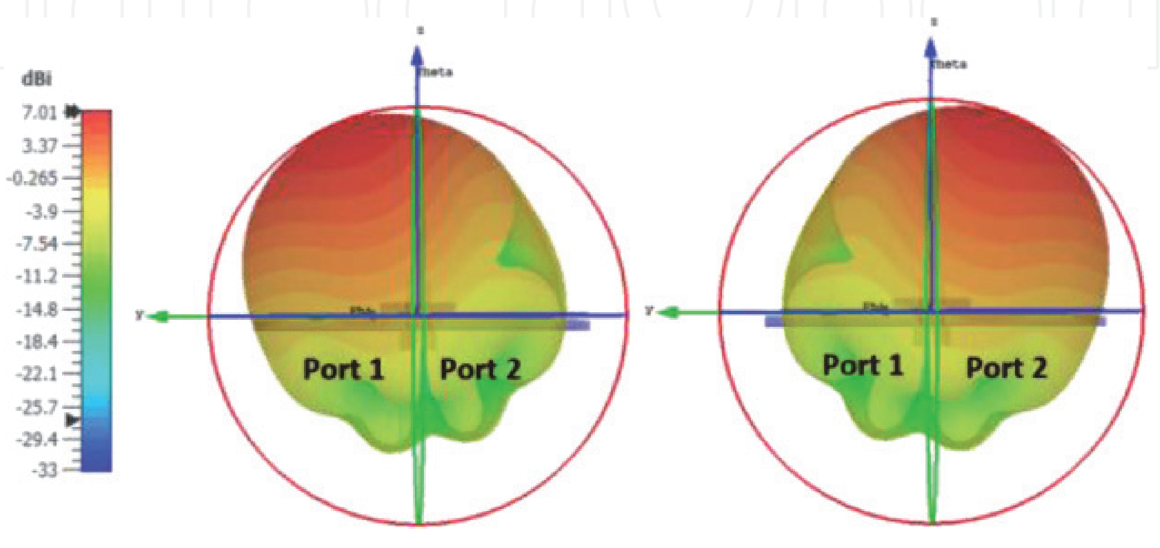


**Figure 5.**
*3D antenna radiation pattern.*

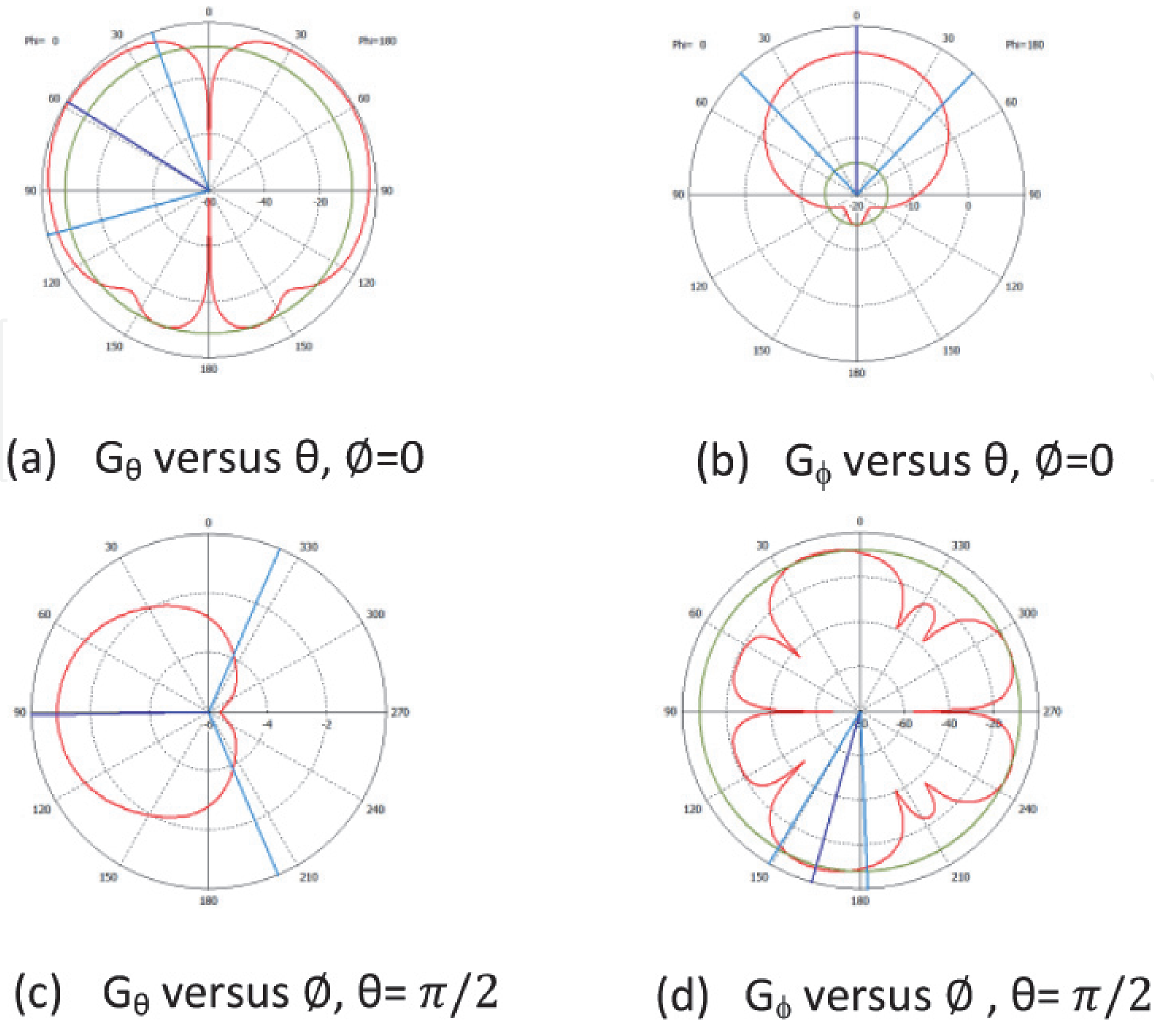


**Figure 6.**
*2D antenna radiation pattern (θ is the complement of the elevation angle and ∅ is the azimuth angle).*

transmission and diffraction per path is seven, one and two, respectively. These numbers are chosen after a trade-off between simulation time and accuracy. The space between the transmitted rays is chosen as $0.25^\circ$. MIMO open-loop scheme with no channel-state information is chosen as the MIMO scheme with no precoding or beamforming using 20 MHz bandwidth. Equal gain combining is used as the combining method operated at the receivers. With the absence of interference in the channel, each MT will experience a unique multipath from the AP and hence resulting in different MIMO channel capacities as shown in **Figure** 7. The average capacity over the 1056 locations considered in the simulation is displayed in **Figure 9** for different SNRs ranging from 5 to 30 dB as the deterministic channel model MIMO capacity results.

A similar scenario is created using MIMObit's TGn 108.11n model B SCM where the AP antenna is used at the same coordinates. However, only one receiving MT antenna is placed at (−10 m, −5 m, 1.5 m) as shown in **Figure 8** and the average capacity is computed over a certain number of channel realizations in the time domain. The model is simulated over 1000 channel realizations where the channel environment changes at each realization resulting in a different set of multipath experienced by the signal traveling from the AP to the MT and hence resulting in a different MIMO channel capacity. The number of realizations has been chosen to achieve statistically reliable results. Comparison of the average MIMO channel capacity is shown versus SNR ranging from 5 to 30 dB in **Figure 9**.

The MIMO channel capacity in the SCM is higher than the capacity obtained from the deterministic channel model at SNR values larger than 20 dB. A

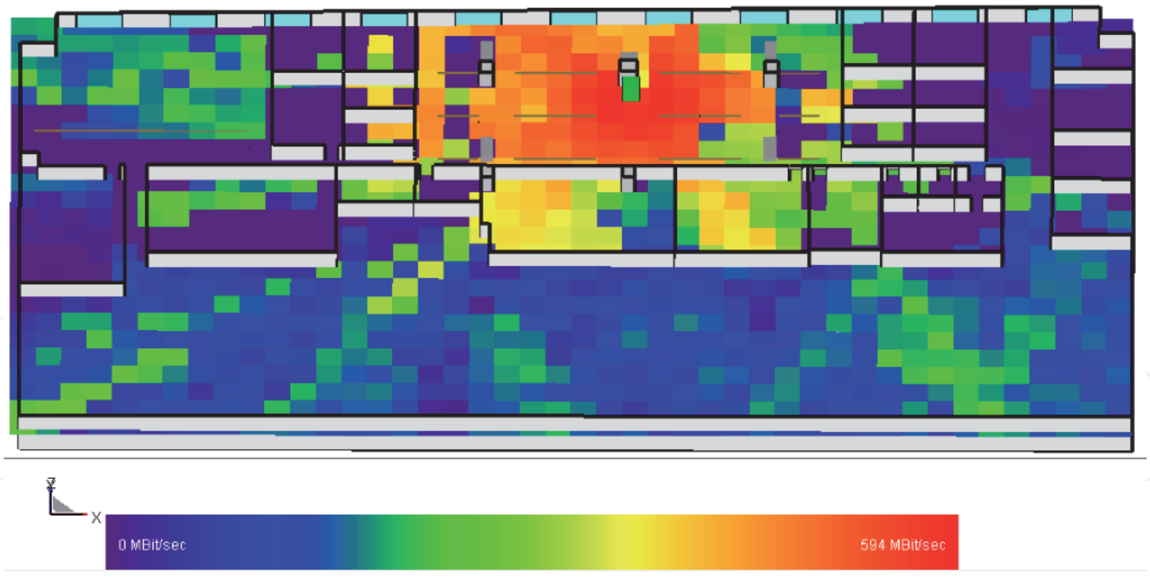


**Figure 7.**
*Indoor model channel capacity.*

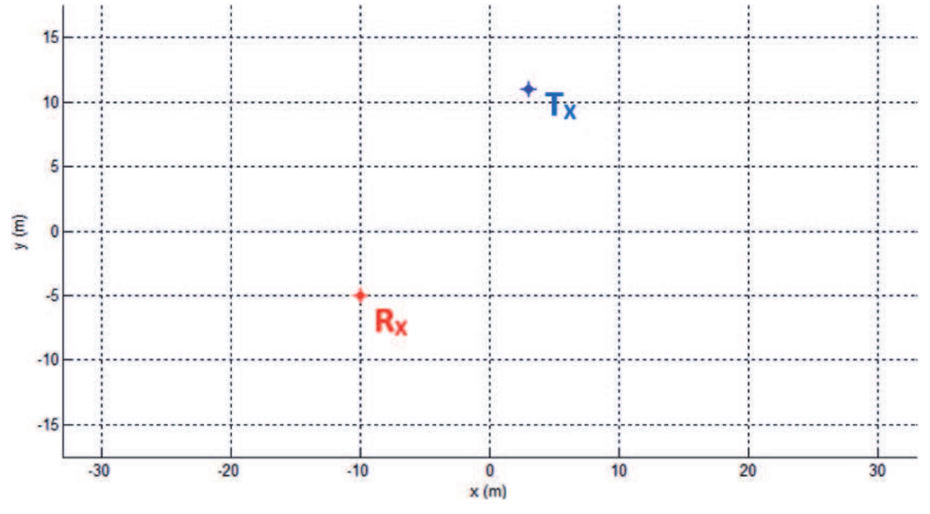


**Figure 8.**
*SCM indoor model.*



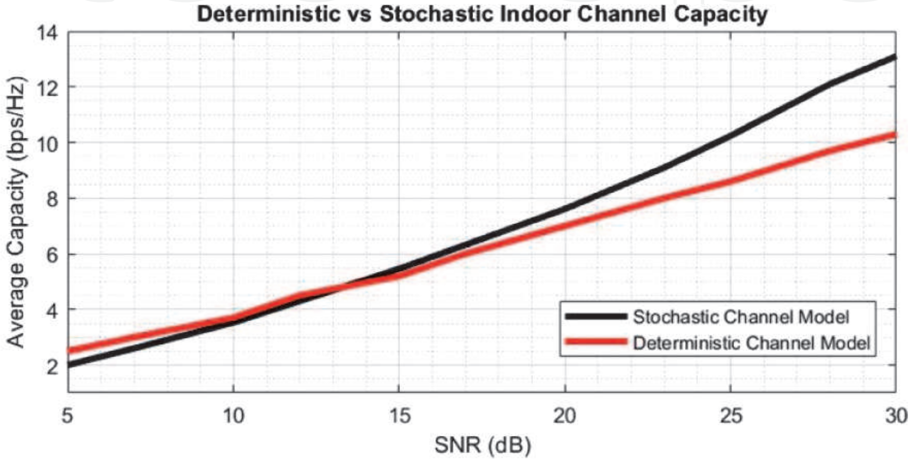


**Figure 9.**
*Indoor MIMO channel capacity.*

maximum difference of 23.9% is observed at a SNR of 30 dB where the capacities are 13.1 and 10.3 bps/Hz from the SCM and RT models, respectively.

To further improve the results obtained from the SCM model, a new simulation scheme is developed in which the number of the receiving MT is increased in MIMObit to six of different locations ranging from 3.16 m to 33.02 m away from the AP all at a height of 1.5 m as shown in **Figure 10**.

**Figure 11** reveals that at a constant SNR, changing the location of the receiving antenna does not have a significant impact on the MIMO channel capacity since each position is simulated 1000 times as the stochastic channel changes resulting in a maximum difference of 3.31% between any two Rx locations at SNR = 15 dB. Therefore, it is concluded that any Rx location within the geometry is valid for the comparison with the MIMO channel capacity generated from the RT tool.

Finally, we conclude that our results provide close agreement in the MIMO channel capacity between the SCM and the RT tools particularly at SNRs below 20 dB. The difference slightly increases at higher SNRs because the effect of MIMO is more prominent and. It should be emphasized that the observed 20% difference in results leads to a difference of only 3 bps/Hz which is accepted given that the SCM and RT are based on entirely different analytical formulations and numerical implementation. Due to space limitation, only one indoor model has been

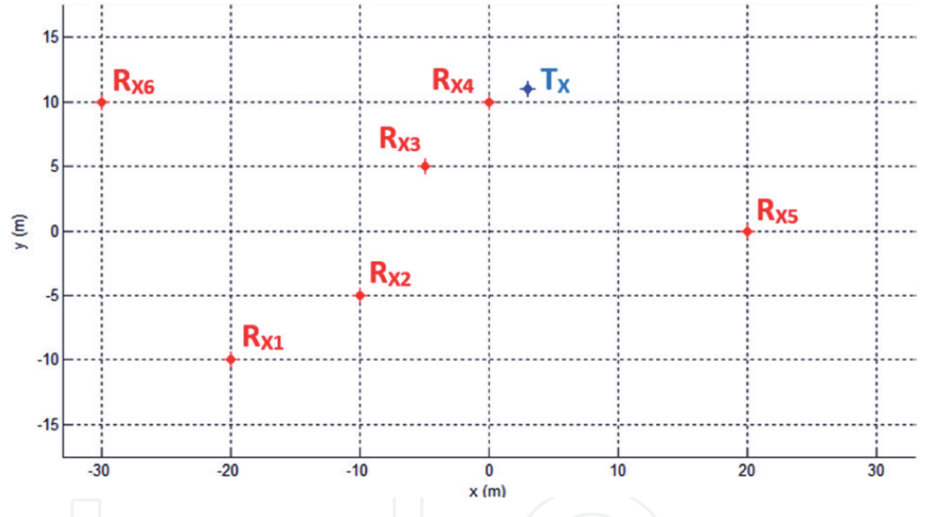


**Figure 10.**
*SCM indoor model with different Rx positions.*

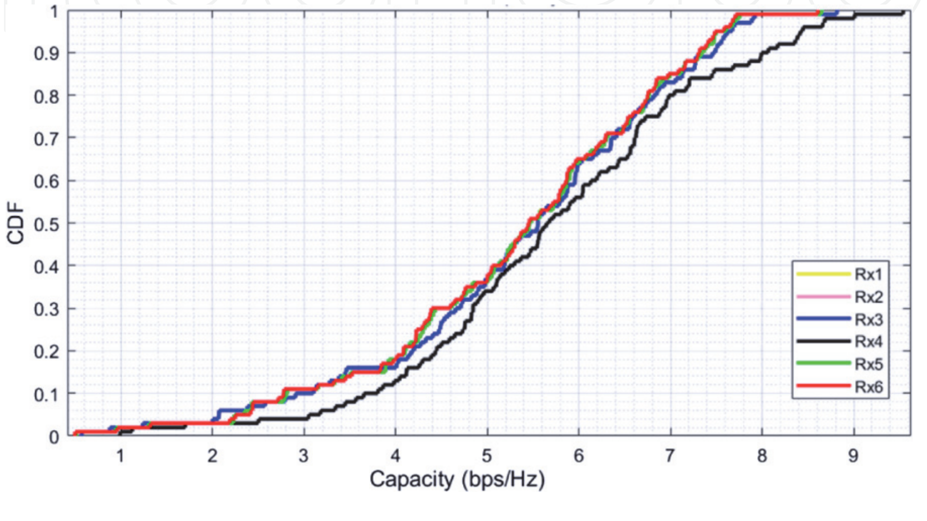


**Figure 11.**
*Indoor MIMO channel capacity for different Rx positions.*

considered in the RT and SCM channel models. We recommend that future research should include different indoor environments to be compared with different SCM models.

## 4. Case study 3: outdoor channel modeling

To further investigate the strengths and limitations of RT and SCM tools, the third case study considers the MIMO channel capacity in a realistic outdoor environment. The same software, MIMObit and Wireless InSite are used to model the stochastic and deterministic outdoor channels, respectively. A 2x2 MIMO antenna array operating in the 5G NR N77/N78 bands is used in the gNB. The 3GPP 3D Urban Macro cell (UMa) channel model is used as the SCM of the urban model.

The deterministic urban channel model is imported from Remcom's example library and is shown in **Figure 12**. It contains 39 buildings with different structures and heights. The gNB MIMO antenna used in this study is the same two-element array from the indoor study operating at 3.7 GHz and is placed at the edge of the rooftop on a building (the green box in **Figure 12**) at a height of 126.57 m with 180° tilt about the x-axis so that the antenna pattern's main-lobes are pointing towards the ground. The MT antennas are two-element dipole arrays operating at 3.7 GHz. 500 MT antennas are placed randomly across the city at different heights ranging from 1.5 to 50 m.

The antenna array at the gNB is fed with a total of 1 W power. The maximum number of ray reflection, transmission and diffraction per path is seven, one and two, respectively. The spacing between the transmitted rays is 0.25°. The MIMO open-loop diversity method is chosen for the study with no precoding or beamforming with 20 MHz allocated signal bandwidth. Equal Gain Combining is used as the combining method operated at the receivers. The average MIMO channel capacity perceived at the MTs is displayed in **Figure 13** under different SNR values ranging from 5 to 30 dB.

The 3GPP 3D UMa SCM is used to represent the stochastic urban environment in a squarish geometry with a length of 500 m. The 3GPP UMa model is used for cities with gNBs located above roof tops of building [20]. The number of clusters and rays per cluster vary with the model and could reaching up to 23 clusters and 20 rays per cluster [20]. Both LOS and NLOS propagations are considered in this

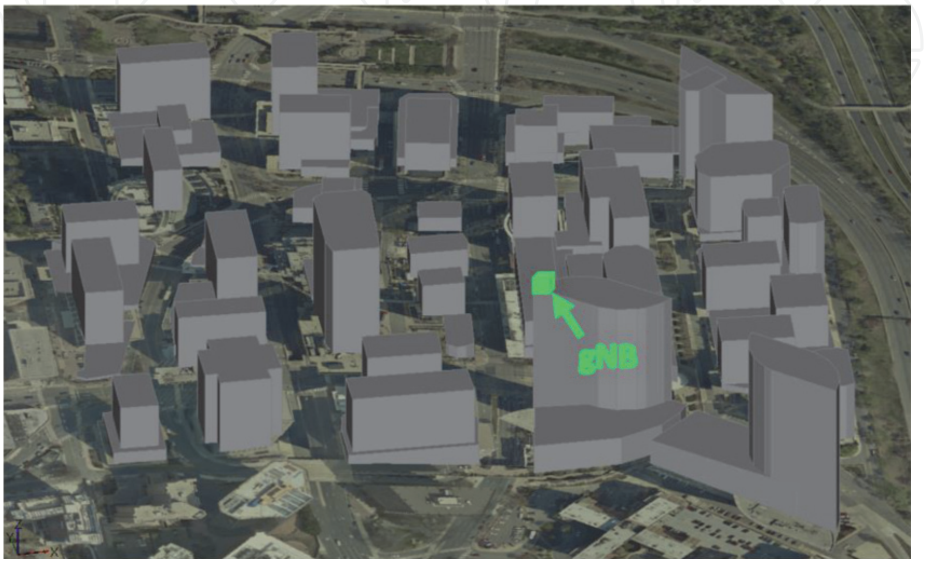


**Figure 12.**
*RT outdoor channel model.*

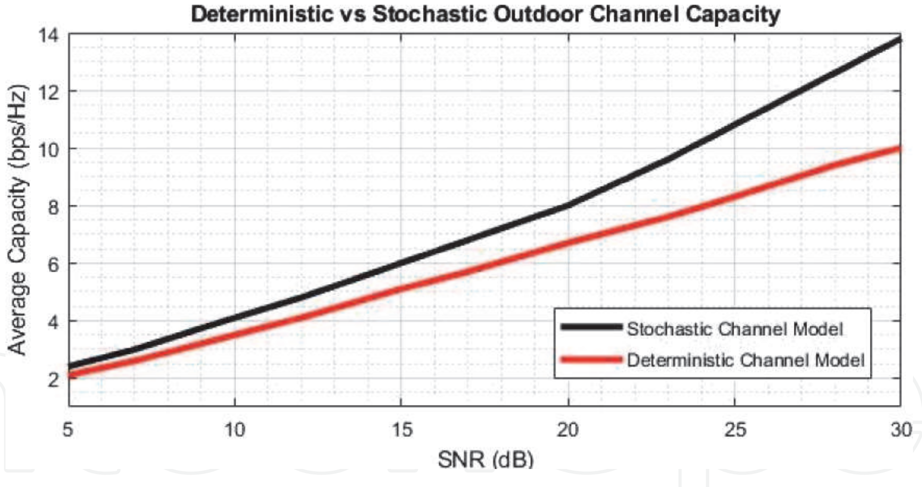


**Figure 13.**
*Outdoor MIMO channel capacity.*

model. The same gNB antenna operating at 3.7 GHz is placed at a height of 126.57 m and a location/orientation similar to that from the RT software. The receiving MT antenna is a two-element half-wavelength dipole array operating at 3.7 GHz and is placed at the center of the model at a height of 1.5 m. The model is simulated under 1000 instantiations and the average MIMO channel capacity for SNRs ranging from 5 to 30 dB is shown in **Figure 13**.

Similar to the results obtained in the indoor environment case study, the MIMO channel capacity in the SCM is close to the one obtained from RT. The difference in the capacity between the two channel modeling tools is 12.3% at SNR = 5 dB where the SCM achieved 2.41 bps/Hz and the deterministic model achieved 2.13 bps/Hz, 14.9% at SNR = 15 dB where 5.97 bps/Hz and 5.14 bps/Hz capacities are achieved in the stochastic and deterministic models, respectively, and 31.9% at SNR = 30 dB where 13.8 bps/Hz and 10 bps/Hz capacities are achieved in the stochastic and deterministic models, respectively.

## 5. Channel modeling for V2X applications

Traditionally, deterministic channel modeling tools are often used in V2X studies to evaluate the performance of antennas designed to operate in free-space when installed on a mast or a vehicle, Advanced Driver-Assistance Systems (ADAS), and interference among different vehicles [21–24]. Specific models have been recently developed for these particular applications utilizing various geometries to assess V2X communication systems in dynamic scenarios, the review of which is provided in [25, 26]. The IEEE 802.11p and LTE-V standards are widely used for V2X communications. However, nowadays, 5G technologies are also being utilized for vehicle communications after the massive development in 5G networks and their capabilities in delivering high speed and reliable links between devices and equipment. In this section, we compare the capabilities and limitations of SCM and RT tools in assessing the performance of V2X communication systems in the physical (PHY) layer.

It should be noted that the RT approach is the method of choice for static indoor and outdoor environments in particular for the initial design and deployment as well as the optimal number of transmitters to ensure coverage for the desired coverage area. Once the network is deployed and operational, the performance will obviously degrade in certain spots due to relative motion between different objects in the network which can be resolved by increasing the transmitted power, adjusting the tilt of the antenna array or installing additional transmitters as needed. In a realistic simulation involving multiple vehicles moving at different speeds on a highway, multiple trajectories have to be defined for several vehicles involved in the scenario. Each vehicle should be represented with the proper geometry to represent the vehicle type such as, sedans, trucks, motorcycles and SUVs with their respective material properties and included in the RT solution at different positions, the number of which depends on the speed of the fastest vehicle and the data rate of the V2X system in order to relate the sampling in time to the channel coherence time. Obviously, this leads to extremely large computational demands that can only be achieved on highly dedicated cluster computers.

Instead, the approach we followed to model simple V2X scenarios involves several simplifying assumptions in order to make the computational demands tractable. The vehicle structure has not been included in the RT approach since a dense outdoor environment is involved. We selected a path as shown in **Figure 14** for which the capacity has been evaluated along 410 m of discrete path points each separated by 1 m.

The same outdoor urban channel model in the previous section is utilized in studying the channel capacity available to vehicles traversing a path of 410 m at a given speed in a city surrounded by concrete buildings while transmitting and receiving signals from a gNB located close to the pathway in a 2 × 2 closed-loop MIMO system with no interference as shown in **Figure 14**. The channel parameters obtained from this model can be used in post processing to test different V2X scenarios. The vehicle has a two-element MIMO antenna array operating in the 5G N77/N78 bands at 3.7 GHz. The radiation patterns of the array shown in

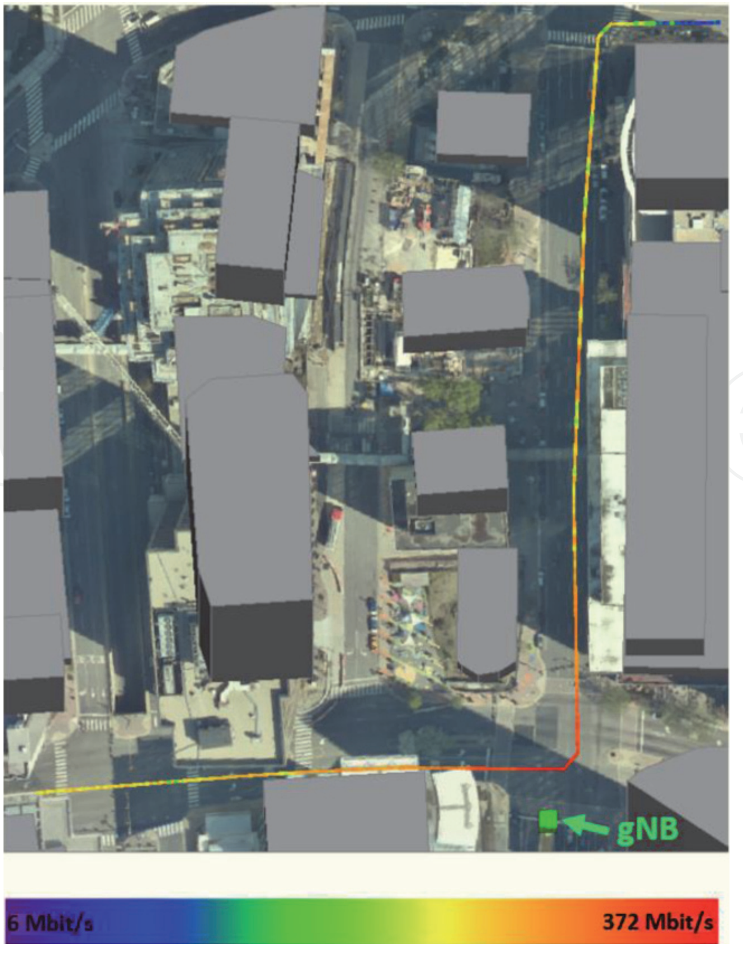


**Figure 14.**
*V2X route MIMO channel capacity.*

**Figures 5** and **6** are used in the simulation. The antenna is placed on the vehicle rooftop, 1.5 m above ground level.

The 2 × 2 MIMO system is simulated with 1 W total transmission power from the gNB. The maximum number of ray reflection, transmission and diffraction per path is seven, one and two, respectively. The spacing between the transmitted rays is 0.25°. The model is simulated as a closed-loop MIMO system with beamforming. The orthogonal radiation patterns of the antenna arrays is optimal for beamforming applications as they provide a narrow beam pointing at the vehicle while it moves, with Maximum Ratio Transmission (MRT) as the precoding scheme. The average MIMO capacity perceived at the vehicle's antenna array is 14.05 bps/Hz at an average SNR of 40 dB. **Figure 14** shows the MIMO channel capacity at each vehicle point along the traversed path in Mbit/sec with 20 MHz bandwidth.

In the absence of a vehicular model in the current version of MIMObit, we utilized the 3GPP 3D Urban UMa channel model as the stochastic channel where a gNB is placed at the coordinates (−150, 0, 50) as illustrated in **Figure 15** with the same MIMO antenna array used in the RT software. Both LOS and NLOS components are considered. To represent a vehicle movement in the SCM, we developed a new approach in which 20 independent MT antenna arrays are placed at different locations along the path. In this approach, each array is assigned a temporal behavior where it turns on momentarily at the time the vehicle reaches that point. For example, assuming the vehicle is moving at 50 km/h, Rx1 turns on at time, t = 0 s, then turns off, Rx2 turns on at t = 1.8 s then turns off, Rx3 turns on at t = 3.6 s then turns off, and so on. The model is simulated as a closed-loop 2x2 MIMO system with beamforming and the average achieved MIMO channel capacity is 15.3 bps/Hz at an average SNR equal to 40.

A 4.32% difference in the closed-loop beamforming MIMO channel capacity between the two modeling approaches is observed. This is due to that the RT study involves a static environment with no object mobility due to the limitations of the available computational resources and hence there is no time-varying signal distortion caused by mobility. However, the cluster birth-death process in different channel realizations accommodates for the non-static channel behavior of the SCM.

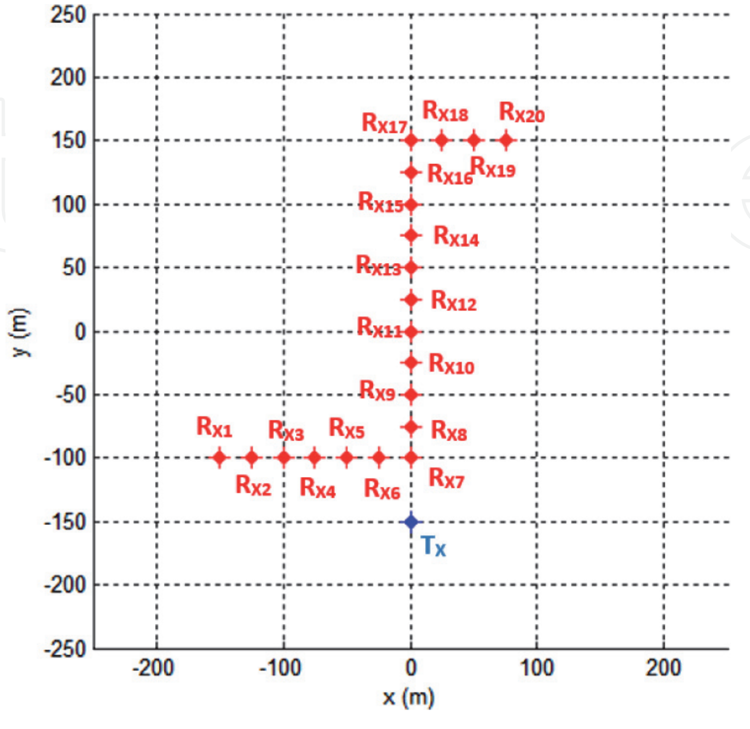


**Figure 15.**
*SCM V2X model.*

Additionally, the temporal characteristics of the Rx antenna defines the vehicle movement in the SCM. Nevertheless, incorporating a large number of vehicles in an RT tool moving in an urban environment with different speeds and trajectories places severe limitations in terms of computational time and resources.

## 6. Conclusion

In the near future, more RT and SCM tools will be developed as the demand and applications of various wireless systems relying on these channel modeling tools constantly grow for the advancement of wireless communications. This chapter provided a case study for the evaluation of the SISO and MIMO channel capacity using the Two-Ray model for validation purpose, studies of the MIMO channel capacity evaluation using RT and SCM tools for indoor and outdoor environments, and a performance evaluation of RT and SCM tools for a V2X communication scenario. In spite of the assumptions made in the RT approach, especially for the V2X applications, there are only minor differences in the MIMO channel capacity between RT and SCM. The SCM is capable of characterizing stationary and non-stationary dynamic V2X communication systems operating at different velocities since it considers the temporal and spatial domains while the deterministic model is capable of representing realistic object geometries. However, in the RT approach, the vehicles' models can only be included at discrete positions and the simulations have to be performed at each location. RT tools, however, yield more accurate results for link-level simulations of static networks as it can model objects such as buildings, road obstacles, traffic signs, etc. and achieve channel information characterizing precise channel effects such as path loss, shadowing and multipath fading. While SCM tools also model these channel effects, its adaptation for temporal behavior and non-stationary channel models makes it more suitable for link- and system-level simulations analyzing data transmission and communications at the bit level.

## Author details

Sulaiman Tariq[1*], Hussain Al-Rizzo[1], Md Nazmul Hasan[2], Nijas Kunju[3] and Said Abushamleh[4]

1 University of Arkansas, Little Rock, USA

2 University of British Columbia, Vancouver, Canada

3 ANSYS Inc., Bangalore, India

4 Indiana Institute of Technology, Fort Wayne, USA

*Address all correspondence to: sztariq@ualr.edu

## References

[1] Jiang W, Han B, Habibi MA, Schotten HD. The road towards 6G: A comprehensive survey. IEEE Open Journal of Communications Society. 2021;**2**:334-366. DOI: 10.1109/ojcoms.2021.3057679

[2] Al-Wahhamy A, Al-Rizzo H, Buris NE. Efficient evaluation of massive MIMO channel capacity. IEEE Systems Journal. 2020;**14**(1):614-620. DOI: 10.1109/jsyst.2019.2900006

[3] Al-Wahhamy A, Buris NE, Al-Rizzo HM, Yahya S. An efficient paradigm for evaluating the channel capacity of closed-loop massive MIMO systems. Progress in Electromagnetics Research C. 2020;**98**:1. DOI: 10.2528/pierc19082806

[4] Isaac AA, Al-Rizzo H, Yahya S, Al-Wahhamy A, Tariq SZ. Miniaturised MIMO antenna array of two vertical monopoles embedded inside a planar decoupling network for the 2.4 GHz ISM band. IET Microwaves, Antennas & Propagation. 2019;**14**(1):132-140. DOI: 10.1049/iet-map.2018.5069

[5] Al-Sadoon MA, Asif R, Al-Yasir YI, Abd-Alhameed RA, Excell PS. AOA localization for vehicle-tracking systems using a dual-band sensor array. IEEE Transactions on Antennas and Propagation. 2020;**68**(8):6330-6345. DOI: 10.1109/tap.2020.2981676

[6] Papamichael VC, Karadimas P. Performance evaluation of actual multielement antenna systems under transmit antenna selection/maximal ratio combining. IEEE Antennas and Wireless Propagation Letters. 2011;**10**: 690-692. DOI: 10.1109/lawp.2011.2161662

[7] Nikkhah MR, Panahi MA, Luyen H, Bahrami H, Behdad N. Capacity enhancement of MIMO systems using electrically-small, biomimetic antenna arrays. IET Microwaves, Antennas and Propagation. 2018;**12**(13):2001-2006. DOI: 10.1049/iet-map.2018.5185

[8] Hoppe R, Ramuh J, Buddendick H, Stabler O, Wolfle G. Comparison of MIMO channel characteristics computed by 3D ray tracing and statistical models. In: 2nd European Conference on Antennas and Propagation (EuCAP 2007). Institution of Engineering and Technology. Edinburgh; 2007. DOI: 10.1049/ic.2007.1049

[9] Georgiou O, Dettmann CP, Coon JP. Network connectivity: Stochastic vs. deterministic wireless channels. In: 2014 IEEE International Conference on Communications (ICC). Sydney, NSW, Australia: IEEE; 2014. pp. 77-82. DOI: 10.1109/icc.2014.6883298

[10] Ademaj F, Schwarz S, Guan K, Rupp M. Ray-tracing based validation of spatial consistency for geometry-based stochastic channels. In: 2018 IEEE 88th Vehicular Technology Conference (VTC-Fall). Chicago, IL, USA: IEEE; 2018. DOI: 10.1109/vtcfall.2018.8690832

[11] Aslam MZ, Corre Y, Bjornson E, Larsson EG. Large-scale massive MIMO network evaluation using ray-based deterministic simulations. In: 2018 IEEE 29th Annual International Symposium on Personal, Indoor and Mobile Radio Communications (PIMRC). Bologna, Italy: IEEE; 2018. DOI: 10.1109/pimrc.2018.8580760

[12] Gao Y, Chen X, Parini C. Experimental evaluation of indoor mimo channel capacity based on ray tracing. In: 2004 Proceedings of the London Communications Symposium. London: University College London; 2004. pp. 189-192

[13] Valle L, Pérez JR, Torres RP. Characterisation of indoor massive

MIMO channels using ray-tracing: A case study in the 3.2–4.0 GHz 5G band. Electronics (Basel). 2020;**9**(8):1250. DOI: 10.3390/electronics9081250

[14] Gkonis PK, Trakadas PT, Kaklamani DI. A comprehensive study on simulation techniques for 5G networks: State of the art results, analysis, and future challenges. Electronics (Basel). 2020;**9**(3):468. DOI: 10.3390/electronics9030468

[15] Buris N. [Internet]. NEBENS. [cited: 2021 May18]. Available from: http://www.nebens.com/

[16] Wireless EMi. Propagation Software - Wireless InSite [Internet]. Remcom. [cited: 2021 May 18]. Available from: https://www.remcom.com/wireless-insite-em-propagation-software/

[17] Rayess W. Wireless Channel Modeling for Networks on Chips [thesis]. Columbia, SC, United States: University of South Carolina; 2016

[18] Shannon CE. A mathematical theory of communication. Bell System Technical Journal. 1948;**27**(4):623-656. DOI: 10.1002/j.1538-7305.1948.tb00917.x

[19] Holter B. Capacity of Multiple-Input Multiple-Output (MIMO) Systems In Wireless Communications. Lecture presented at Trondheim, Norway. 2002 Nov 15; 2002

[20] Buris N. MIMObit user manual [Internet]. NEBENS; Available from: http://www.nebens.com/

[21] Sial MN, Deng Y, Ahmed J, Nallanathan A, Dohler M. Stochastic geometry modeling of cellular V2X communication over shared channels. IEEE Transactions on Vehicular Technology. 2019;**68**(12):11873-11887. DOI: 10.1109/tvt.2019.2945481

[22] Yi W, Liu Y, Deng Y, Nallanathan A, Heath RW. Modeling and analysis of MmWave V2X networks with vehicular platoon systems. IEEE Journal on Selected Areas in Communications. 2019;**37**(12): 2851-2866. DOI: 10.1109/jsac.2019.2947928

[23] Gustafson C, Mahler K, Bolin D, Tufvesson F. The COST IRACON geometry-based stochastic channel model for vehicle-to-vehicle communication in intersections. IEEE Transactions on Vehicular Technology. 2020;**69**(3):2365-2375. DOI: 10.1109/tvt.2020.2964277

[24] Reichardt L, Maurer J, Fugen T, Zwick T. Virtual drive: A complete V2X communication and radar system simulator for optimization of multiple antenna systems. Proceeding of the IEEE Institute of Electrical and Electronics Engineering. 2011;**99**(7): 1295-1310. DOI: 10.1109/jproc.2011.2124430

[25] Matolak DW. Modeling the vehicle-to-vehicle propagation channel: A review. Radio Science. 2014;**49**(9): 721-736. DOI: 10.1002/2013rs005363

[26] Mehta KM. A survey on channel modeling for vehicular communications [thesis]. San Diego, CA, USA: San Diego State University; 2019