ADVANCING EARTH AND SPACE SCIENCE

Radio Science

COMMENTARY
10.1029/2022RS007447

**Key Points:**

- Radio Channel modeling for 6G
- Millimeter wave and Terahertz transmission
- Stochastic and deterministic channel models

**Correspondence to:**

S. Salous,
sana.salous@durham.ac.uk

**Citation:**

Salous, S., Haneda, K., & Degli-Esposti, V. (2022). 5G to 6G: A paradigm shift in Radio Channel Modeling. *Radio Science*, *57*, e2022RS007447. https://doi.org/10.1029/2022RS007447

Received 7 FEB 2022
Accepted 25 JUN 2022



# 5G to 6G: A Paradigm Shift in Radio Channel Modeling

**S. Salous[1], K. Haneda[2], and V. Degli-Esposti[3]**

[1]Durham University, Durham, UK, [2]Aalto University, Espoo, Finland, [3]University of Bologna, Cesena, Italy

**Abstract** Since the publication of the special collection on Radio Channel Modeling for 5G Millimeter Wave Communications in the Built Environments new frequency bands, new antennas and new transmission techniques are being proposed to cope with the demanding requirements of beyond-5G systems. In this commentary, we provide an overview of the new technology and on how it will impact on radiowave propagation characteristics, and the way radio channel models will be developed and used in the future.

## 1. Introduction

Numerous high data rate applications are envisaged for 5G and for future 6G mobile radio networks. These include immersive applications, such as teleportation, virtual and augmented reality, joint communication and sensing, connected intelligence for health care, autonomous mobility and advanced industrial automation. A very important concept for future applications is the "Digital Twin" concept that allows real-time monitoring and control of critical scenarios, for example, a factory, a vehicular scenario, etc., by building remote, virtual replicas of them that can be studied and monitored by expert operators. Digital twin technology may allow to predict and avoid critical incidents but will require ultra-high-performance computation and communication capabilities.

According to the European 6G flagship Hexa-X project, 6G wireless communication will be a "fabric of connected intelligence, networks of networks, sustainability, global service coverage, extreme experience, and trustworthiness" (Uusitalo et al., 2021). In order to enable the foregoing applications, that require data rates on the order of Gbit/s or even Tbit/sec and very low latency, transmission will have to be moved into the millimeter-wave (mm-wave) or Terahertz (THz) ranges, where several GHz of contiguous spectrum are available. In the 2019 World Radiocommunications Conference five bands were agreed for harmonization with bandwidths of 1–5 GHz in the frequency range of 24–71 GHz. Higher frequencies above 100 GHz would provide tens of GHz of contiguous spectrum in the W band (75–110 GHz) and in the D band (110–170 GHz) according to the ECC report 282. The frequency band 231.5–275 GHz and extending up to 700 GHz is also on the WRC 2027 agenda for millimeter and sub-millimeter wave imaging systems, border checkpoint and crowded area security screening. Frequencies in the THz region have been proposed for indoor office applications and for chip-to-chip communication.

At these frequencies path loss is very high due to (a) higher diffraction losses (b) higher penetration losses through walls and objects and (c) scattering from rough surfaces (Rappaport et al., 2019). Fortunately, due to the small wavelength, relatively small antennas with high directivity, powerful beamforming, focusing, and spatial multiplexing capabilities can be realized to counter the higher path loss, supress interference and therefore achieve unprecedented system capacity and throughput gains. However, this will determine a change in the way we study radio wave propagation and design future wireless networks.

## 2. New Propagation Characteristics

In current mobile radio systems, we are used to thinking of the wireless signal as something that naturally propagates through the environment, marginally affected by the presence of walls and obstacles, with the only caveats of progressive attenuation with distance and of the presence of multipath fading and time/angle dispersion. With next-generation wireless networks making use of mm-wave and THz transmission our approach to radio propagation studies, and to the design and deployment of radio systems will have to change to take into account the actual environment configuration, the position of obstacles and the characteristics of the beamforming antennas.

Radio wave propagation and interaction with objects in the cellular context has been thoroughly studied through both theory and experimental evidence. The fundamental theory of Maxwell's equations governs the wave propagation we observe, which depends on the frequency and on the dielectric properties of the objects it interacts with. It is known that isotropic, free-space attenuation increases with frequency, and that atmospheric gases such as water vapor and oxygen can cause additional attenuation peaks at certain frequencies, such as the 15 dB/km additional attenuation of Oxygen at 60 GHz and even higher peaks above 100 GHz. Moreover, while rain attenuation is almost negligible below 10 GHz, moderate rain conditions of 50 mm/hr can cause an attenuation of 20 dB/km above 100 GHz that must be taken into account in propagation models.

However, there is little knowledge of common environment material properties above 100 GHz. Such properties for below-100 GHz are available in recommendation ITU.P 2040 only for a limited set of materials and wave-object interaction types, for example, penetration of a plane wave through a finite thickness plasterboard. Moreover, the exact knowledge of our living environment, for example, shapes of trees and leaves, layered wall structures and their dielectric constants is essential to know the attenuation during wave-object interaction, but it isn't always available or accessible and hence left as a challenge. Therefore, a great deal of work is still needed to characterize the scattering properties of many construction materials for the several mm-wave and sub-THz frequencies that are being proposed for beyond-5G wireless systems (Possenti et al., 2020; Zhang et al., 2020).

The necessary use of high-gain or even focusing antennas that will be necessary at those frequencies will make the channel highly directional and space selective. Therefore, besides the basic question "what's the signal strength?", future channel models will have to address also "where is the signal?" with reference to both space, and Doppler domain: the answer is crucial to determine which beamforming solutions should be used for transmission. Multi-dimensional channel characterization, including the space/angle, time and polarization domains is now necessary more than ever before.

## 3. New System and Transmission Techniques

The role of antenna aperture/array becomes much more significant at millimeter and Terahertz waves radio links than legacy below-6 GHz links. It is widely thought that very directive, "pencil beam" antennas will be introduced at link ends to effectively exploit antenna directivity, but their low-loss implementation and optimization of beam searching strategies leaves room for further research given the multipath wave propagation conditions of most radio links. Since the Fraunhofer far-field distance is proportional to frequency, several links will have to operate in near-field conditions. This fact will make usual theories based on far-field and plane-wave assumption obsolete but will also open the way to new applications where the transmitting antenna or other parts of the radio link will be able to focus the signal onto the desired space location in order to reduce path loss and improve the radio channel's characteristics.

Management of coverage, co- and adjacent channel interference is a practical open issue in millimeter wave and Terahertz wave cellular deployment. It has been thought that interference management is straightforward at these frequencies due to the high transmission loss through objects and walls in our living spaces, and due to the use of pencil beam antennas at link ends. Outdoor and indoor cells are most likely realized by separate cellular infrastructure and no outdoor-to-indoor service coverage would be effective. Pencil beamforming might make cochannel interference negligible in dense device-to-device millimeter wave links in an enclosed space (Haneda et al., 2015). Moreover, it will reduce the number of relevant paths therefore greatly extending the channel's coherence bandwidth and reducing distortion. However, numerical evidence of those conjectures is still very limited, let alone experimental verification. The use of reconfigurable meta-surfaces (see below) and integration of waveguiding and relaying antenna arrays into building walls (Vähä-Savo et al., 2021) are possible ways to expand coverage beyond the present reach and may change the co/adjacent channel interference conditions completely.

The propagation environment so far has been considered the only part of a radio system that cannot be engineered. In next-generation systems a new breakthrough technology will determine a change of paradigm: the use of reconfigurable meta-surfaces will make it possible to tailor the propagation environment in order to improve the channel's characteristics (Di Renzo et al., 2020). On one hand, large, semi-passive and relatively cheap meta-surfaces to be installed on building walls will allow dynamic modification of their reflection or transmission properties to improve coverage and reduce interference. On the other hand, reconfigurable meta-surface technology could help realize beamforming antennas at mm-wave and sub-THz frequencies that would be very expensive—if not impossible - to build using conventional antenna array technology (Minatti et al., 2016).

## 4. Trends in Propagation Modeling

Mobile radio propagation is an intrinsically complex phenomenon that, due to terminal mobility and unknown environment characteristics, must often be described as a stochastic process. Propagation (or channel) models are simplified representations developed for the sake of design, optimization, simulation or prediction of mobile radio systems. Physical models are based on Physics, that is, on a rigorous albeit approximated theory of wave propagation for a well-defined environment and therefore can be considered deterministic. Conversely, Empirical Models are derived from measurements by sounding the radio channel in different environments and deriving statistical models of wave propagation characteristics: therefore, they are usually defined stochastic, although deterministic and stochastic elements always coexist in any propagation or channel model. In the last two decades, Geometry-based Stochastic Channel Models (GSCM) have been developed where the channel is simulated using multiple spatial scatterer distributions with given statistical distributions and then multipath propagation characteristics are generated according to a ray-based approach.

Cellular industrial standardization requires a reference channel model for comparisons of candidate methods. Fully stochastic, GSCM has been adopted in the standardization of cellular networks in the past few generations, including 5G. While defining the radio channels based on the link geometry allows scalability of the number of base and mobile stations, the present fully stochastic modeling in the 3GPP 5G new radio (NR) has inherent limitations in simulating the radio channels with proper mobile channel dynamics and inter-link correlation, also denoted as *spatial consistency*. Other fully stochastic GSCM, like the models discussed in the COST community bring implicit spatial consistency at the expense of increasing model's complexity. It has become apparent that conventional GSCM is too rigid and/or complex to accommodate all the cellular usage scenarios realized by a combination of large and small cells exploiting the wide spectrum of radio frequencies from Megahertz to Terahertz. One approach to the development of a reference channel model for future generation cellular is the hybrid approach that combines stochastic and site-specific modeling, often called map-based channel modeling, to cater for specific usage scenarios (Medbo et al., 2016). For example, setting constraints to the possible locations of communication devices and wave-interacting clusters on the geometry of the channel model is one such approach so that specific scenarios of, for example, street canyon, highway, and tunnels, lead to different typical channels.

Therefore, going up in frequency, the radio channel's behavior must be considered more deterministic. While the actual location of obstacles can no longer be neglected due to the severe signal blockage that obstacles such as building walls, cars and even humans can cause, at the same time the cell size becomes relatively small compared to lower frequencies, which facilitates an accurate description of the environment and deterministic or hybrid propagation modeling approaches.

Besides traditional applications of propagation and channel models, such as the design of the radio interfaces and of network layout (planning), and system simulation for performance evaluation, a novel application of propagation and channel models is emerging. Since the knowledge of the channel's state is crucial at higher radio frequencies where the use of beamforming antennas are pre-requisite for transmission, but it is time consuming and difficult to optimize beams through channel measurements, deterministic ray-based channel models combined with localization techniques and machine learning algorithms could be used to assist– if not to replace - channel measurements in real time (Fuschini at al., 2019). Joint Communication and Sensing and radar techniques will allow the system to acquire environment representations in real-time—including major moving objects such as vehicles—in dynamic applications for vehicular and industrial environments. In other words, real-time ray tracing and/or machine learning can be used to realize “environment aware” or “location aware” communication systems, which might yield significant performance improvements (Koivisto et al., 2017).

To conclude, it is evident from the foregoing discussion that radio propagation channel modeling addresses evolving questions as NR frequency spectrum emerges for communications and as limitations of existing channel models become more apparent. There is still a long road ahead to address the requirements of future-generation wireless systems.

## Data Availability Statement

No data was created or used in the writing of this manuscript.

## References

Di Renzo, M., Zappone, A., Debbah, M., Alouini, M. S., Yuen, C., de Rosny, J., & Tretyakov, S. (2020). Smart radio environments empowered by reconfigurable intelligent surfaces: How it works, state of research, and the road ahead". *IEEE Journal on Selected Areas in Communications*, *38*(11), 2450–2525. https://doi.org/10.1109/jsac.2020.3007211

Fuschini, F., Zoli, M., Vitucci, E. M., Barbiroli, M., & Degli-Esposti, V. (2019). A study on mm-wave multi-user directional beamforming based on measurements and ray tracing simulations. *IEEE Transactions on Antennas and Propagation*, *67*(4), 2633–2644. https://doi.org/10.1109/tap.2019.2894271

Haneda, K., Jarvelainen, J., Khatun, A., & Takizawa, K. (2015). Spatial coexistence of millimeter-wave distributed indoor channels. In *Proc. IEEE 81st vehicular technology conf* (pp. 1–5).

Koivisto, M., Hakkarainen, A., Costa, M., Kela, P., Leppanen, K., & Valkama, M. (2017). High-efficiency device positioning and location-aware communications in dense 5g networks. *IEEE Communications Magazine*, *55*(8), 188–195. https://doi.org/10.1109/mcom.2017.1600655

Medbo, J., Kyosti, P., Kusume, K., Raschkowski, L., Haneda, K., Jamsa, T., et al. (2016). Radio propagation modeling for 5G mobile and wireless communications". *IEEE Communications Magazine*, *54*(6), 144–151. https://doi.org/10.1109/mcom.2016.7498102

Minatti, G., Caminita, F., Martini, E., Sabbadini, M., & Maci, S. (2016). Synthesis of modulated-metasurface antennas with amplitude, phase, and polarization control. *IEEE Transactions on Antennas and Propagation*, *64*(9), 3907–3919. https://doi.org/10.1109/tap.2016.2589969

Possenti, L., Pascual-García, J., Degli-Esposti, V., Lozano-Guerrero, A., Barbiroli, M., Martinez-Inglés, M. T., et al. (2020). Improved Fabry-Pérot electromagnetic material characterization: Application and results. *Radio Science*, *55*(11), 1–15. https://doi.org/10.1029/2020rs007164

Rappaport, T. S., Xing, Y., Kanhere, O., Ju, S., Madanayake, A., Mandal, S., et al. (2019). Wireless communications and applications above 100 GHz: Opportunities and challenges for 6G and beyond. *IEEE Access*, *7*, 78729–78757. https://doi.org/10.1109/access.2019.2921522

Uusitalo, M. A., Ericson, M., Richerzhagen, B., Soykan, E. U., Rugeland, P., Fettweis, G., et al. (2021). Hexa-X the European 6G flagship project. *Joint European Conference on Networks and Communications & 6G Summit (EuCNC/6G Summit)*, 580–585.

Vähä-Savo, L., Garrido Atienza, A., Cziezerski, C., Heino, M., Haneda, K., Icheln, C., et al. (2021). Passive antenna systems embedded into a load bearing wall for improved radio transparency. In *Proc. 50th European microwave conf* (pp. 424–427).

Zhang, J., Liao, X. I., Glazunov, A. A., Shao, Y. U., Wang, Y., Chu, X., & Zhang, J. (2020). Two-ray reflection resolution algorithm for planar material electromagnetic property measurement at the millimeter-wave bands. *Radio Science*, *55*(3), 1–14. https://doi.org/10.1029/2019rs006944