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Research Article

Review of Channel Measurements and Modeling for Successful 5G System Deployments

Akorede Kola-Jnr[1], Francis Ibikunle[3,*], Ariba Folashade Olamide[1], Bright Unaegbu[2], Olubiyi Joshua[1], Adedire Collins[1]

[1]Electrical and Information Engineering, Land-Mark University, OmuAran, Nigeria
[2]Electrical and Information Engineering, Obafemi Awolowo University, Ile-Ife, Nigeria
[3]Electrical and Electronics Engineering, Hensard University, Toru Orua, Bayelsa, Nigeria

Abstract

The deployment of 5G wireless networks has enabled the investigation of numerous potential applications across a variety of sectors. To enhance the efficiency of 5G systems, it is imperative to have a thorough understanding of millimeter-wave wireless channels, different multi-access techniques, massive MIMO technologies, beamforming, modulation, and coding. Adjusting the channel modeling approach to accommodate specific characteristics of the deployment site, such as geographical obstructions like hills, tunnels, road infrastructure, and mountains, may prove to be crucial. This review paper delves into the challenges associated with channel modeling, underscoring the importance of multipath components and the diverse measurement techniques required for enhancing 5G communication. Additionally, it delves into the complexities of accurately depicting the behavior of wireless channels in various scenarios and assesses the key factors that could significantly affect the functionality of 5G networks across different environments. For instance, it becomes clear that indoor channels provide a greater impediment than outdoor channels because barriers such as walls, furniture, and human activities can impede signal transmission and interrupt communication. Indoor channels display complex characteristics that include fluctuations in the angles at which signals arrive, transmission of numerous signals over different paths, and a wide range of scattering qualities that are specific to indoor environments. Hence, it is crucial to modify the measurement procedures to correspond to the unique characteristics of indoor channels. Indoor wireless communication relies on channels available both within and outside the structure. Evaluation aspects such as, macroscopic fading, microscopic fading, and shadow fading are critical because these elements have a significant impact on the channel capacity.

Keywords

Millimeter Wave, 5G, Massive Multiple Inputs Multiple Outputs, Beamforming, Angle of Arrival, Angle of Departure, High Speed Train, Vehicle-2-Vehicle

1. Introduction

Experts expect the imminent deployment of 5G technology to enhance inter-device communication across diverse network configurations [1]. Experts project that this technological progress will facilitate faster wireless data sharing, reduced latency, and enhanced transmission speeds [2-4]. Researchers are currently investigating various emerging

*Corresponding author: francisayoleke@gmail.com (Francis Ibikunle)

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technologies within the realm of 5G systems, such as millimeter-wave communication, for their potential to offer extensive bandwidth, despite the possibility of signal degradation at higher frequencies [4]. Presently, researchers are exploring the integration of massive multiple-input, multiple-output (MIMO) communication as a solution to this issue [5]. The inclusion of massive MIMO has the potential to improve the system's overall performance and reliability. The continuous evolution of 5G technologies underscores their adaptable utility in rural, suburban, and urban settings. The efficacy of any wireless communication system is contingent upon a precise characterization of the transmission channel.

The development of transmission channels for 5G technology poses several challenges within the framework of diverse technologies. The challenge is that devices must have the capacity to function well over a broad spectrum of frequencies, ranging from 500 MHz to 100 GHz, and support numerous frequency bands [5]. In addition, the system needs to work well in a lot of different places, including rural, urban, suburban, indoor, high-speed trains (HST), and more [6]. Bidirectional three-dimensional modeling is required for accurate three-dimensional propagation and antenna design [7]. As communication systems progress, they need to integrate beam-tracking and mobility capabilities [8]. Transmitters and receivers must have consistent spatial properties, such as signal weakening at different levels, being able to see without any problems, being able to work indoors or outdoors, choosing the right frequencies, and interacting with frequencies that are close by [9, 10]. An accurate description of large-scale MIMO channels requires a comprehensive understanding of spherical wavefronts and array non-stationarity [11, 12]. For the successful capture of Doppler frequencies and non-stationarity, it is crucial to consider high-mobility situations, namely speeds that surpass 500 km/h in high-speed train (HST) environments [13]. The paper is organized as follows, Section II discusses channel measurement for 5G wireless networks in millimeter wave, massive MIMO, high-speed trains, and vehicle-to-vehicle communications. Section III studies the channel modeling technique for millimeter Wave networks, and section IV gives the conclusion on the review paper.

2. Channel Measurements for 5G Wireless Networks

5G technology performs efficiently in a variety of challenging environments, such as tunnels and underground areas. In these settings, investigating channel modeling presents distinct challenges. These environments often rely on channel measurements to assess their unique conditions and dispersion characteristics. Currently, intensive efforts are underway to address these challenges. This section offers a brief summary of the different methods employed for measuring and characterizing communication channels, with a specific emphasis on advancements in 5G technology.

2.1. Millimeter Wave (mm-Wave) Channel Measurements

Currently, scholars are encountering a significant obstacle in attaining high data rates during mobility. To tackle this issue, a transition towards millimeter-wave frequencies is essential, as they have the capability to facilitate quicker data transfer. Utilizing millimeter-wave technology allows for faster data speeds and simplified air interfaces because of the abundant bandwidth in this frequency spectrum [13]. In recent times, there has been a rising interest in employing millimeter-wave frequencies for the advancement of 5G technologies. The opportunity for high-speed data transmission enabled by millimeter-wave carrier frequencies presents a promising prospect for upcoming wireless networks [14]. Elevated operating frequencies not only increase the bandwidth, but also increase the capacity of radio antennas to achieve greater directivity, thereby improving both the accuracy of the system signal and its spectral efficiency [15]. Operating within the millimeter waveband provides the benefit of mitigating minimal diffraction effects, which are typically a constraint in wireless communication systems. The diminished diffraction resulting from shorter wavelengths within this frequency band enhances the reliability of millimeter-wave communication systems [16].

Most tests conducted on mmWave channels have focused on significant path loss, which presents a major hurdle to deploying mmWave communication systems. The 38 GHz and 28 GHz measurements were meant to get information on things like RMS delay spread, angle of departure (AOD), path loss, angle of arrival (AOA), and the way potential mmWave channels reflect light [16, 17]. The authors compared urban and light urban areas and discovered that signal propagation was very different. They found that multipath delay spread was higher in large urban areas compared to lighter urban zones. The research conducted in [18] examined an improved version of the well-established close-in (CI) and floating intercept (FI) path loss models. The experimental configuration utilized an enclosed corridor, focusing on both vertical-horizontal (VH) and vertical-vertical (V-V) antenna polarization. A significant outcome of this research indicates that the improved models demonstrate superior performance across different antenna polarizations compared to their traditional versions, thereby validating their elevated accuracy levels. These findings imply that the refined or modified CI and FI models yield more precise path loss predictions in enclosed environments, especially within the framework of 5G networks. In [19], researchers investigated a variety of models, such as single-frequency, directional, omnidirectional, and multi-frequency to analyze and compare the results.

2.2. Massive MIMO Channel Measurement

MIMO approaches have attracted significant interest in wireless communication because they can provide several benefits, including fast data transfer and dependable connections, without requiring improvements in the signal strength. Fourth-generation LTE mobile networks are currently deploying MIMO, a technology that effectively integrates with OFDM.

Using a 50 MHz bandwidth, researchers evaluated frequencies at 2.6 GHz. The base station (BS) conducted the evaluations using a 128-element linear virtual array [20]. The analysis revealed significant disparities in the angular power spectrum (APS), K-factor, and channel gain within the linear array. In massive MIMO systems, the research shows that the assumptions of plane waves or far-fields have not been tested. In addition, a MIMO arrangement using a linear array incorporates several important antennas. The experiment in [21] used a frequency spectrum spanning 15 gigahertz, with a bandwidth of 5 gigahertz. The virtual planar antenna array consisted of 1600 elements, which were separated into various subarrays to study the dynamic properties of the massive MIMO channels for each antenna element. This study investigates many critical aspects, including delay spread, azimuth angular spread of arrival (AASA), elevation angular spread of arrival (EASA), and the K-factor. The array plane clearly illustrates the significant variations in these characteristics among individual sites. In [22-26], the papers evaluated the effectiveness of channels utilizing Multiple-Input Multiple-Output (MIMO) technology. The paper examined frequencies ranging from 16, 11, 38, and 28 GHz for indoor channel environments.

2.3. High-Speed Train (HST) Channel Measurement

The propagation channel has a significant impact on the study and implementation of a remote control system for railway routes, especially in the context of high-speed trains. People view high-speed trains as a cost-efficient and environmentally friendly option for long-distance mass transit. The GSM-R system was designed as a vital component for integrating traffic management and security systems on railroads using wireless communication. Significant disparities arise in the transmission routes between the cellular system and high-speed trains, mainly because of variations in antenna placement and surrounding transmission conditions [27]. Directional transmitting antennas are necessary for enabling communication in high-speed train systems.

Precisely delineating signal transmission routes is a significant challenge in the realm of scientific investigation. Prior research has built specialized radio propagation models to tackle this difficulty, specifically in the context of high-speed train networks. The main goal of these models, as explained in [28, 29], is to accurately guess where trains are by looking at things like the K-factor, the Doppler frequency, and the time delay spread, all of which change when the signal strength does. The studies are performed using data acquired at a frequency of 2.35 GHz. Also, researchers have created position-based channel models that accurately show channel properties. This makes it easier to test and verify wireless communication systems in similar situations. The study described in [30] conducted a measuring campaign to investigate the communication channels used by high-speed train networks that employ Long-Term Evolution Advanced (LTE-A) technology. Cell-specific reference signals (CRSs) facilitated the process of obtaining channel impulse responses (CIRs). The findings suggest that most channels primarily use non-line-of-sight (NLOS) passageways instead of line-of-sight (LOS) routes. The analysis of delay patterns yielded valuable insights on geometric properties, such as train velocity and the most efficient route between the transmitter and receiver. In addition, a thorough analysis was performed to examine and evaluate the properties of signal attenuation in different orientations, specifically focusing on the Universal Mobile Telecommunications System (UMTS). In [31], a ray-tracing technique was used to construct models of environmental structures at various elevations, both above and below the surface. Certain geographic regions limit these models, and they do not account for random occurrences [32].

2.4. Vehicle-to-Vehicle (V2V) Channel Measurement

Vehicle-to-vehicle communication is essential for improving road safety and effectively managing traffic congestion [32]. The propagation channel's attributes have a significant impact on wireless systems' efficiency. The study described in [33] aimed to assess the V2V channel in both urban and highway settings, with a particular emphasis on the 5 GHz frequency range. Throughout the investigation, scientists performed tests with a 50 MHz test signal and omnidirectional antennas positioned both within and outside the automobiles. The channels were modeled using frequency correlation functions and the root mean square (RMS) delay spread. In highly crowded metropolitan regions, the estimated root mean square (RMS) delay spread is approximately one microsecond, leading to coherence bandwidths ranging from 1 to 2 megahertz (MHz) [34]. Currently, there is ongoing research on the practicality of using the 2.4 GHz radio band. Changes in Doppler spread and signal weakening have been studied before in close-range indoor machine-to-machine (M2M) communication situations, as shown in [34, 35]. Researchers in [36, 37] recorded the results of analytical tests conducted under comparable channel conditions.

The study in [38] conducted calculations on the unique characteristics of narrowband communications in the 5 GHz frequency region. In [39], the authors investigated the phenomenon of fading in vehicle channels by evaluating the radio channel data obtained from various traffic scenarios. The authors analyzed samples of the time-varying frequency response to identify large-scale fading (LSF), and they created statistical models for the second-order Doppler spread and time-frequency-dependent RMS delay spread. The distributions of Doppler spread and RMS delay spread under different traffic conditions.

3. Channel Modeling in 5G Wireless Networks

Having a thorough grasp of the millimeter-wave spectrum is crucial for optimal communication networks. The visualization in Figure 1 illustrates the attributes of the millimeter-wave spectrum. Accurate channel modeling plays a critical role in the efficient functioning of millimeter-wave communication systems. Parameters such as Root Mean Square (RMS), Angle of Arrival (AoA), Angle of Departure (AoD), signal attenuation, and reflections from surfaces are significant factors influencing the propagation of millimeter waves over different types of surfaces.

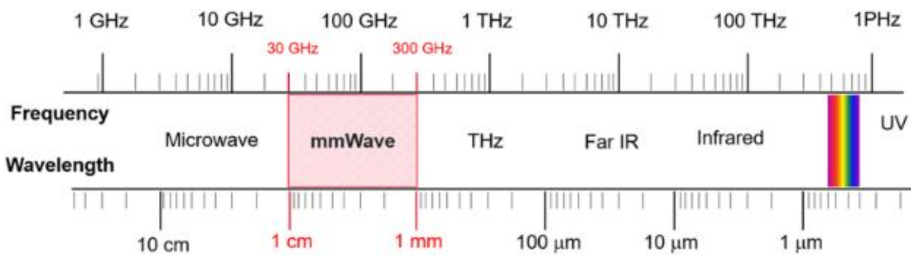

Figure 1. *Millimeter Wave Spectrum [17].*

Recently, academic research in the field of millimeter-wave (mm-wave) technology has focused on finding ways to test indoor channels without using blind methods, by using pilot/data support systems. Each of these scholarly inquiries has focused on specific facets of this subject matter. For example, [40] highlighted a particular study that involved setting up a measurement setup in an indoor office setting using a 60 GHz frequency band and a Vector Network Analyzer (VNA). The principal objective of this investigation was to replicate a wide signal by transmitting it through a specific channel for a defined duration, followed by utilizing the VNA output to scrutinize the amplitude and phase attributes.

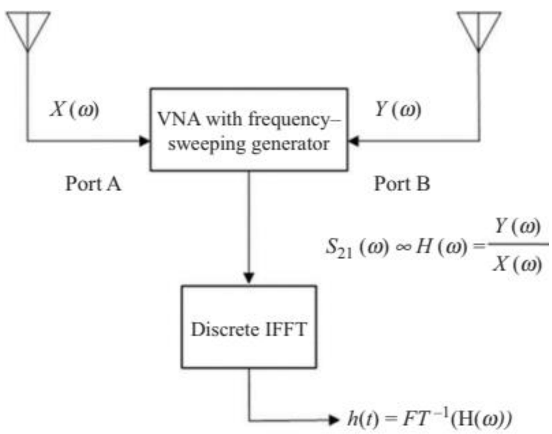

Figure 2. *Vector Network Analyzer or Channel Sounder [16].*

Figure 2 shows how the Vector Network Analyzer (VNA) scans a single carrier across different frequencies, looking at how the signal's amplitude and phase change at each frequency point. The VNA is capable of discerning a channel's intricate frequency traits and impulse response by applying an inverse Fourier transform to the collected data [16]. Engineers frequently use these instruments to analyze channel responses in close indoor environments or restricted spaces, but their slow scanning speeds lead to stagnant or slow channel changes over extended periods [25]. Furthermore, their cumbersome design poses challenges in terms of mobility, especially when endeavoring to synchronize the transmitter and receiver over distances exceeding a few hundred meters.

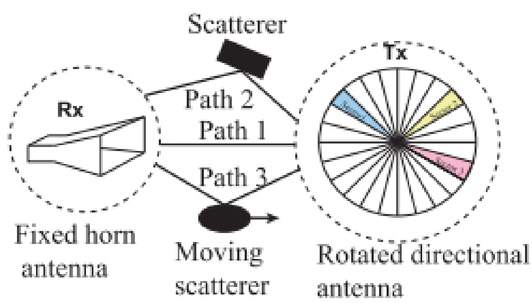

Figure 3. *Rotated Directional Antenna Measurement Method [40].*

In general, there are two primary methodologies for evaluating the angular properties of indoor millimeter wave (mmWave) channels. One method involves the utilization of a Rotating Directional Antenna (RDA), while the other utilizes a standardized uniform virtual array (UVA) [40]. These methodologies are predominantly effective in quasi-static scenarios due to the time-intensive nature of scanning the antenna in three-dimensional space. There is an RDA method for getting data that uses a much focused antenna along with either a vector network analyzer (VNA) or a channel sounder [40]. Figure 3 illustrates how a mechanism affixes the antenna, enabling precise scanning at designated angles in both horizontal and vertical planes while gathering pertinent data [16].

The precise positioning of the antenna is crucial for determining the Angle of Arrival (AoA) or Angle of Departure (AoD) of the Multipath Components (MPC), as dictated by its narrow signal beam. The accurate placement of the antenna plays a critical role in correctly measuring the angles at which signals enter or leave a multipath setting.

The UVA technique involves replacing the RDA with a 3-D omni-directional antenna that moves in small steps within a space smaller than half a wavelength [40], as shown in figure 4.

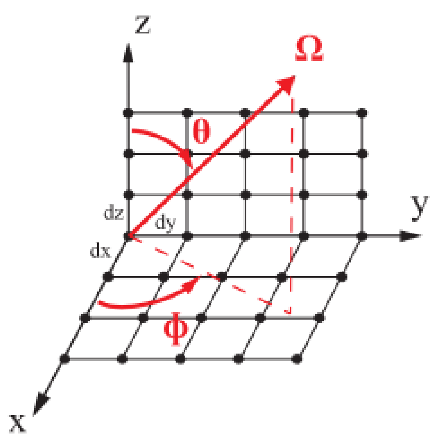

Figure 4. Uniform Virtual Array configuration and direction characterization [40].

Communication methods at UVA frequently incorporate mathematical techniques, including subspace methods and rotational symmetry. Beyond simple methods, UVA also uses more complex ones, like space-alternating generalized expectation maximization (SAGE) and Richter's ML parameter estimation model, to guess what multipath components (MPCs) are like. The primary objective of the IEEE 802.15.3c and 802.11ad standards was to facilitate wireless communication within the 60-GHz frequency band. The IEEE 802.15.3c standard stresses channel design, with a particular emphasis on the analysis of the Angle of Arrival (AoA) in the horizontal plane. On the other hand, the IEEE 802.11ad standard caters to a specific channel type, providing accurate data on angle parameters in two distinct orientations. Both standards employ a finely tuned Saleh (S-V) model to meet the distinct structural demands of the channel. The IEEE 802.11ad channel model enhances the Saleh-Valenzuela model by integrating cluster characteristics in both temporal and spatial dimensions, particularly in indoor settings. This study utilizes an improved S-V model to evaluate the characteristics of a 60-GHz indoor channel, with the objective of examining the impact of environmental elements and their combined properties in terms of time and space. In addition, the channel model incorporates sophisticated 3D S-V-based millimeter-wave channel models specifically designed for indoor settings. The papers [41-45] examined distinct features inside clusters and investigate shared qualities among different clusters.

Indoor channels provide a greater impediment than outdoor channels because barriers such as walls, furniture, and human activities can impede signal transmission and interrupt communication. Indoor channels display complex characteristics, including fluctuations in the angles at which signals arrive, the transmission of numerous signals over different paths, and a wide range of scattering qualities that are specific to indoor environments. Hence, it is crucial to modify measuring procedures to correspond with the unique characteristics of indoor channels. Indoor wireless communication relies on channels that are available both within and outside of structures. Evaluating aspects such as macroscopic fading, microscopic fading, and shadow fading is critical because these elements have a significant impact on channel capacity.

Research at the 60 GHz frequency, with a special focus on generating channel models suited for WLAN networks led to the development of the IEEE 802.11ad standard. The main goal of this research is to improve the efficiency and performance of wireless local area networks by examining signal transmission characteristics in the 60 GHz frequency band. The model examines the channel's response to impulses, considering the polarization of antennas and their capacity to focus beams in certain directions. This model, as described in the equations below, incorporates the polarization features described in [43].

$$h(t,\varphi_{tx},\theta_{tx},\varphi_{rx},\theta_{rx}) = \sum_i H^{(i)} C^{(i)}\left(t - T^{(i)}, \varphi_{tx} - \varphi_{tx}^{(i)}, \theta_{tx} - \Xi_{tx}^{(i)}, \varphi_{rx} - \varphi_{rx}^{(i)}, \theta_{rx} - \Xi_{rx}^{(i)}\right) \quad (1)$$

Where,

H () = Channel impulse response consists of inputs from various channel segments. This happens when we merge the feedback from different channel groups.

$t, \varphi_{tx}, \theta_{tx}, \varphi_{rx}, \theta_{rx}$ = Measurements of the time, azimuth, and elevation were taken at both the sender and receiver positions;

$T^{(i)}, \varphi_{tx}^{(i)}, \Xi_{tx}^{(i)}, \varphi_{rx}^{(i)}, \Xi_{rx}^{(i)}$ = Time angular coordinates for each cluster denote the unique spatial and temporal locations of the cluster within a particular timeframe;

$H^{(i)}$ = 2 x 2 Matrix gain of a specific cluster refers to the measurement that characterizes the polarization aspects of a cluster;

$C^{(i)}$ = The mathematical equation that describes the channel impulse response for a particular group, known as the ith cluster, can be expressed in [43] as:

$$C^{(i)}(t,\varphi_{tx},\theta_{tx},\varphi_{rx},\theta_{rx}) = \sum_k \alpha^{(i,k)}\,\delta(t-\tau^{(i,k)})\,\delta(\varphi_{tx}-\varphi_{tx}^{(i,k)})\,\delta(\theta_{tx}-\theta_{tx}^{(i,k)})\,\delta(\varphi_{rx}-\varphi_{rx}^{(i,k)})\,\delta(\theta_{rx}-\theta_{rx}^{i,k}) \quad (2)$$

Here,

δ (0) = Dirac delta function

$\alpha^{(i,k)}$ = amplitude of the k-th ray of the i-th cluster

$\tau^{(i,k)}$, $\varphi_{tx}^{(i,k)}$, $\theta_{tx}^{(i,k)}$, $\varphi_{rx}^{(i,k)}$, $\theta_{rx}^{i,k}$ = Using its angular coordinates in relation to time and direction, one can determine the exact position of a ray in a cluster, providing accurate positional information within a specific category.

At 60 GHz for IEEE 802.11ad, the research results look at different parts of all rays, such as their strength, phase, and polarization, as well as their spatial and temporal properties [43]. The azimuth and elevation angles at both the sender and receiver positions influenced the beam's properties. The IEEE 802.11ad model in [43] allows for the analysis of three propagation scenarios: conference room, cubicle, and living room setup.

4. Conclusions

This review paper delves into the intricate and complex aspects of channel modeling, channel measurements, and the numerous multipath components (MPC) that play a crucial role in shaping the complexity of building 5G networks. Understanding the characteristics of wireless channels is critical for channel modeling, particularly in scenarios such as underground tunnels, mountainous regions, and construction sites along roadsides. Precise channel measurements play a key role in improving the efficiency and reliability of channel models. Employing specialized measurement techniques tailored to address the unique characteristics of the subject under study is crucial to achieving accurate outcomes. To sum it up, the precise measurement and characterization of 5G channels hold immense importance, as they will have a profound impact on the future progression and advancement of wireless communication technologies in the coming years.

Abbreviations

MIMO	Multiple Inputs Multiple Outputs
mMIMO	Massive Multiple Inputs Multiple Outputs
5G	Fifth Generation communication
MPC	Multi-path Component
AoA	Angle of Arrival
APS	Angular Power Spectrum
BS	Base Station
RMS	Root Mean Square
AASA	Azimuth Angular Spread of Arrival
EASA	Elevation Angular Spread of Arrival
AoD	Angle of Deviation
mmWave	Millimeter-Wave
HST	High Speed Train
V2V	Vehicle2vehicle
UMTS	Universal Mobile Telecommunications System
S-V	Saleh-Valenzuela.
M2M	Machine2Machine
LSF	Large Scale Fading
OFDM	Orthogonal Frequency Division Multiplexing
LTE-A	Long-Term Evolution Advanced (LTE-A)
C-S-R-S	Cell-Specific Reference Signals
CIR	Channel Impulse Response
NLOS	Non-line of Sight
LOS	Linear of Sight
VNA	Vector Network Analyzer
SAGE	Space-Alternating Generalized Expectation Maximization
UVA	Uniform Virtual Array
RDA	Rotated Directional Antenna

Author Contributions

Akorede Kola-Jnr: Conceptualization, Data curation, Formal Analysis, Investigation, Methodology, Software, Writing – original draft

Francis Ibikunle: Conceptualization, Formal Analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Supervision, Validation, Visualization, Writing – review & editing

Ariba Folashade Olamide: Conceptualization, Investigation, Methodology, Supervision, Validation, Writing – review & editing

Bright Unaegbu: Conceptualization, Formal Analysis, Funding acquisition, Resources, Validation, Visualization

Olubiyi Joshua: Conceptualization, Data curation, Resources, Visualization

Adedire Collins: Conceptualization, Investigation, Methodology, Resources, Validation

Conflicts of Interest

The authors declare no conflicts of interest.

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