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Evaluation of Multipath Mechanism Modeling of Reflection, Scattering Diffraction and Fading

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Abstract

This paper presents a comprehensive review, modeling, simulation, and evaluation of multipath propagation mechanisms—reflection, scattering, diffraction, and fading—relevant to 5G communication, with a focus on typical Malaysian deployment conditions. Malaysia's dense urban areas, mid-rise concrete structures, and mixed building materials (reinforced concrete, glass, and metal cladding) create strong reflection and scattering environments, making accurate multipath modeling essential for 3.5 GHz networks. The study integrates established theoretical models with MATLAB simulations to quantify the impact of each mechanism. Reflection and scattering losses are evaluated as functions of incidence and scattering angles, while diffraction loss is analyzed using the knife-edge model, where a Fresnel parameter of 3.74 yields a 24.3 dB loss. A three-ray Rayleigh fading model embedded in an OFDM system is used to assess small-scale fading, revealing severe BER degradation and constellation distortion. The findings demonstrate that multipath significantly affects link reliability under Malaysian propagation conditions and highlight the importance of precise modeling for network planning and optimization.

Keywords

Multipath Mechanism, Reflection, Scattering, Diffraction, Fading

1. Introduction

Multipath propagation occurs when transmitted RF signals reach the receiver through multiple paths created by reflection, diffraction, and scattering from obstacles such as buildings, terrain, vehicles, and atmospheric conditions [1]. Instead of a single line-of-sight path, the receiver gets multiple copies of the signal with different amplitudes, phases, delays, and angles of arrival, causing constructive and destructive interference [2].

Reflection occurs when waves strike smooth large surfaces, creating delayed replicas of the signal. Scattering happens when waves hit rough surfaces or small objects, spreading energy in many directions and introducing random variations. Diffraction allows signals to bend around edges or corners, enabling communication without direct LOS but adding delayed components. Combined, these effects cause fading, delay spread, and reduced signal quality, especially in urban and terrestrial environments [3].

Malaysia's propagation environment exhibits several characteristics that make multipath modeling particularly important. Major cities such as Kuala Lumpur, Johor Bahru, and Penang contain dense clusters of mid-rise concrete buildings, reflective glass facades, narrow streets, and metallic signboards that intensify reflection and scattering [4]. Tropical weather introduces additional variability through humidity, rainfall, and foliage density, further affecting scattering and fading. These conditions justify the need to evaluate classical multipath mechanisms at the 3.5 GHz band, which is the primary frequency allocated for 5G deployment by MCMC.

This work reviews, models, simulates, and evaluates multipath mechanisms—reflection, scattering, diffraction, and fading—which define how mobile devices receive signals from base stations. With 5G adoption in Malaysia still at an early stage and limited simulation-based publications, understanding these multipath mechanisms is essential for improving 5G performance and supporting future deployments.

2. Multipath Mechanism

5G networks use the 30 - 300 GHz mmWave spectrum for high-bandwidth services, but high frequencies cause strong free-space path loss, limiting coverage and reliability [5]. Multipath propagation—via reflection, diffraction, and scattering—degrades BER and SNR [6]. Measurements show more complex multipath at higher frequencies, with weaker diffraction and stronger specular reflections. These are modeled using ray tracing, hybrid deterministic-stochastic methods, and machine learning. Ray tracing for mmWave MIMO aligns well with measurements, while deep-learning methods like ALISTA-Net improve channel estimation, mitigate beam-squint, and enhance MIMO-OFDM and mixed-ADC system performance.

Due to dynamic multipath, fast and slow fading still impact link stability. Mitigation techniques—MIMO diversity, adaptive equalization, OFDM, and intelligent reflecting surfaces (IRS)—improve robustness, supported by hybrid deep-learning models. Overall, precise multipath modeling remains crucial for optimizing mmWave 5G performance and maintaining stable high-rate communication. Researchers particularly highlight reflection, diffraction, and scattering as the key factors influencing 5G propagation [7] [8].

2.1. Reflection

Reflection drives multipath in wireless systems. When waves strike large surfaces—like buildings or the ground—they create additional paths that combine with the direct signal, causing interference. Reflection dominates indoor and urban environments, with material, geometry, and frequency affecting coefficients. At millimeter-wave and terahertz bands, reflections are directional, and surface roughness affects strength. Ray tracing, image theory, and Fresnel-based models analyze reflections, improving link reliability, antenna placement, and enabling MIMO, beamforming, and IRS.

Balachandran [9] proposes a single-target tracking framework fusing direct and multipath radar measurements, using FIM and EKF to improve tracking accuracy and reduce RMSE despite uncertain surface geometry. Swathi [10] studies how specular and diffuse reflection coefficients affect GPS multipath errors, showing polarization and phase shifts depend on incidence angle and surface type. Parrish [11] attributes SPR in ATIR setups to Fano resonance, demonstrating that interference between discrete and continuous pathways explains asymmetric reflectance more accurately than the Kretschmann-Raether model.

2.2. Scattering

Scattering occurs when waves strike irregular surfaces or particles, spreading energy and creating weak, randomly phased components that distort signals. Prominent in urban, vegetated, and indoor environments, it increases at millimeter-wave and terahertz frequencies. Channel models, ray tracing, Monte Carlo simulations, and measurements capture its effects. Diversity reception, equalization, and beamforming help mitigate scattering's impact on fading, delay spread, and system performance.

Tang [12] used broadband FEKO simulations and RCS tests (8 - 12 GHz, mono-/bistatic) and proposed a low-scattering metal enclosure (conical/pyramidal) that redirects target-ground reflections, reducing clutter by up to 20 dB (horizontal) and 40 dB (vertical). It is more robust than polyurethane absorbers in rain and humidity. Suenobu [13] introduced a multipath-exploitation inverse-scattering method for NLOS imaging of PEC targets using linearized inverse scattering with physical-optics approximation and numerical Green's functions in a T-junction. Verified by 3-D EM simulations and anechoic-chamber tests, it accurately reconstructs hidden metallic plates. Li [14] enhanced ray tracing with a Monte Carlo diffuse-scattering module that launches one diffuse ray per interaction with Russian-roulette termination, providing unbiased estimates of infinite paths. Tested on synthetic rooms and DICHASUS hallways, it predicts dense multipath accurately with stable runtime and RMS delay-spread fidelity.

2.3. Diffraction

Diffraction bends radio waves around obstacles or through openings, allowing signals to reach beyond the line of sight. It is more pronounced at longer wavelengths, enabling waves to bend around buildings or terrain more easily than higher-frequency signals, though it also spreads and weakens them. S. Rimac-Drlje [15] modeled NLOS propagation in region P6 using the knife-edge diffraction model, treating the corner between P1 and P6 as the obstacle. Measurements confirmed good performance except deep within the NLOS zone. Zhang and Lim [16] applied the knife-edge model to propagation along antique shophouses in Penang, comparing flat, knife-edge, and square-pillar approximations, though limited by sparse measurements. Maohui [17] analyzed single and multiple knife-edge scenarios using the Two-Way Finite Element-Based Parabolic Equation (2W-FEMPE) combined with 2WFSS, achieving closer agreement with real-world behavior than traditional PE methods.

2.4. Fading

Fading refers to fluctuations in signal strength caused by constructive and destructive interference. Multipath propagation is a key source, as signals arriving via different paths may strengthen or weaken the received signal. Major types include flat fading, frequency-selective fading, fast fading, and slow fading [18]. The ITU-R P.530 model provides an improved empirical representation of flat fading in fixed wireless channels [19], using deep and shallow fade depths as performance metrics and its probability density function in Monte Carlo simulations. Alves and Alencar [20] showed that a short pulse transmitted through a multipath channel produces a train of pulses with varying amplitude, delay, and waveform. Frequency-selective fading is more complex to model than flat fading due to its dependence on bandwidth and delay spread.

3. Multipath Mechanism Modeling

The proposed models were evaluated based on 5G implementation in Malaysia as per guidelines and licensing by MCMC. Typical key parameters for 5G implementation are frequency at 3.5 GHz, height of the mobile receiver at 1.5 meters and transmitter height of 15 meters. Maximum distance between base station and mobile receiver was set at 3 km for a maximum quality service.

The knife-edge model was selected for diffraction analysis because it is the most common first-order approximation for urban obstacles like building edges and provides reliable loss estimates with low computational cost. For fading analysis, a three-ray Rayleigh model was used as it represents dominant effects in suburban and urban microcells, where signals arrive through direct, ground-reflected, and building-reflected paths. Together, these models balance realism and computational efficiency for 3.5 GHz 5G planning.

3.1. Reflection

Reflection is a dominant mechanism in multipath propagation, occurring when waves strike surfaces larger than the wavelength—such as buildings, walls, or the ground—and are redirected along multiple paths. This creates additional components with varying phases and delays, causing constructive or destructive interference. Reflected-wave behavior follows Fresnel's equations, with the reflection coefficient determined by incidence angle, polarization, and the permittivity of the materials.

3.2. Scattering Loss

Scattering occurs when waves interact with irregular surfaces, objects, or particles, spreading energy in many directions and creating weak, randomly phased components. These paths affect small-scale fading, delay spread, and angular dispersion, especially in urban, indoor, and vegetated environments. Combined with the direct path, they cause constructive and destructive interference, degrading signal quality. Scattering intensity depends on the size of irregularities relative to wavelength, with Rayleigh scattering dominating when the particle size is much smaller than the wavelength ($a \ll \lambda$).

3.3. Diffraction Loss Model

The knife-edge diffraction model uses Fresnel diffraction to estimate signal loss from an obstruction. The loss is expressed via the Fresnel diffraction parameter (v), which depends on the obstacle height (h), distances from the transmitter (d_1) and receiver (d_2), and the signal wavelength. Based on the Huygens-Fresnel principle, the edge is treated as a secondary source, and attenuation in the shadow region is computed using a Fresnel integral. In this setup, the obstacle height is 20 m (with the base station antenna at 15 m), the distance to the transmitter is 2 km, and to the receiver is 1 km.

3.4. Fading Loss Model

Fading loss is modeled using a 5G-like OFDM system at 3.5 GHz with a 100 Mbps data rate. Rayleigh fading is employed due to its common use. The OFDM system has 256 subcarriers, 80% for data and the rest as guard bands, with a 32-sample cyclic prefix to mitigate ISI. The channel follows a three-ray Rayleigh model, with each path having distinct delay and power to represent realistic 5G multipath. AWGN is added using a specified Eb/N_0 to simulate receiver noise. At the receiver, the cyclic prefix is removed, FFT converts the signal to the frequency domain, and data subcarriers are demodulated using 16-QAM. The fading loss was modeled using a three-ray Rayleigh channel, where each path is assigned a distinct delay and relative average power to reflect realistic 5G multipath conditions.

4. Results and Discussion

This section presents results assessing multipath loss under varying parameters. Simulations were conducted in MATLAB, with data visualized graphically and tabulated where necessary. The proposed model was evaluated for 5G implementation in Malaysia, with key parameters including a 3.5 GHz frequency, mobile receiver height of 1.5 m, and transmitter height of 15 m. Additional model-specific parameters are also provided.

4.1. Reflection Model Analysis

Figure 1 shows the Reflection Loss (in dB) across various reflection angles (*θ*), obtained from MATLAB simulations. At a 60˚ incidence, L is approximately −6.02 dB at 3.5 GHz, within the 5G band. The loss reflects partial power attenuation from surface interactions, increasing at higher incidence angles due to air-surface impedance mismatch, which enhances signal attenuation and phase changes.

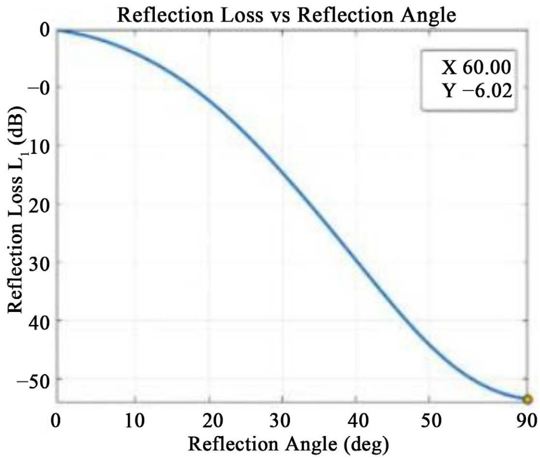


Figure 1. Reflection graph.

4.2. Scatterings Loss Analysis

Figure 2 shows Scattering Loss (Ls) in dB versus scattering angle (*θ*) from MATLAB simulations. At 3.14 rad (180˚), L is −9.92 dB at 3.5 GHz (5G).

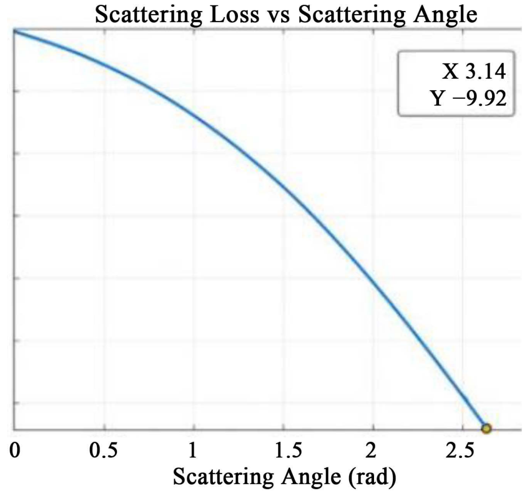
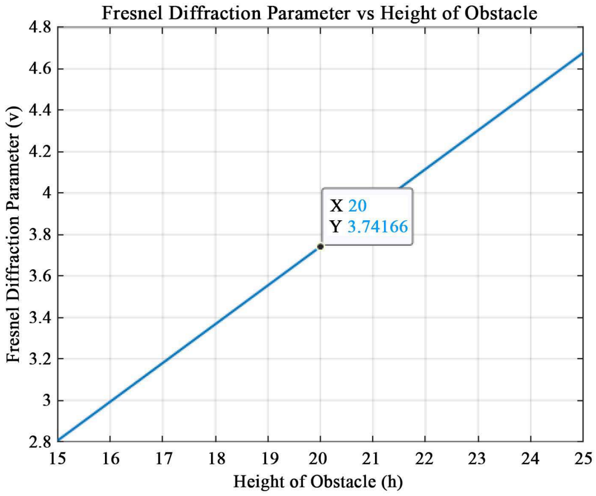


Figure 2. Scattering graph.

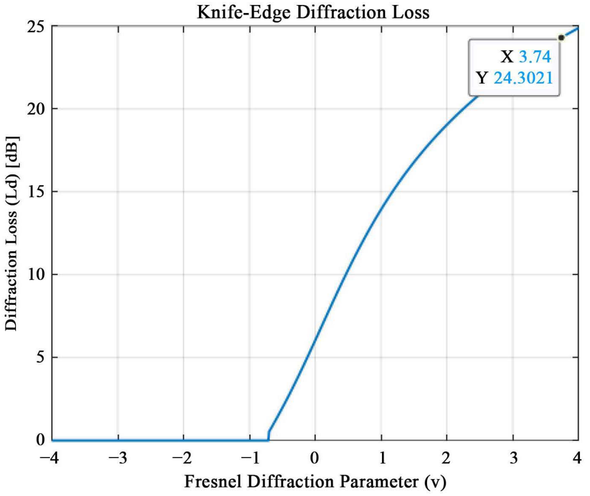
4.3. Knife-Edge Diffraction Analysis

Figure 3(a) shows the relationship between heights of the obstacle to the Fresnel

Diffraction Parameter. For obstacle with 20 meters of height, the value of Fresnel Diffraction Parameter is 3.74166. From the simulation result, the sampling rate is 31.37 MHz and the Bit Error Rate (BER) = 4.98672e−01 (203,458 errors out of 408,000 bits). Figure 3(b) shows the Diffraction Loss in dB over different Fresnel Diffraction Parameter using model simulated by MATLAB software. Value of Fresnel Diffraction Parameter (v) is 3.74 and Knife-Edge Diffraction Loss (Ld) is 24.30 dB at the frequency 3.5 GHz for 5G implementation. A diffraction loss of 24.3 dB is significant and would noticeably degrade received power in an urban 5G network. For network planners, such a loss indicates that a base station signal cannot reliably bend around obstacles of comparable height unless additional support such as repeaters, denser small-cell placement, or beam-steering solutions is introduced. In Malaysian cities with closely spaced buildings, this level of attenuation highlights the need for careful site planning to maintain coverage continuity.



(a)

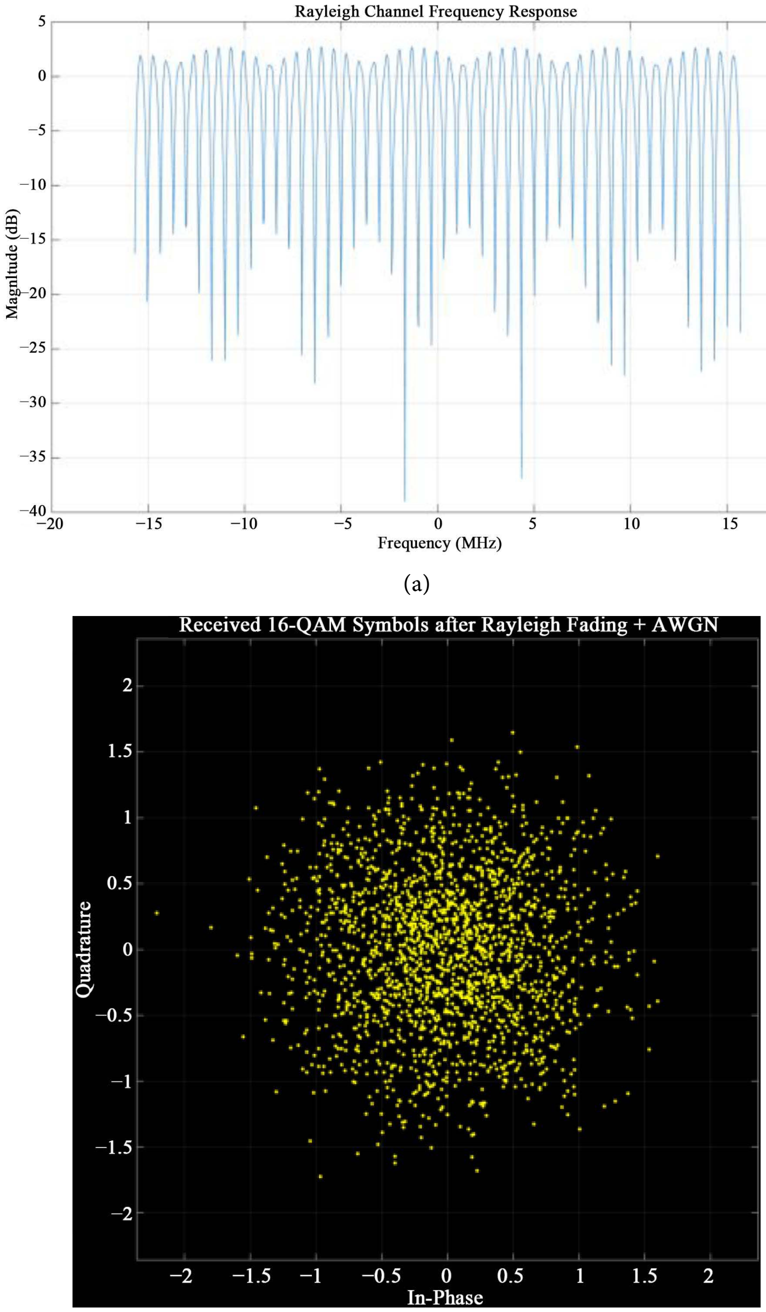


(b)

Figure 3. (a) Fresnel diffraction parameter over obstacle height, (b) Knife-Edge diffraction loss.

4.4. Fading Loss Analysis

From the OFDM fading simulation using the three-ray Rayleigh model, the resulting Bit Error Rate (BER) is 4.98672e–01 (203,458 errors out of 408,000 bits) at the selected SNR level. This confirms the severe degradation caused by multipath fading. **Figure 4(a)** shows that the Rayleigh Channel Frequency response with deep notches indicates multipath fading pattern. **Figure 4(b)** shows the output 16-QAM constellation which was distorted by fading.



(a)

(b)

Figure 4. (a) Rayleigh channel frequency response, (b) Received 16-QAM symbols.

5. Conclusion

The design and simulation of multipath propagation mechanisms using MATLAB demonstrate its effectiveness as a valuable tool for modeling and analyzing wireless propagation and loss characteristics. MATLAB remains a valuable tool for developing propagation and loss models for engineers. Researchers continue to improve traditional models as mobile spectrum demands grow. Simulation results confirm that multipath effects significantly impact received power in 5G environments. Reflection and diffraction dominate large-scale fading, while Rayleigh fading governs small-scale variations. MATLAB modeling effectively supports both propagation prediction and educational understanding. This study demonstrates how multipath mechanisms—reflection, scattering, diffraction, and fading—affect signal strength and link reliability in 5G systems operating at 3.5 GHz under Malaysian propagation conditions. The modeling and simulation results provide insight into large-scale effects (reflection and diffraction) as well as small-scale fading behavior within an OFDM system. The findings reinforce the importance of accurate multipath characterization for effective 5G network design, cell planning, and optimization.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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