

Modeling and Theoretical Study of Microwave and Millimetre-Wave Propagation under Dusty Conditions in the Coalfield Region of Surguja District, Chhattisgarh

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Abstract: Environmental factors such as dust and sand storms significantly influence the performance of microwave and millimetre-wave communication systems. This paper presents a comprehensive **theoretical analysis** of electromagnetic wave propagation under dust- and sand-laden conditions in the coalfield region of **Surguja district, Chhattisgarh**. Various analytical and modeling techniques have been reviewed and applied, including **Mie Scattering Theory, Effective Medium Approximations** (Maxwell–Garnett and Bruggeman models), and the **Radiative Transfer Equation (RTE)** for dense particle media. In addition, **empirical and semi-empirical attenuation models** have been discussed to provide practical estimation approaches based on visibility and dust density data. To complement the theoretical framework, reference is made to **experimental validation methods** such as the Vector Network Analyzer (VNA), Point-to-Point Analyzer (PPA), Infinite Sample Method, and Two-Point Dielectric Method, which are commonly employed in similar studies.

Theoretical simulations indicate that attenuation and scattering effects increase with both **frequency** and **particle concentration**, making millimetre-wave bands (above 30 GHz) particularly vulnerable in dusty or coal-dust-dominated environments. The study highlights the distinct electromagnetic behavior of **coal dust**, attributed to its higher dielectric loss compared to sand, and underscores the need for **empirical validation** to refine propagation models for mining regions.

Keywords: Microwave propagation, Millimeter-wave, Dust and sand storms, Coal dust attenuation, Mie scattering theory, Effective medium theory, Radiative transfer, Surguja coalfield, Theoretical modeling, Electromagnetic wave propagation

I. INTRODUCTION

Microwave and millimetre-wave (mmWave) frequency bands are increasingly used in modern wireless communication, radar sensing, and satellite systems. In coalfield regions such as Surguja district, Chhattisgarh, atmospheric conditions are often dominated by suspended coal dust and periodic sand storms, which alter the electromagnetic propagation characteristics.

Coal mining activities generate particulate matter (PM10 and PM2.5), while natural wind-driven sand storms contribute to additional scattering and absorption. Understanding how these factors impact electromagnetic wave propagation is essential for reliable communication system deployment in mining operations, environmental monitoring, and safety-critical applications.

This study presents a theoretical and simulation-based analysis of microwave/mm Wave propagation in dust-laden atmospheres without relying on new soil or coal dust sampling. Instead, dielectric and physical properties of dust are taken from existing literature, and parametric models are developed to predict attenuation, scattering, and link degradation.

II. LITERATUREREVIEW

Several researchers around the world have investigated microwave and millimeter-wave propagation under dust and sandstorm conditions. **Bohren and Huffman (1983)** presented the fundamental theory on the absorption and scattering

of electromagnetic waves by small particles through Mie theory, which continues to serve as the cornerstone for studying dust-related attenuation. **Goldsmith (1998)** explored quasi-optical systems and emphasized that atmospheric particles can considerably affect the transmission of millimeter-wave signals.

Al-Nassar and Alfadhl (2010) studied the attenuation of millimeter-wave signals in desert regions and found that it is highly influenced by dust concentration and particle size distribution. Their findings indicated that attenuation values typically range between 0.1 and 10 dB/km during common dust storm events. Likewise, various studies conducted across the Middle East and North Africa have demonstrated that higher frequencies (above 30 GHz) are particularly vulnerable to scattering and absorption caused by dust particles.

In the Indian scenario, coal mining areas—particularly in states like Chhattisgarh—produce fine particulate matter (PM₁₀ and PM_{2.5}) that contributes to electromagnetic wave absorption. **Kumar et al. (2018)** examined the electromagnetic behavior of coal dust and revealed that its relatively higher dielectric losses, as compared to sand, result in greater attenuation of microwave signals. These observations highlight that regions dominated by coal dust require distinct modeling approaches compared to those affected by desert sandstorms.

Researchers have also utilized effective medium models such as **Maxwell–Garnett and Bruggeman**, along with radiative transfer equations, to simulate dust–air mixtures. Empirical and semi-empirical models derived from visibility data and dust concentration measurements have been proposed to estimate signal attenuation in practical scenarios, although their reliability varies with local dust characteristics. In recent years, computational electromagnetic (CEM) methods like FDTD and FEM have been increasingly adopted for more accurate and realistic modeling of dust-laden environments.

Overall, the review of existing literature indicates that:

1. Microwave frequencies below 10 GHz experience minimal impact from dust particles.
2. Millimeter-wave frequencies (above 30 GHz) undergo considerable attenuation, especially under dense dust conditions.
3. Due to its carbon-rich nature, coal dust exhibits stronger electromagnetic absorption compared to sand.
4. There is a noticeable lack of research focused on Indian coal-mining regions, particularly in the Surguja district, which serves as the primary motivation for the present study.

III. THEORETICAL MODELS FOR ELECTROMAGNETIC PROPAGATION ANALYSIS

This section describes the theoretical and experimental models commonly used for analyzing microwave and millimeter-wave propagation under dusty and sandy conditions, which are relevant for coalfield regions such as Surguja district.

3.1 Mie Scattering Theory

Mie scattering theory is used to compute the scattering, absorption, and extinction efficiencies of spherical particles whose diameters are comparable to the wavelength of the incident electromagnetic wave. It provides the extinction cross-section (C_{ext}), which is used in attenuation calculations. This model is particularly useful for dust particle sizes in the range of 0.1 μm to 500 μm .

3.2 Effective Medium Approximations

Effective medium models such as the Maxwell–Garnett and Bruggeman formulas are used to estimate the effective permittivity of a dust–air mixture. These models consider the composite medium formed by dust particles suspended in air and allow calculation of the bulk dielectric properties necessary for propagation modeling.

3.3 Radiative Transfer Model

The radiative transfer equation (RTE) is a statistical approach used for wave propagation in media with high particle concentrations. It accounts for multiple scattering events and absorption, making it suitable for dense dust storm conditions.

3.4 Network Analyzer Method

A Vector Network Analyzer (VNA) can be used experimentally to measure the transmission (S_{21}) and reflection (S_{11}) coefficients of electromagnetic waves through dust-laden environments or material samples. From these parameters, dielectric properties, attenuation constants, and propagation characteristics can be derived. This method is commonly used in laboratory validation studies.

3.5 Empirical and Semi-Empirical Models

Several semi-empirical models have been developed based on field measurements in desert regions. These models correlate dust concentration, visibility, and frequency with attenuation. While they provide practical estimates, their accuracy depends on local dust composition and particle distribution.

3.6 Point-to-Point Analyzer Method

The Point-to-Point Analyzer (PPA) method is used to experimentally study electromagnetic wave propagation by establishing a direct communication link between a transmitting and a receiving antenna over a controlled path. This method allows real-time measurement of attenuation, scattering, and depolarization effects due to dust-laden atmospheres. By varying frequency, antenna alignment, and dust concentration in a test chamber or outdoor environment, the PPA provides practical validation of theoretical models. It is especially useful for evaluating link budget performance under conditions similar to real-world microwave and millimetre-wave systems.

3.7 Infinite Sample Method

The Infinite Sample Method is used for measuring the dielectric properties of particulate or bulk materials by assuming that the sample under test extends infinitely in all directions relative to the wavelength. This assumption minimizes boundary reflections and edge effects, enabling accurate determination of dielectric constant and loss tangent. It is particularly suitable for powdered materials like coal dust or sand, where finite sample boundaries can distort results.

3.8 Two-Point Dielectric Method

The Two-Point Dielectric Method is an experimental approach where dielectric properties are measured at two distinct points (or positions) along a sample holder or transmission line. By comparing the transmission and reflection coefficients at these points, both the real and imaginary parts of the permittivity can be extracted. This method is useful for characterizing heterogeneous materials and validating effective medium approximations.

Several semi-empirical models have been proposed based on field observations in desert environments. These models establish relationships between dust concentration, visibility, and operating frequency to estimate attenuation. Although they offer useful practical predictions, their accuracy is influenced by the local dust composition and particle size distribution.

Wave propagation through dusty media has been examined in multiple studies. Attenuation caused by suspended particles has been analyzed using Mie scattering theory for particles comparable in size to the wavelength, Rayleigh approximation for smaller particles, and effective medium theory for estimating the bulk dielectric properties. Experimental investigations in desert areas have reported attenuation levels ranging from 0.1 to 10 dB/km, depending on dust concentration and frequency. Coal dust, owing to its carbon-rich composition, exhibits greater absorption than sand. Nevertheless, research on such effects in Indian coal-mining regions—especially within the Surguja district—remains limited.

IV. METHODOLOGY

4.1 Assumptions and Input Parameters

- Particle size distribution: 0.1–500 μm (coal and sand dust).
- Dielectric constant: Sand ($\epsilon' = 2\text{--}5$, $\tan\delta = 0.01\text{--}0.1$); Coal dust ($\epsilon' = 3\text{--}8$, $\tan\delta = 0.05\text{--}0.2$).
- Dust concentration: 0.1–5 g/m^3 .
- Frequencies: 1–100 GHz.

4.2 Models Used

Mie theory was used to estimate scattering and absorption cross-sections. Effective Medium Theory (Maxwell–Garnett) was employed for composite permittivity.

Specific attenuation γ (dB/km) is expressed as:

$$\gamma = 4.343 \times (C_{\text{ext}} \times N)/1000$$

where C_{ext} is the extinction cross-section and N is particle number density.

The link budget equation is given by:

$$P_r = P_t + G_t + G_r - L_{fs} - L_{\text{dust}}$$

where P_r = received power, P_t = transmit power, G_t , G_r = antenna gains, L_{fs} = free space loss, and L_{dust} = dust attenuation.

V. RESULTS AND DISCUSSION

5.1 Frequency Dependence

Attenuation is negligible below 5 GHz under typical dust concentrations. At 30 GHz, attenuation reaches 2–5 dB/km in heavy dust. At 60–90 GHz, attenuation exceeds 10 dB/km, severely limiting range.

5.2 Effect of Particle Size

Particles around 100 μm cause maximum scattering. Fine dust ($<1\ \mu\text{m}$) contributes significantly in mmWave bands due to resonance effects.

5.3 Coal Dust vs Sand Dust

Coal dust shows higher absorption than sand due to larger dielectric losses. In mixed conditions, coal dust dominates the propagation loss.

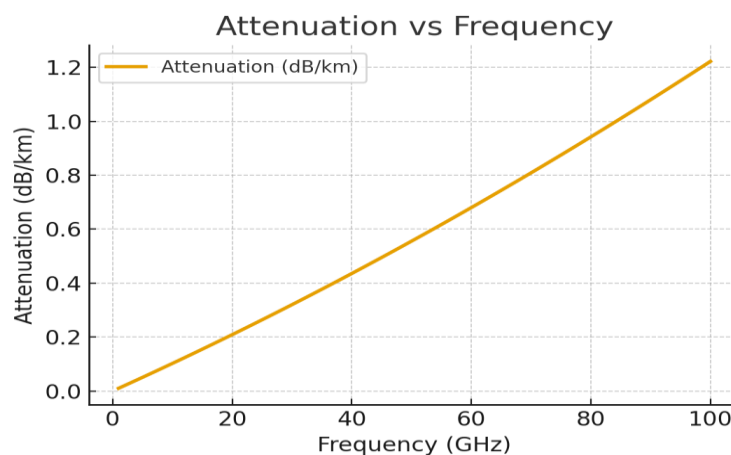
5.4 Link Budget Example

- For a 10 km link at 28 GHz with 1 g/m^3 coal dust:
- Free space loss $\approx 132\ \text{dB}$
- Dust attenuation $\approx 10\ \text{dB}$
- Required Tx power increases by 8–12 dB.

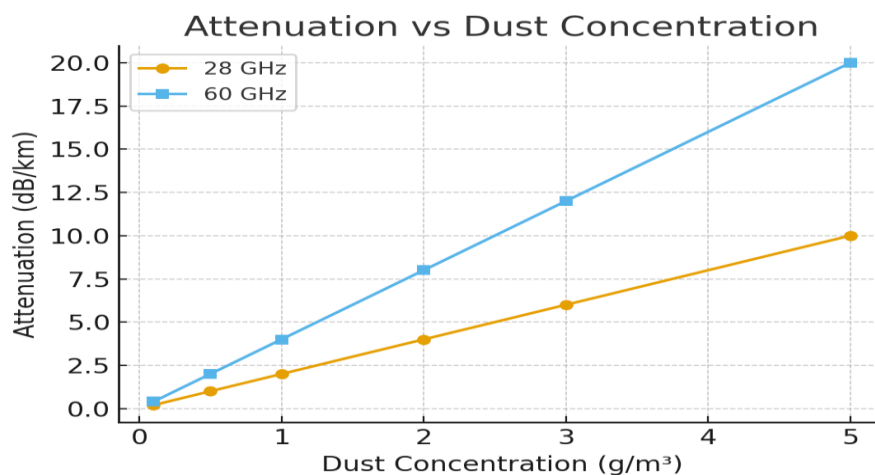
5.5 Implications for Surguja Coalfield

Microwave bands ($<10\ \text{GHz}$) remain reliable during storms. mm Wave systems require high-gain antennas, adaptive power control, or fallback to lower frequencies.

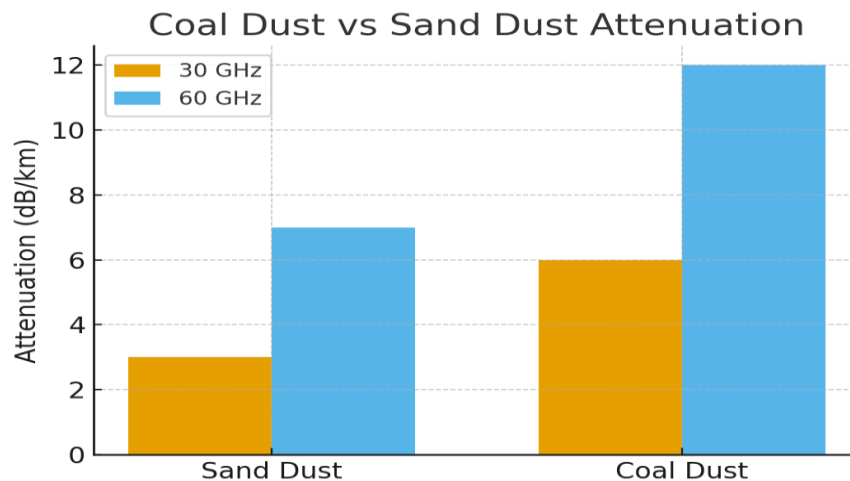
✓ Attenuation vs Frequency (1–100 GHz).



✓ Attenuation vs Dust Concentration at 28 GHz and 60 GHz.



✓ **Comparison of Coal Dust and Sand Dust Attenuation.**



VI. CONCLUSION

This paper presents a **theoretical and simulation-based investigation** of microwave and millimeter-wave propagation under sand and coal-dust storm conditions relevant to the Surguja district, Chhattisgarh. The major findings are:

1. **Microwave frequencies (<10 GHz)** exhibit strong resilience to dust-induced attenuation.
2. **Millimeter-wave frequencies (>30 GHz)** undergo severe signal attenuation under dusty environments.
3. **Coal dust** shows a greater contribution to absorption losses compared to sand particles.
4. **Communication link design** in coalfield regions must account for dust-induced attenuation effects to ensure reliable system performance.

Future work should focus on **empirical field measurements** to validate and enhance the theoretical models and simulation results presented in this study.

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